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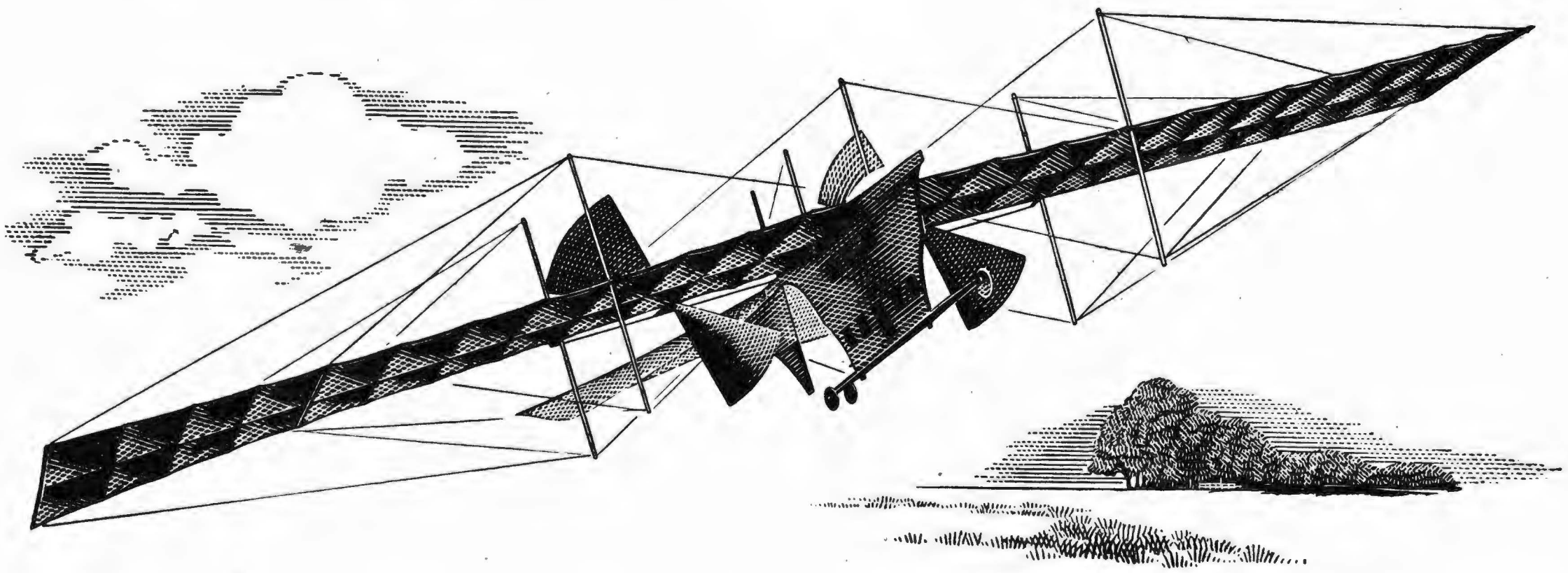

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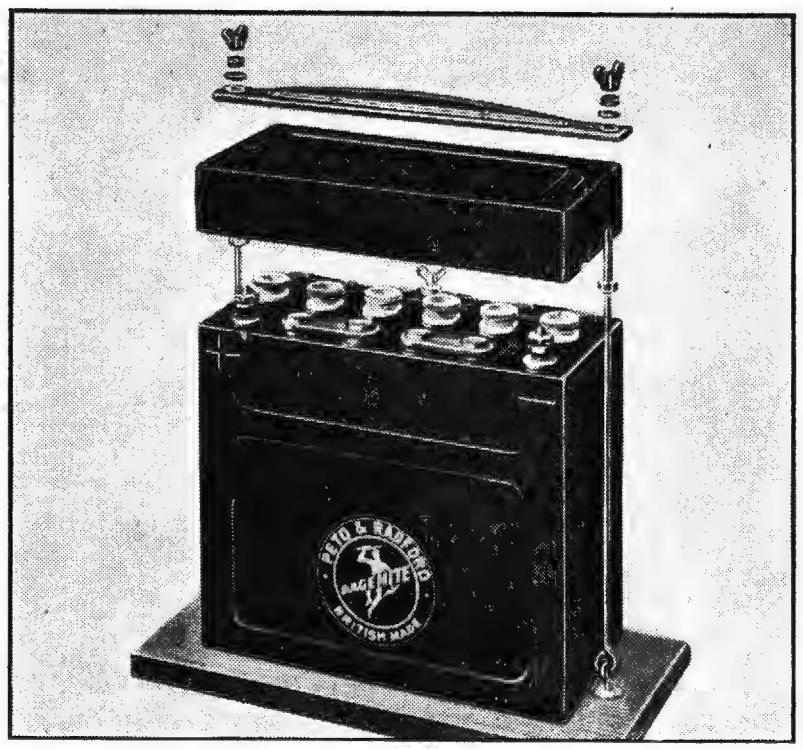

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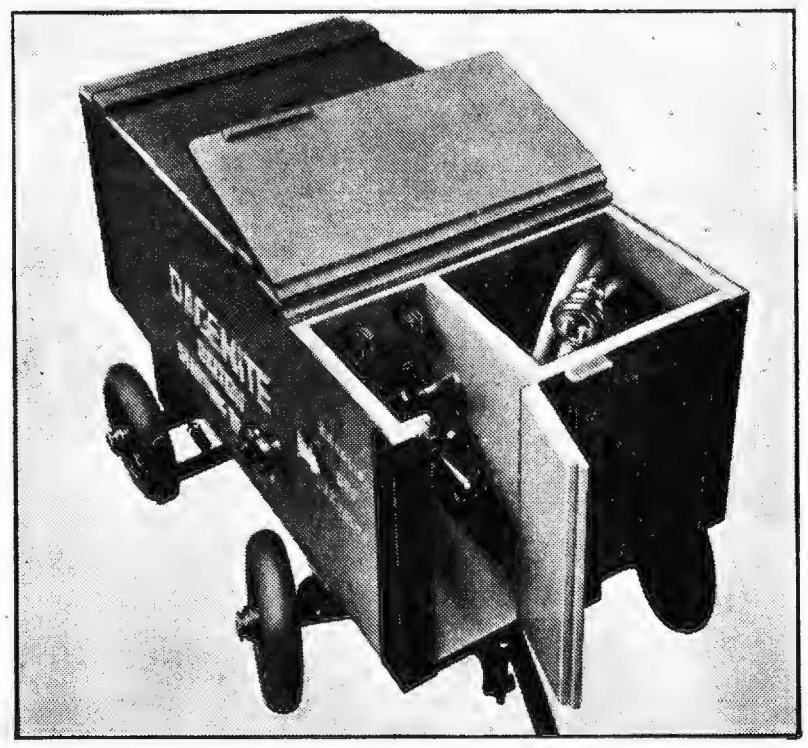

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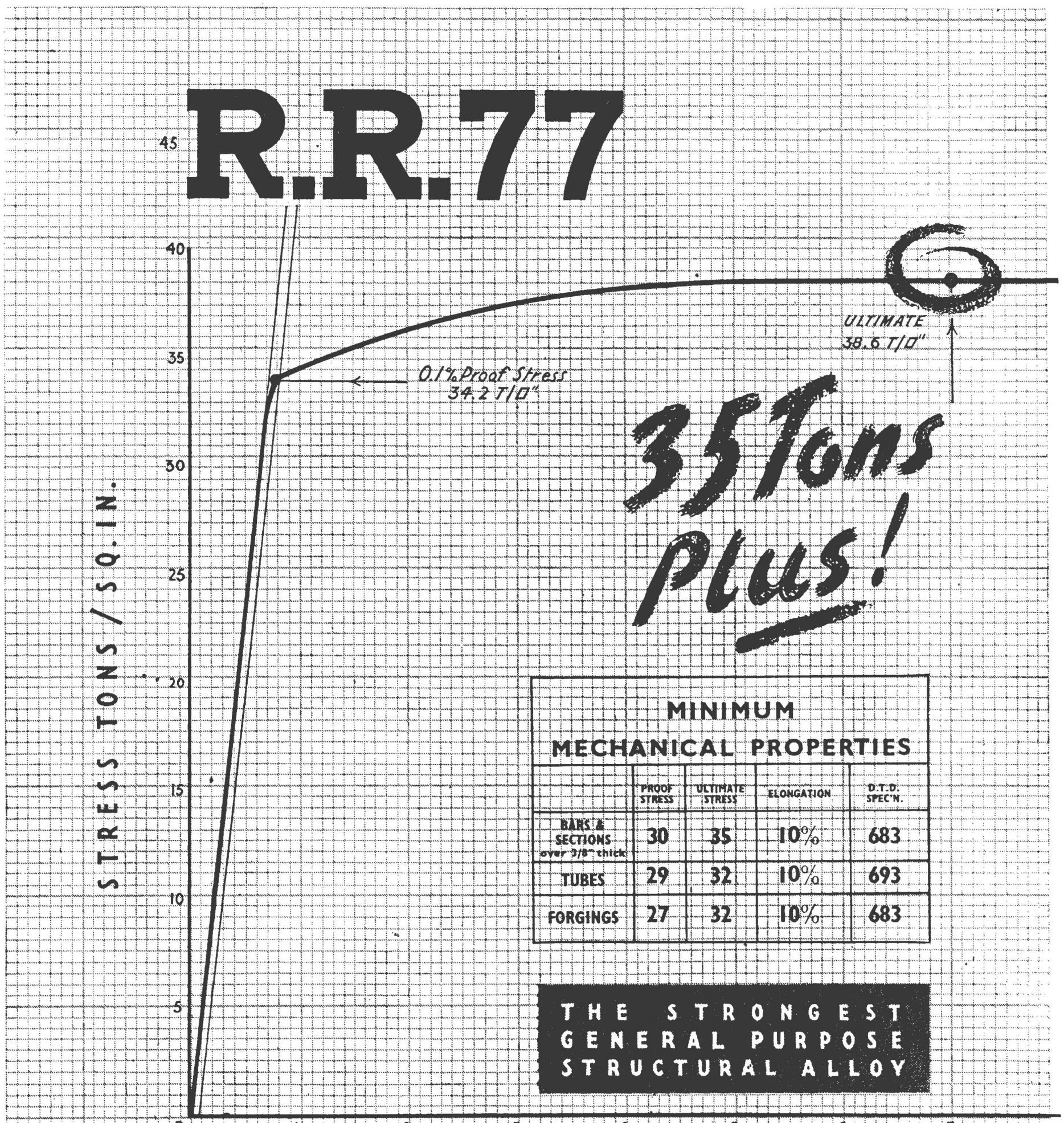

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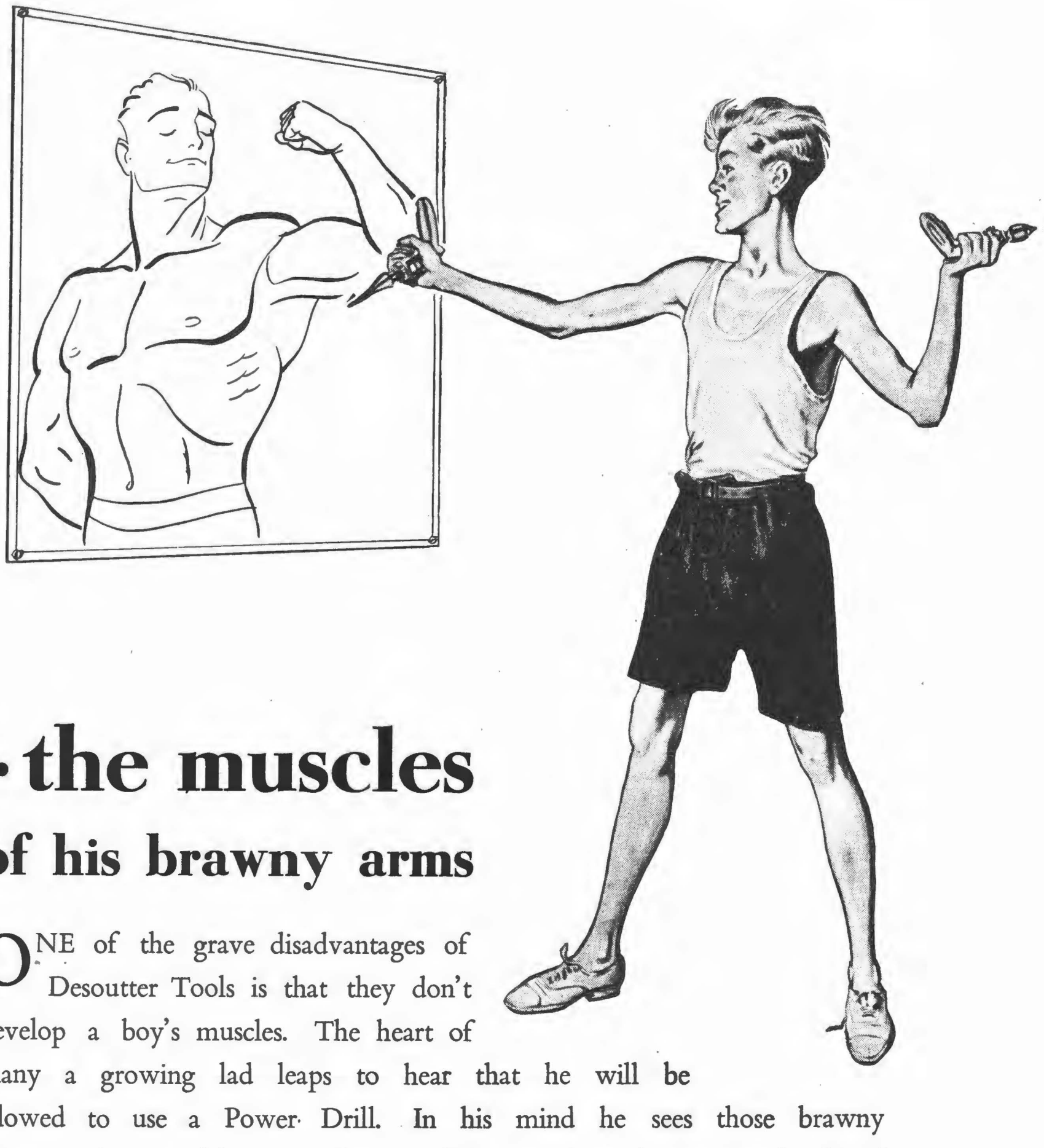

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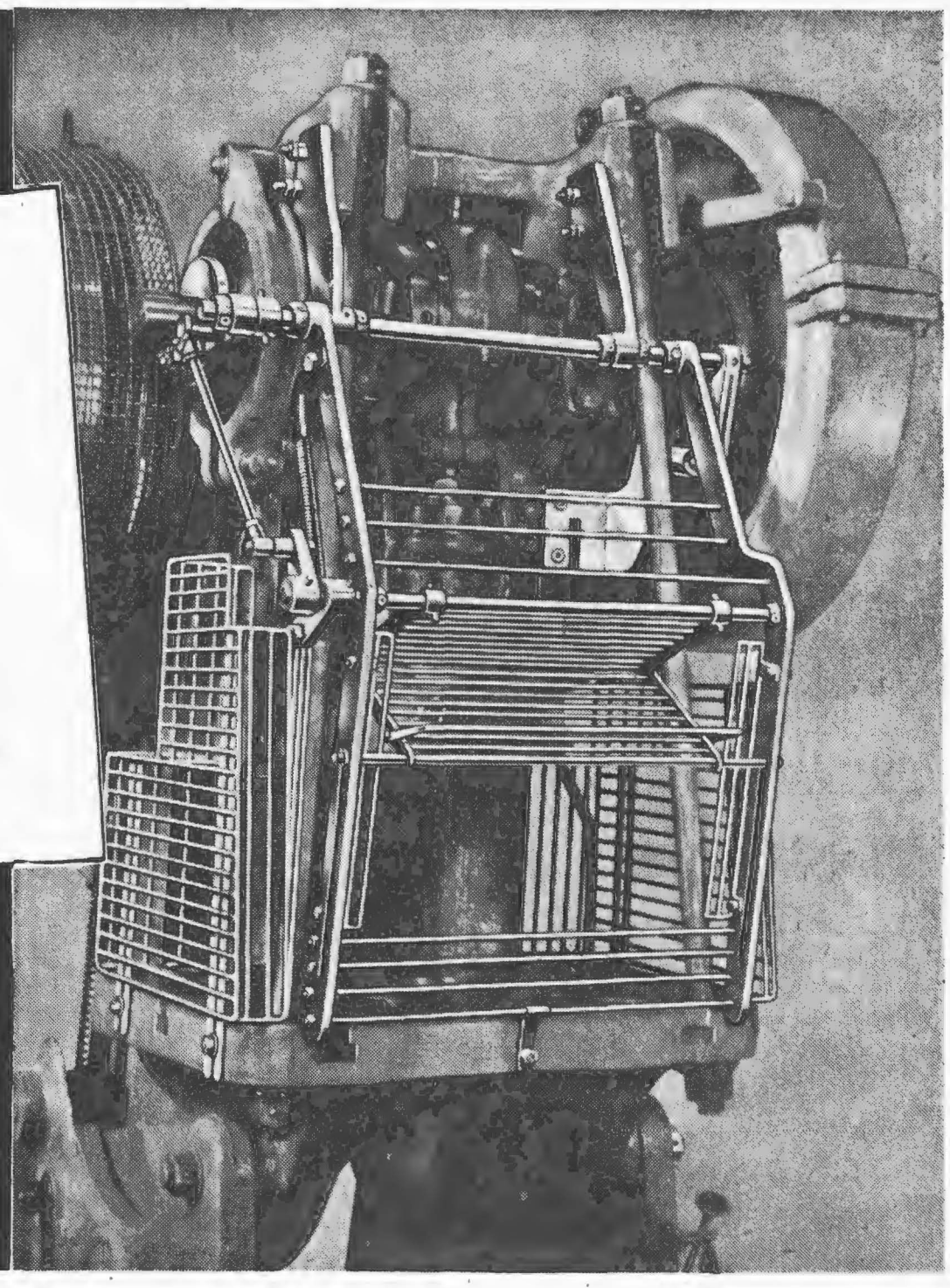

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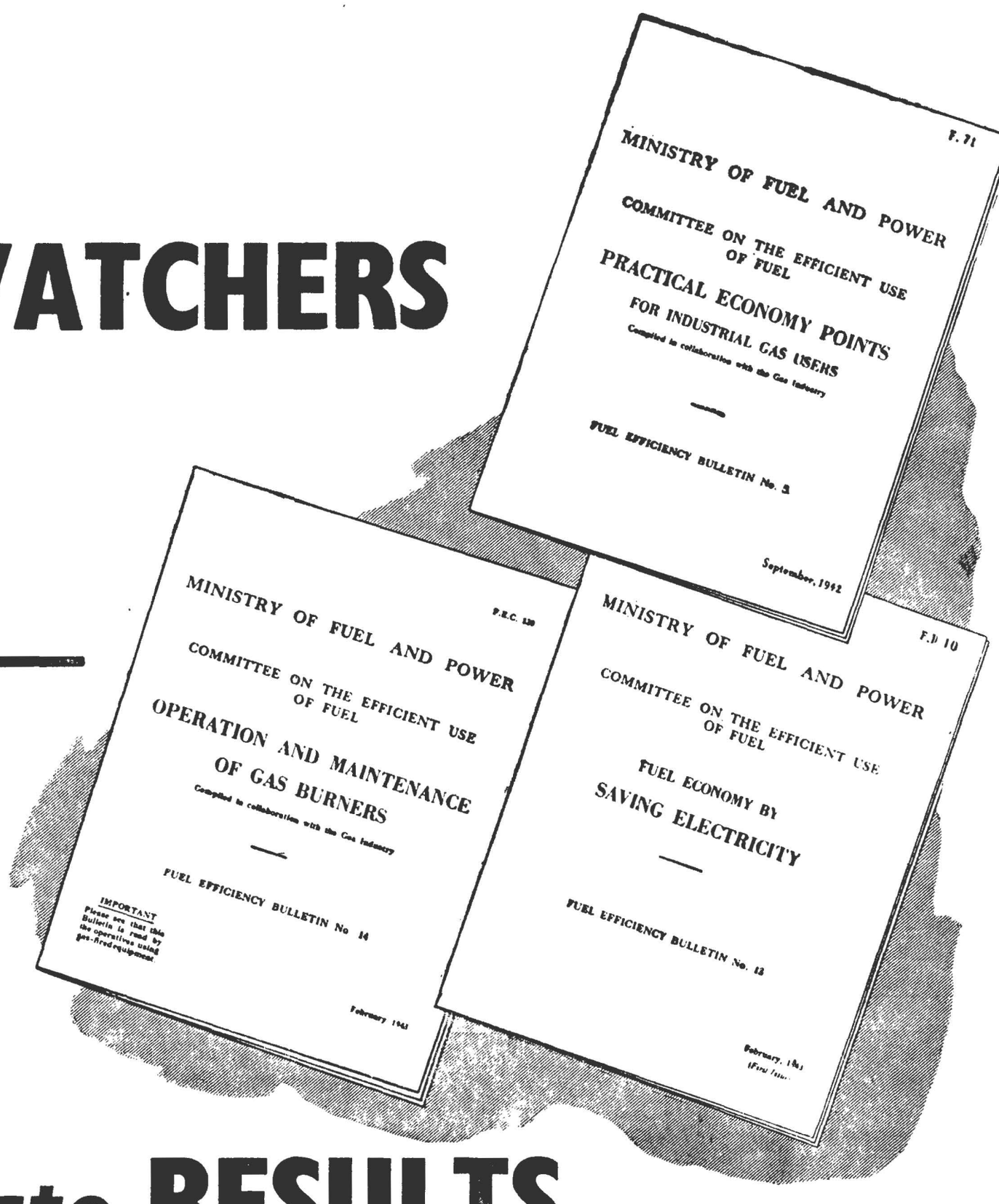

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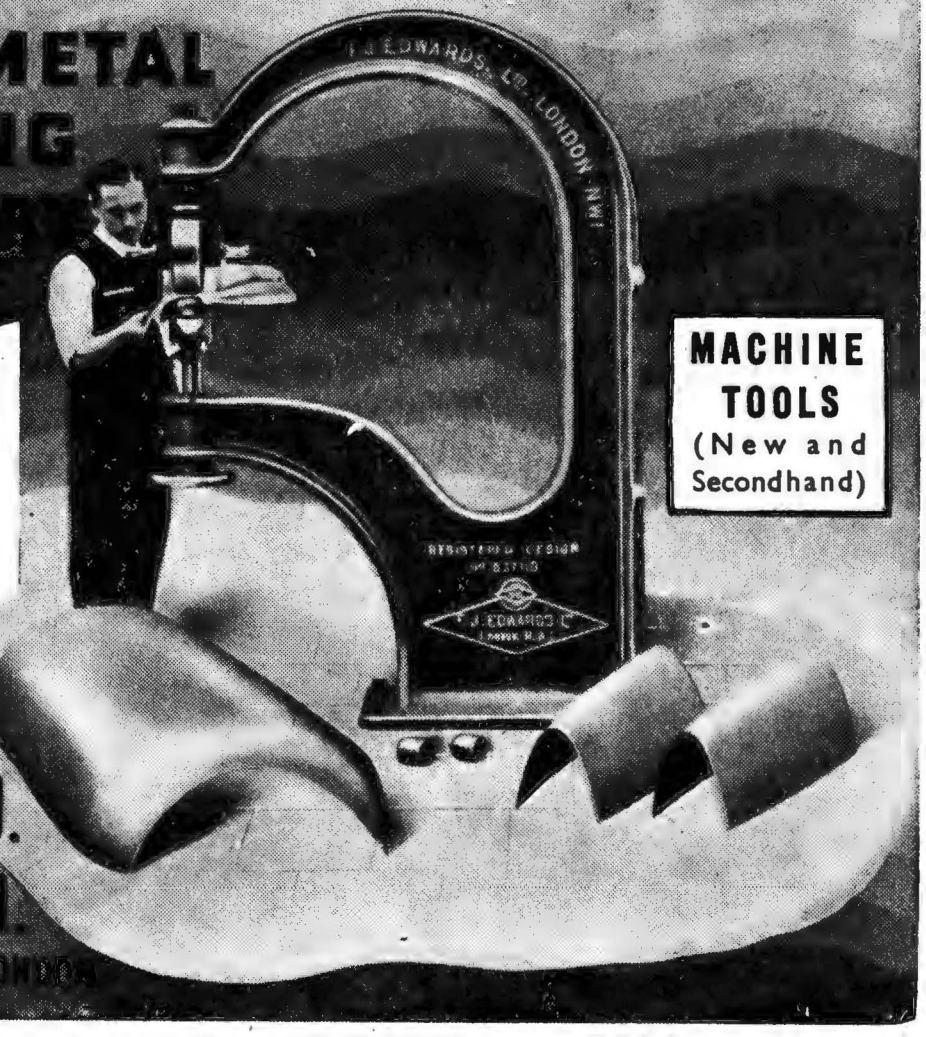

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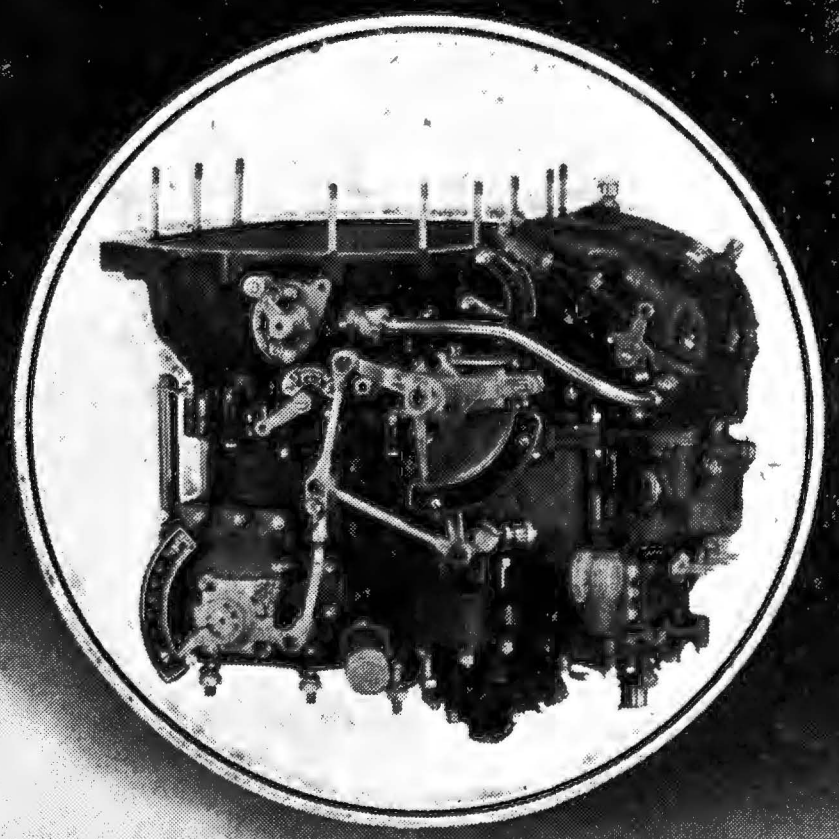

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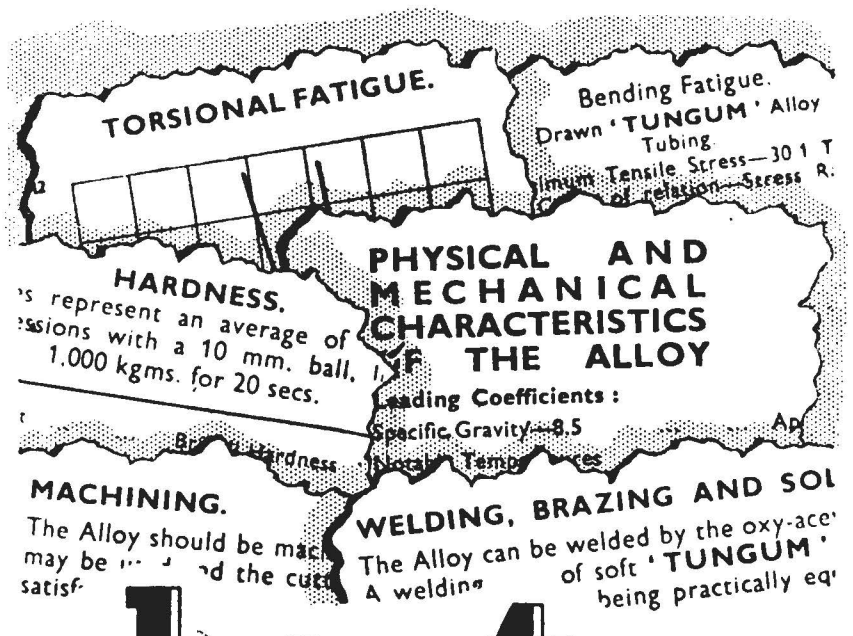

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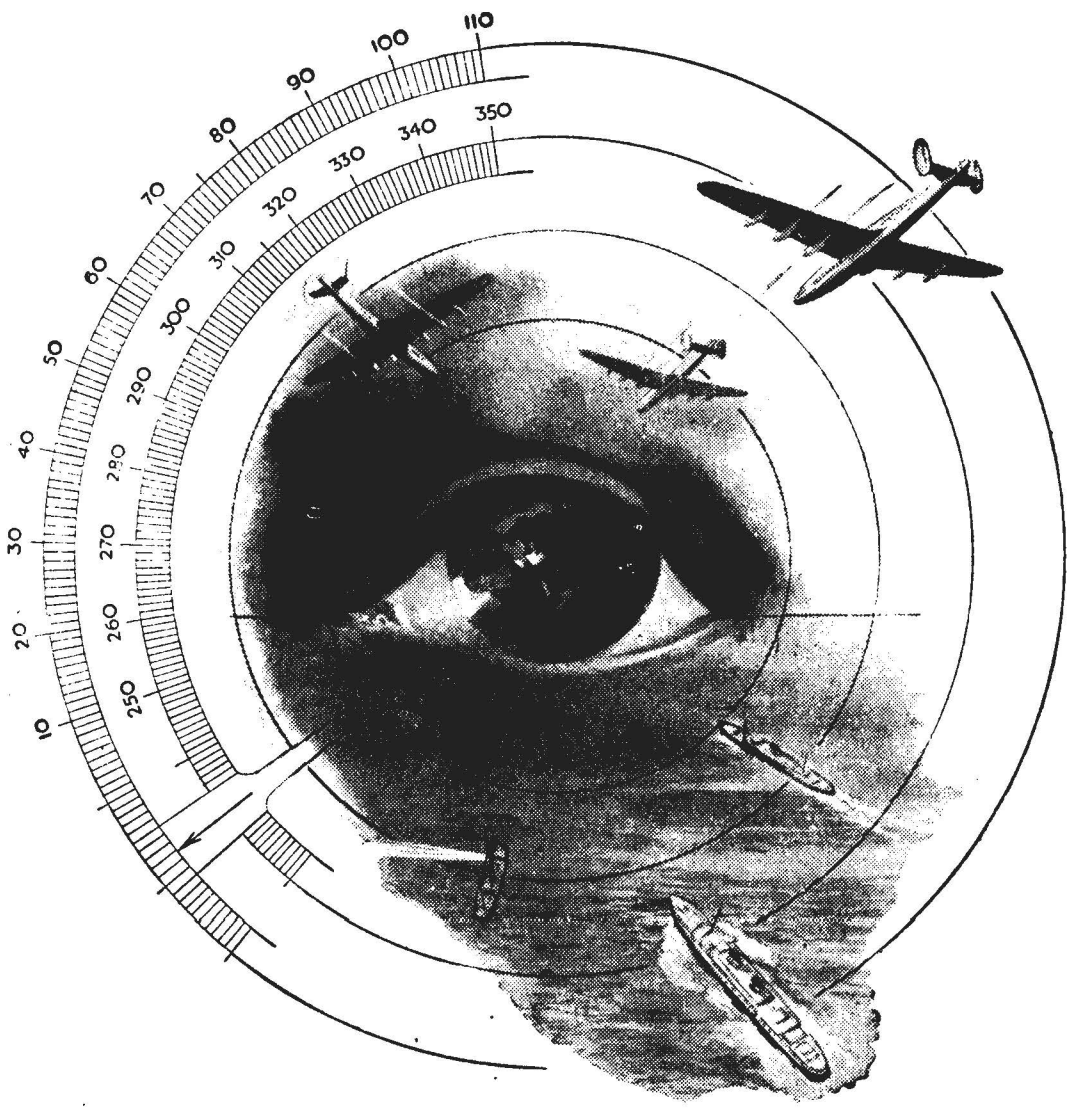

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Vol. XVII No. 193
MARCH - 1945
Published about the 18th of the month

Aircraft Engineering

FOUNDED 1929

Editor: Lieut.-Col. W. Lockwood Marsh, O.B.E., F.R.Ae.S., M.S.A.E., F.I.Ae.S.

EDITORIAL ADDRESS & ADVERTISEMENT OFFICE
12 Bloomsbury Square, London, W.C.1

Telephone: HOLborn 4842-3

Telegrams: Ikaros, Westcent, London

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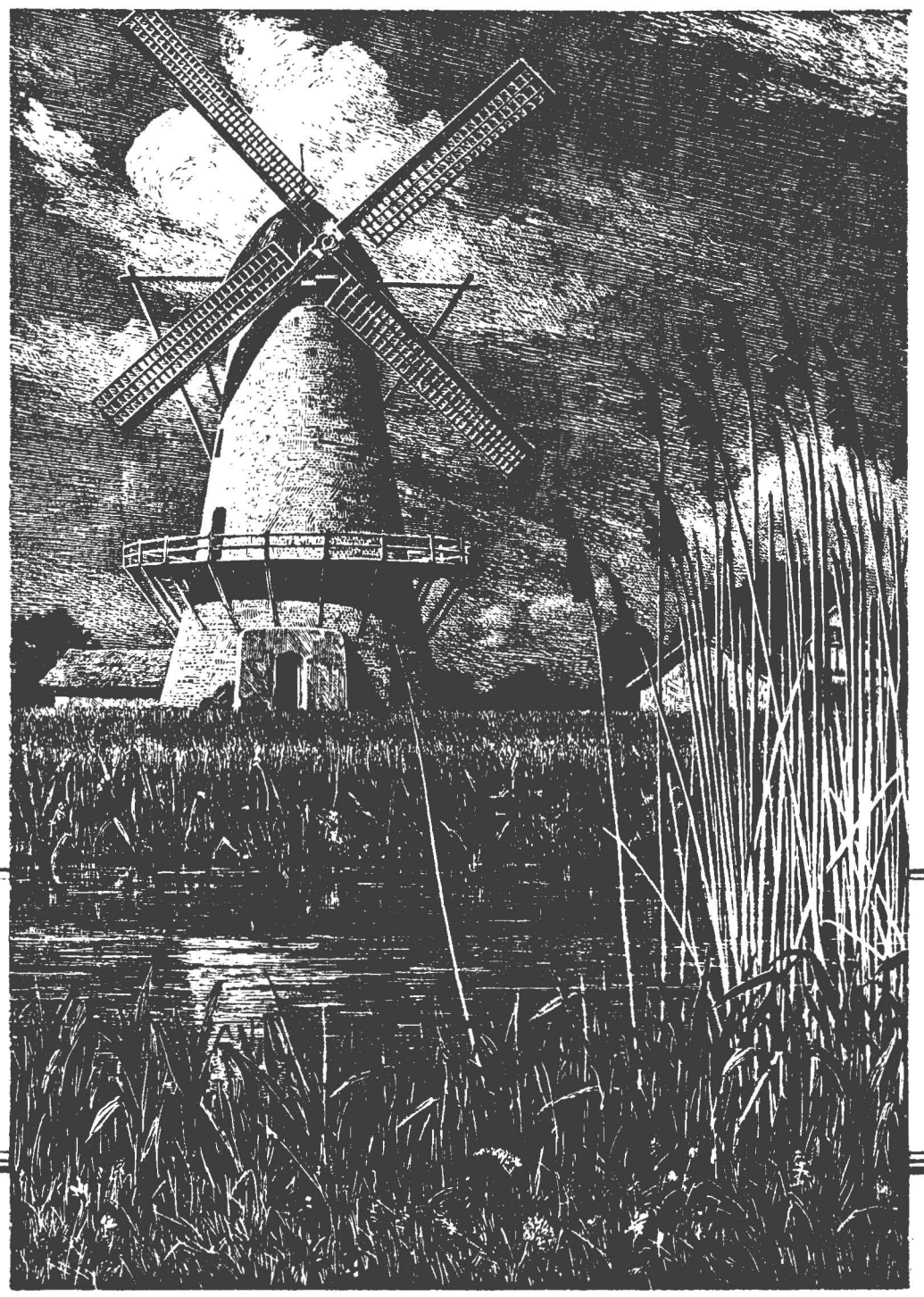

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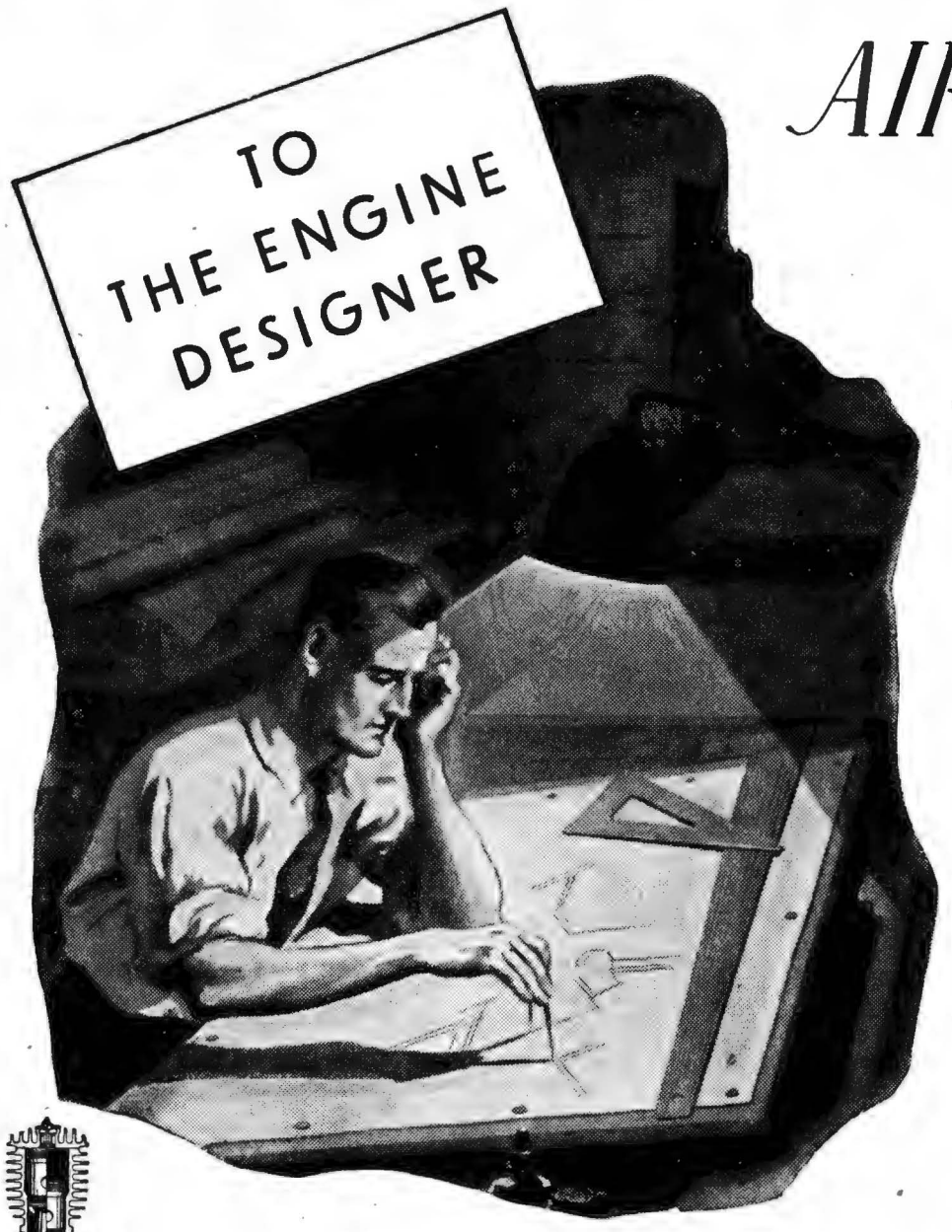

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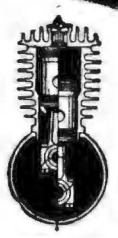

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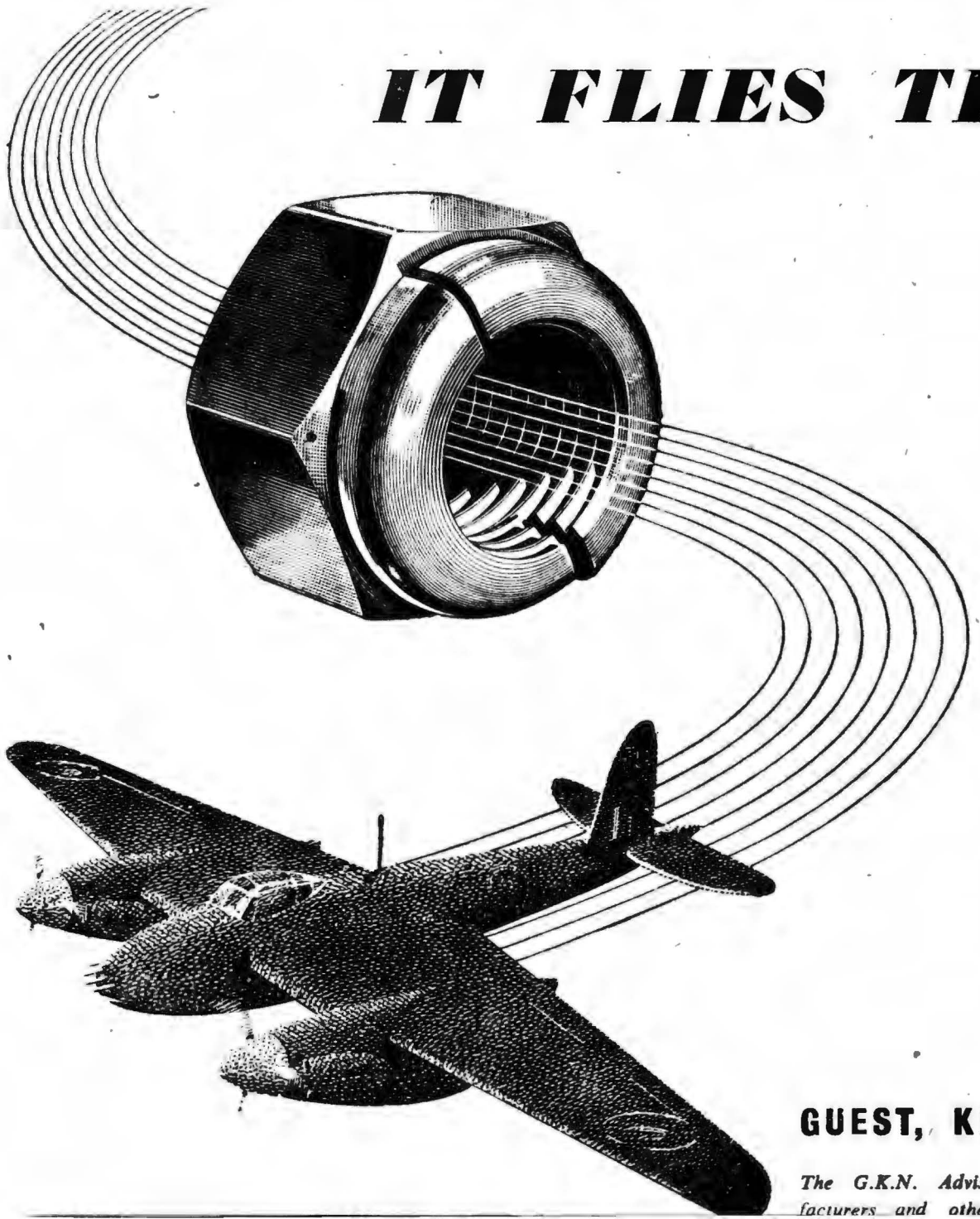

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Aircraft Engineering

The Monthly Scientific and Technical Organ of the Aeronautical Engineering Profession

Editor: Lieut.-Col. W. Lockwood Marsh, O.B.E., F.R.Ae.S., M.S.A.E., F.I.Ae.S.

Vol. XVII. No. 193 **March, 1945**

A NOTABLE ACHIEVEMENT

IN this issue we are able to give the first authoritative description of the extremely ingenious equipment providing "automatic" aids to air navigation which has been under development in this country since before the war, but even the fact of the existence of which has only recently been released for publication.

British Supremacy

It is perhaps desirable to emphasize, since it has been installed in long-range aeroplanes of the Allies in general, that it is purely and entirely a British development and credit is solely due to the staff of the ROYAL AIRCRAFT ESTABLISHMENT for the initial design and to the British firms who have co-operated in its development and manufacture. In this respect it is to be put alongside the equally ingenious electric gun sight, which has made the fire power of British fighter pilots so infinitely more effective, and it links up with the R.A.E. automatic pilot and the bomb sights which, despite all that has been written by interested parties and the contrary, are without equal among other nations. These devices together have immeasurably lightened the task of bomber pilots, navigators and bomb-aimers and have together contributed to the outstanding and unique precision of British bombing by comparison with the attacks of the other combatant nations. In case this is considered to be a controversial statement we would like to add that it is made with a full sense of responsibility and is borne out by overwhelming evidence supplied by contemporaneous air photographs, now, at long last, confirmed by examination of the targets by the ground forces which have taken and occupied the sites, as well as by numerous eye-witnesses who have experienced the attacks. The photographs that have appeared recently of the still-standing towers of Cologne Cathedral and the practically undamaged state of the residential areas of that city alongside the devastated industrial quarters is, almost of itself, sufficient confirmation even without all the other supporting testimony from innumerable sources.

A Shelter Puzzle

Incidentally, to digress from the main subject on which we are writing, published accounts of the conditions that have been found to exist in captured German cities—notably Krefeld—seem to indicate that the Germans have "got something" in regard to air-raid shelters that is a considerable advance on anything that has been erected in England. It is stated by a *Times* Special Correspondent that in that town there was only one subterranean shelter. Protection had been given to the remainder of the population of about 120,000 civilians by the erection of 21 enormous surface shelters—each capable of housing between 5,000 and 10,000 people—built entirely above ground to a height of about 50 feet. According to another account these are reinforced concrete structures with 3-feet thick walls and 6-feet thick roofs. Full details of these buildings would be extremely interesting as the information so far available hardly seems to explain their apparent complete immunity from the effects not only of blast but of direct hits—for it seems, too, unlikely to assume that they have in every case been so fortunate as to escape a direct hit in view of the statement that "though entire blocks of buildings have been laid waste around them these shelters have not suffered in the slightest." the sparse structural details we have quoted certainly would not imply such strength and resistance to explosions as they undoubtedly appear to possess. The point is of considerable importance because the existence of air-raid shelters of this massive type serves to explain the hitherto puzzling feature of the continuance of life and activity in towns which have been subjected to repeated and concentrated attack by high explosive bombs of the largest calibre in enormous numbers from great fleets of Allied bombers.

The Distant Reading Compass

To revert to the subject of the British navigational equipment described by MESSRS. SCRIMSHAW & WELLS, this consists of three separate but mutually inter-related units: the Distant Reading Compass, the Air Mileage Unit (or air log) and the Air Position Indicator. The first is the master instrument and combines the functions of the old magnetic compass and directional gyro. The combination permits of the corrections being transmitted automatically from the one to the other at frequent intervals and thus eliminates the need for the application of them manually—and inevitably less frequently. The possibility of errors creeping in is thereby reduced to the minimum—as will be appreciated when it is realized that they are made every 5 or 6 seconds. The value of this to the pilot of an aeroplane during the time of attacking operations is manifest. With an ordinary type of aircraft compass it used to be necessary for the aeroplane to be flown on a straight and level course for an appreciable length of time—measured in minutes, during which it might be desirable to take violent "evasive action" in avoidance of *flak*. Now an accurate reading can be obtained in a matter of a few seconds, which also of course enormously helps the bomb-aimer and increases the precision of his work.

Not the least of its minor advantages is that in the worst conditions false corrections—arising from external causes—are in the same way put right quickly and will not give rise to prolonged inaccuracies in bearing direction. The instrument thus finally eliminates the bugbear of Northerly Turning Error.

The A.M.U. and the A.P.I.

The Air Mileage Unit similarly removes from the navigator the responsibility for computing from the A.S.I., altimeter and thermometer readings the true air speed, and resulting distance flown. These calculations are automatically done for him by the A.M.U.

The two sets of results, from the D.R.C. and the A.M.U., are finally automatically combined in the Air Position Indicator which gives a continuous air-plot and shows the precise air position at any time in degrees and minutes of latitude and longitude.

Apart from the various "repeater" instruments distributed at convenient points in the aeroplane, sufficient power is provided to enable the compass to operate the latest type of bomb-sight, leading to the increased accuracy to which we have already referred, as well as the automatic pilot.

We have endeavoured to give just a brief survey of the essential features of the complete instrument comprising the three units and to indicate its importance as an aid to those operating large aeroplanes. It will be almost as valuable and essential a piece of equipment in long-range commercial aeroplanes—as witness its proved assistance to Coastal Command—as in military bombers. It is impossible to praise too highly the skill and ingenuity of those responsible for its evolution and it is good indeed to know that it is exclusively and incontrovertibly British.

FLYING CHARACTERISTICS

One of the perennial difficulties is arriving at some quantitative assessment of the flying characteristics of an aeroplane from the pilot's point of view. Individual pilots will differ in their judgment of the desirability or otherwise of the idiosyncracies in regard to control of any given type of aeroplane, and it is only natural that the human element should introduce certain prejudices and predilections. In this issue DR. HICK interestingly tries to average the pilot, treating him as it were as a "robot" with assessable qualities; thus approaching the subject from the opposite angle.

Automatic Air Navigation*

A Description of Some New British equipment

By F. H. Scrimshaw, B.Sc., A.Inst.P. and J. A. Wells, A.F.R.Ae.S.

THE basic method of air navigation is deduced reckoning or simply dead reckoning. The method comprises the maintenance of an air pilot, which is made by calculating true airspeed and hence air distance run and then plotting this along the aircraft's heading from some initial ground fix. Subsequent ground positions may then be deduced by laying off the wind vector from the air position. As an example (Fig. 1) suppose an aircraft flies for one hour on a true heading of 060 deg. starting from an initial ground position A. If the true airspeed is 180 knots the air position will be at B, and if the mean wind over the flight is 45 knots from 340 deg. true then the ground position (by D.R.) corresponding to an air position at B would be at C. Now if the aircraft flies for the next hour on a true heading of 085 deg. and the mean wind over this hour is 30 knots from 310 deg. true, the air position with respect to A would be at D and the ground position at F. If a new air plot had been started at C then the air position, at the end of the second hour, would be at E and the ground position (by D.R.) again at F.

Forecast meteorological winds may be used or the wind may be found by drift measurements or by calculation from simultaneous ground positions and calculated air positions.

The data for maintaining the air plot is all available inside the aircraft, viz., from A.S.I. altimeter, air thermometer, compass and computors, and under ideal conditions a manual air plot can be maintained by a navigator to within an accuracy of about 2 per cent of the air distance covered. With the onset of war it soon became obvious that the need for an automatic air position indicator was very urgent in Bomber Command aircraft, since the navigator was quite unable to maintain an accurate manual air plot with the continual and sudden changes of course, height and airspeed which were made by the pilot to evade flak and searchlights.

This article describes equipment, now in general service use, which has been designed to maintain an automatic air plot during all normal manœuvres of heavy aircraft, to within an accuracy of 2 per cent of the total air distance covered.

The equipment may be divided into three main units, (*a*) the Distant Reading Compass (D.R.C.), (*b*) the Air Mileage Unit (A.M.U.), (*c*) the Air Position Indicator (A.P.I.). These three items are described in some detail later, but briefly the D.R.C. provides a remote stabilized indication of aircraft heading which is transmitted to the A.P.I. The A.M.U. transmits air distance run to the A.P.I. which combines this with the heading to maintain the air plot; this is shown on counters in terms of latitude and longitude to facilitate its transference to a chart

The development of the D.R.C. was started well before the outbreak of war and the first operational squadron, No. 7 (Stirlings), was fitted with D.R.C. equipment in March, 1941. This compass has now become standard equipment in nearly all medium and heavy British aircraft and some have been fitted into U.S.A.A.F. bombers.

Several early attempts had been made to devise an A.P.I. and some of these met with partial success; the major problem, however, was in the design of a simple and reliable A.M.U. or, as it was then called, an air log. The development of the present A.P.I. and A.M.U. were started in parallel in 1940 and production commenced towards the end of 1942. By February, 1943, the first squadron, again No. 7 of the Pathfinder Force, was fitted with A.P.I. and A.M.U. equipment, and since then the equipment has spread generally into the heavy aircraft.

The instruments have proved successful not only in routine operations but also in such actions as the epic attack on the Mohne and Eder dams in May, 1943, and in the American attack on the Ploesti oilfields in June, 1943. A limited number of Liberators were especially fitted with this equipment for the latter attack.

The Gyro-Magnetic Distant Reading Compass

It will be evident that only a brief description of the apparatus is possible. An elementary knowledge of the magnetic compass and the simple gyroscope is assumed.

The gyro-magnetic compass equipment consists of a master unit and a repeater system and, in common with other types of distant-reading compass, has the advantage that the master unit can be installed in a position in the aircraft where it is relatively free from magnetic disturbance. Repeaters are installed in front of the pilot, the navigator and in any other place where a knowledge of the aircraft's heading is required.

The master unit was designed to eliminate acceleration error, "liquid swirl" and other typical defects of the magnetic compass. Before its introduction the pilot of an aircraft kept himself informed of the aircraft's heading by using his magnetic compass in conjunction with a directional gyro. The latter instrument is a free gyroscope with horizontal spin axis. The vertical gimbal is fitted with a compass card and, although not north seeking, the instrument if set manually to a known heading will maintain that heading to within about 3 deg. over periods of 15 min. Thus, a pilot can set his directional gyro to the heading indication of the magnetic compass when the aircraft is in unaccelerated horizontal flight. Afterwards the directional gyro will give an approximately correct indication during all normal flight manœuvres. But, the instrument must be reset manually at intervals and under conditions suitable for the magnetic compass.

It will be obvious that the more frequently corrections are applied to the directional gyro the more accurate will its indications be. The gyro-magnetic compass uses a magnetic compass to apply automatically a frequent correction to a directional gyro; actually a correction is made every 5 to 6 seconds. The control is based on the heading of the magnetic compass and no account is taken of the aircraft's motion. Since the magnetic element is subject to all the usual errors it follows that the directional gyro receives a percentage of false corrections. It should be appreciated, however, that errors of the magnetic compass are of a transient nature and here their effect is minimized by using a small and constant rate of control over the gyroscope. The control is sufficient to correct for any free azimuth precession of the gyroscope but if incorrectly applied for short periods will not cause prolonged inaccuracies in heading indication. Under the worst circumstances, such as a slow turn through a northerly direction the heading indication may be as much as 2 deg. or 3 deg. in error, but this will be automatically corrected by continuing the turn or after less than one minute of straight flight. The gyro can be said to indicate the mean magnetic heading from a series of observations and in normal flight the indications will not differ appreciably from the correct magnetic heading at any time. A comparison of the heading indications of the D.R. compass with two magnetic compasses A and B of orthodox design is shown in Fig. 2. The aircraft actually turned from W through N to E wih a 40 deg. bank and the compass readings were recorded automatically at one second time intervals by means of a ciné camera. The gyro magnetic compass shows a practically constant rate of change of heading during ½ min. Compass A tends to indicate a reverse turn while compass B, with less damping has indicated a turn in the reverse direction of the aircraft's actual heading.

The complete D.R. compass system is operated from the 24-v. D.C. supply of the aircraft. The pilot or the navigator is provided with control switches for starting and stopping the master unit and also a device, the variation setting corrector (V.S.C.), which enables him to adjust the repeater to read true instead of magnetic heading at any time during flight. On the present equipment any number of repeaters up to a maximum of six may be employed.

The Master Unit

Referring to Fig. 3 it will be seen that the

* The authors wish to thank the Ministry of Aircraft Production for permission to publish this article, and also Mr. H. C. Pritchard, B.A., A.F.R.Ae.S., and Mr. F. J. Twiney, B.Sc., for their help and advice. Figures 3, 4, 7, 9 and 10 are Crown Copyright Reserved and published by permission of H.M. Stationery Office

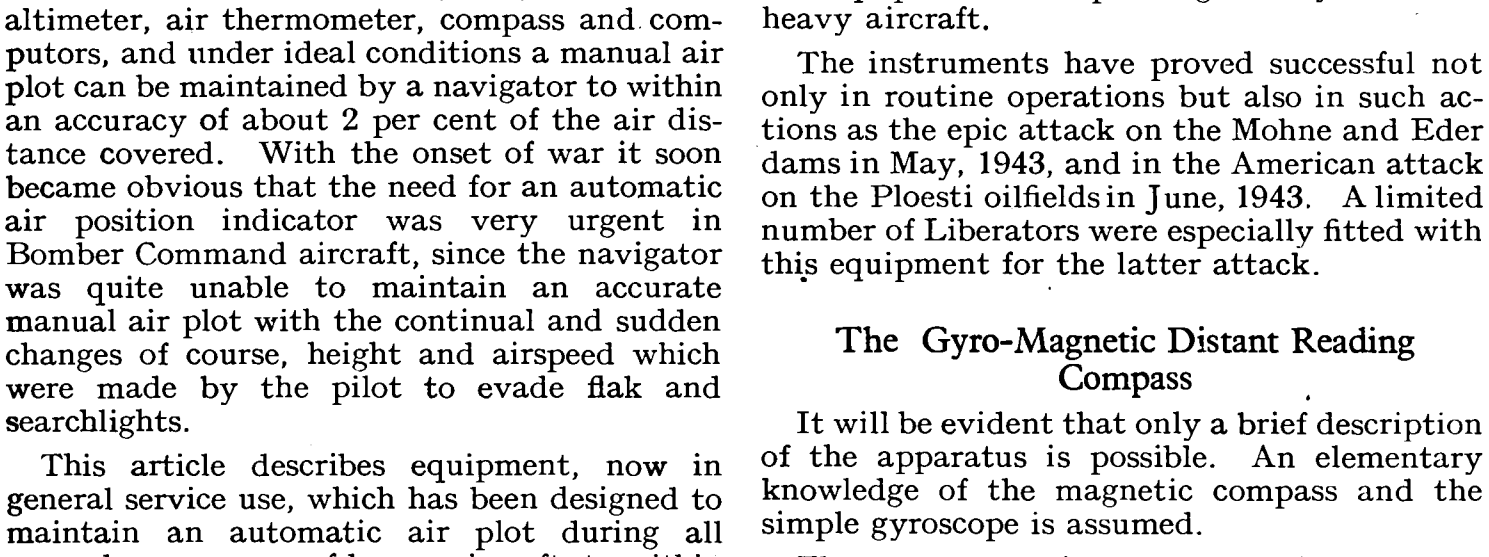


FIG. 1.—*Example of D.R. plot*

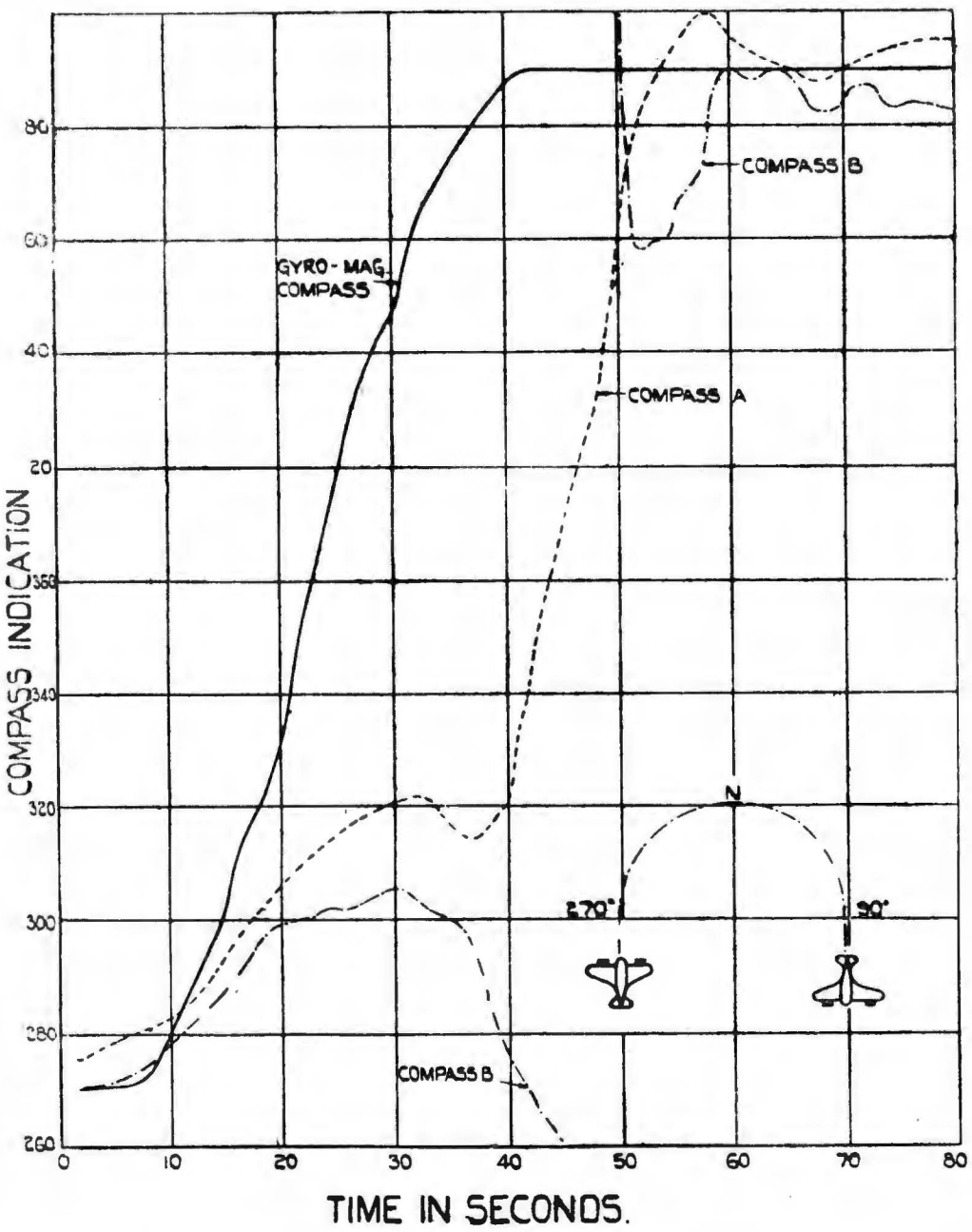


FIG. 2. — *Compass indications during a turn through W — N — E on a 40 deg. bank*

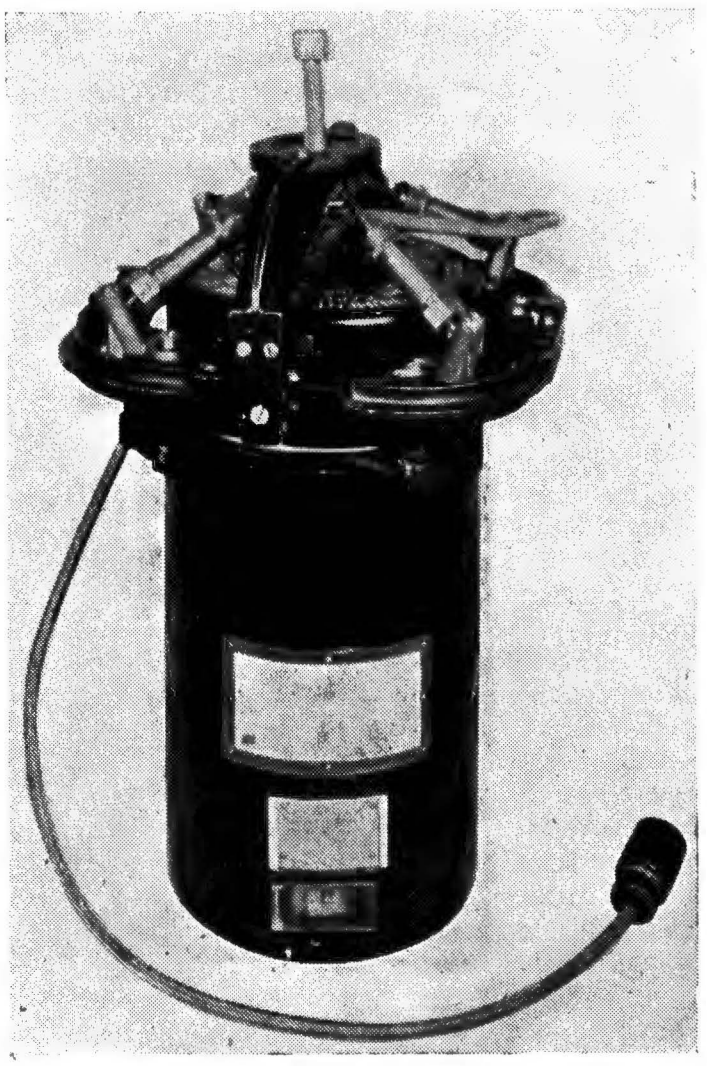


FIG. 3.—*Master unit*

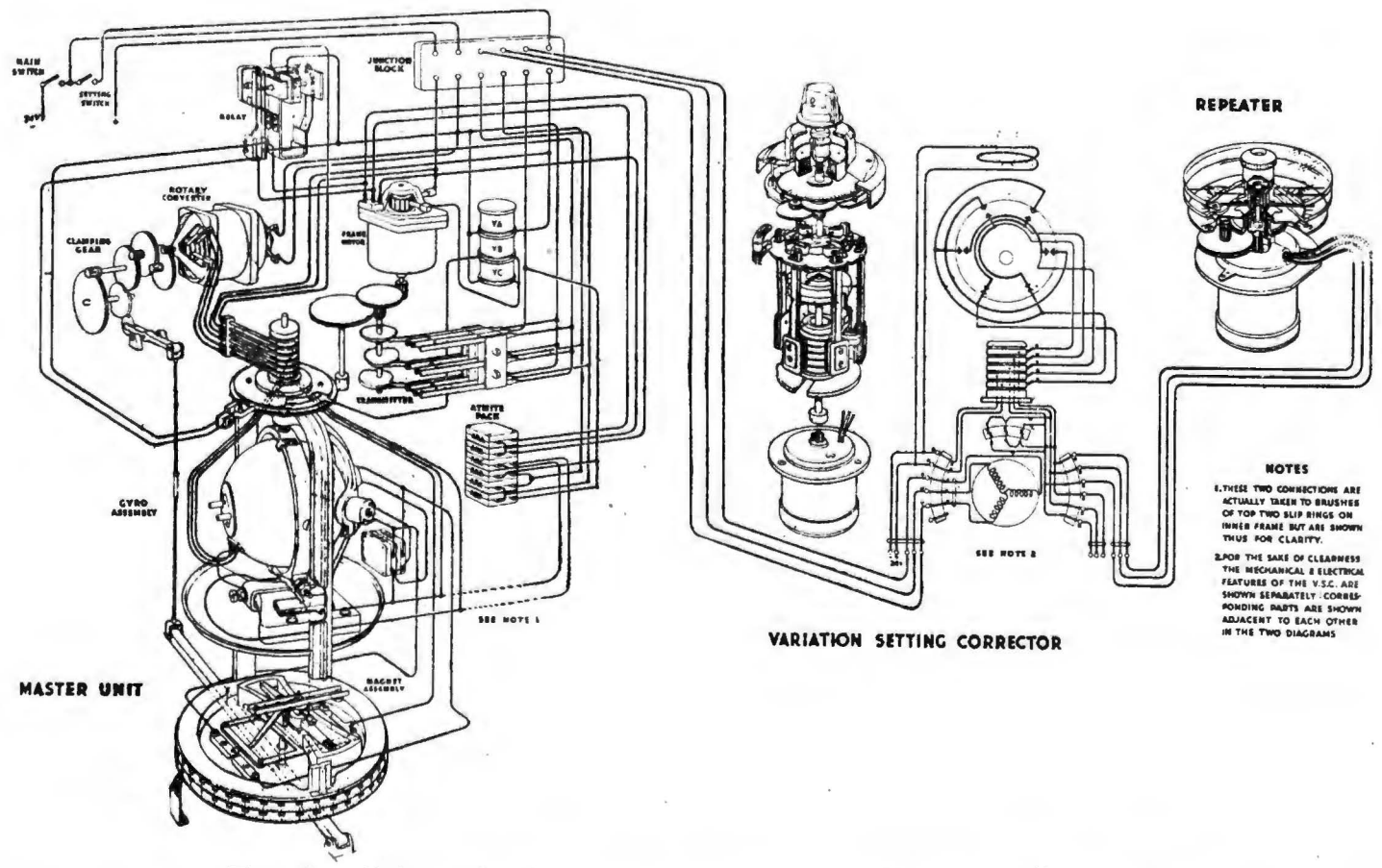


FIG. 4.—*Schematic diagram of gyro-magnetic distant-reading compass*

complete master unit assembly is suspended in gimbals so that in unaccelerated flight it will hang in a vertical position. The mechanism is totally enclosed and a small window is provided in the lower cover for reading the heading indication. This is required for synchronizing repeaters. A schematic diagram of the mechanism is shown on the left in Fig. 4. The gyroscope and the magnetic assembly are supported on platforms attached to a rectangular frame. This will be referred to as the inner frame. It is rotatable in plain bearings in a main frame which supports the remaining components, the frame itself being omitted in Fig. 4.

The magnet assembly comprises a single bar magnet, double pivoted and with ± 10 deg. freedom in azimuth. The magnet is enclosed in a metal box which provides air and eddy-current damping. A ball shaped platinum contact is carried on an arm fixed to the magnet spindle at right angles to the magnet. This contact is free to swing between a fixed contact assembly and a contact strip which, with the compass functioning, is raised and lowered every 5–6 secs. As shown in Fig. 4 the fixed contact assembly consists of two flat contacts separated by a narrow strip of insulation.

The gyroscope comprises a three-phase squirrel cage motor of special design. The rotor axis is horizontal and the bearings are offset to enable a hemispherical copper dome to be secured at one end. The motor case, which forms the inner gimbal of the gyroscope, pivots about a horizontal axis with ± 75 deg. of freedom in the vertical gimbal. The latter has ± 40 deg. freedom about a vertical axis. The support frame for the vertical gimbal carries two small electro magnets, termed "pot-magnets". These are set to have a small clearance from the rotor dome and when the gimbal system is orthogonal they are symmetrical about the spin axis. Each pot magnet is wired to one contact of the fixed assembly previously mentioned.

The gyroscope is supplied with 3-phase A.C. through light flexible leads from the rotary converter on the main frame and reaches its nominal speed of 11,000 r.p.m. in about 2 min. The rotary converter also operates the clamping contact strip on the magnet assembly through a gear box, a cam and levers as shown in Fig. 4.

The inner frame is kept aligned with the vertical gimbal by a small continuously energized shunt motor, termed the frame motor, whose direction of rotation is reversible by completing a circuit to one or the other of its two field windings by means of a relay. The vertical gimbal carries a light spring contact which moves over a quartz and a metal strip secured to the inner frame. When gimbal and inner frame are aligned the contact is just passing from quartz to metal or *vice versa*. If it rests on the quartz the relay is unenergized and the motor rotates the frame counter-clockwise round the gyro until the gyro contact passes on to the metal. The relay then operates and energizes the other field winding of the motor which reverses its rotation and the quartz is again driven under the gyro contact. This cycle is repeated about 2 or 3 times per sec. Thus when the gyro is on a steady heading the inner frame makes a continuous oscillation or "hunt" about the aligned position. If the gyro moves in azimuth the inner frame follows and afterwards continues to oscillate in the new aligned position. Similarly, if the aircraft turns, the inner frame tends to move with it but, since the gyro remains put, is immediately driven in the reverse direction relative to the aircraft to maintain its previous alignment with the gyro. Since the gyro is constrained to remain in the magnetic meridian the magnet contacts on the inner frame are kept in correct alignment with the compass magnet. This means that the azimuth freedom of the magnet can be limited to that necessary for the normal damped oscillation after a disturbance.

The action of the "pot" magnets in keeping the gyro spin axis at right angles to the magnetic meridian is as follows. The ball contact on the magnet arm is clamped for $2\frac{1}{2}$ sec. in every 5– to 6–sec. clamping cycle and although it is

possible for clamping to occur on the insulation, a circuit is normally completed between the clamping contact and one of the fixed contacts wired to the pot magnets. Thus depending on whether the gyro has precessed to one side or the other of the aligned position the appropriate pot magnet is energized. Since the gyro dome is rotating at high speed considerable eddy currents are induced in the copper and a drag force is exerted at a tangent to the dome. This force has a component producing a torque about the horizontal gimbal axis and thus precesses the gyro about its vertical axis. The pot magnet connections are arranged so that the direction of precession is towards the magnetic meridian. If the pot magnets are not aligned with a diameter of the gyro dome the eddy current drag is inclined to the vertical gimbal axis and the precessional torque has a component about the vertical gimbal axis. Thus the precessional corrections also keep the gyro-system orthogonal provided that it is approximately in static balance about the vertical axis in the first instance.

From what has been said it will be seen that the gyro controls the frame motor, to align the inner frame on the mean heading given by the magnet. The main objects in stabilizing a rotatable frame in the magnetic meridian are :—(*i*) to keep the pot magnets aligned with the spin axis, and (*ii*) to transmit the heading indication to the repeaters and thus reduce mechanical restraint on the gyro to a minimum.

The heading of the master unit is read from a scale carried by the inner frame. This is not under observation during flight but is necessary for checking that the repeaters are synchronized before flight.

The weight of the master unit is 20 lb.

Circuit Details

A schematic wiring diagram is shown in Fig. 5. In normal operation the pot-magnet circuit is completed through the 90-ohm resistor YA and each pot-magnet then gives a precession of about 0·6 deg. each time it is energized, i.e. a mean rate of 5 to 6 deg./min. over a period. When starting the compass the control switches are moved to ON and SETTING respectively. In the SETTING position resistor YA is short-circuited and with the pot-magnets thus fully energized the mean precession rate is increased to about 45 deg./min. The object here is to reduce the time taken by the master unit in reaching a heading after starting up on the ground. Thus in the extreme case, when the aircraft is on the reciprocal of the bearing indicated by the master unit, a wait of 4 to 5 min. is necessary before the compass is ready for use. Afterwards the control switch is restored to normal.

When the master unit is on a steady heading the frame motor functions with a 90-ohm resistor YB in its armature circuit. Under these conditions the inner frame oscillates about $\pm 1/3$ deg. about the mean heading. During a turn the resistance in the armature circuit is reduced to 30 ohm by automatically shunting YB with the 45-ohm resistor YC. This is done by the " fast follow-up " device fitted near the top of the inner frame. The two fixed contacts of this device are secured to the main frame and the " changeover " contact is operated by a friction-held ring fitted above the gear wheel on the inner frame.

The reduced resistance of 30 ohm allows the frame motor to drive the inner frame at about 6 to 7 r.p.m. This follow-up rate in conjunction with the ± 40 deg. azimuth freedom of the gyro gives an adequate safety margin over the maximum rate of turn of the aircraft.

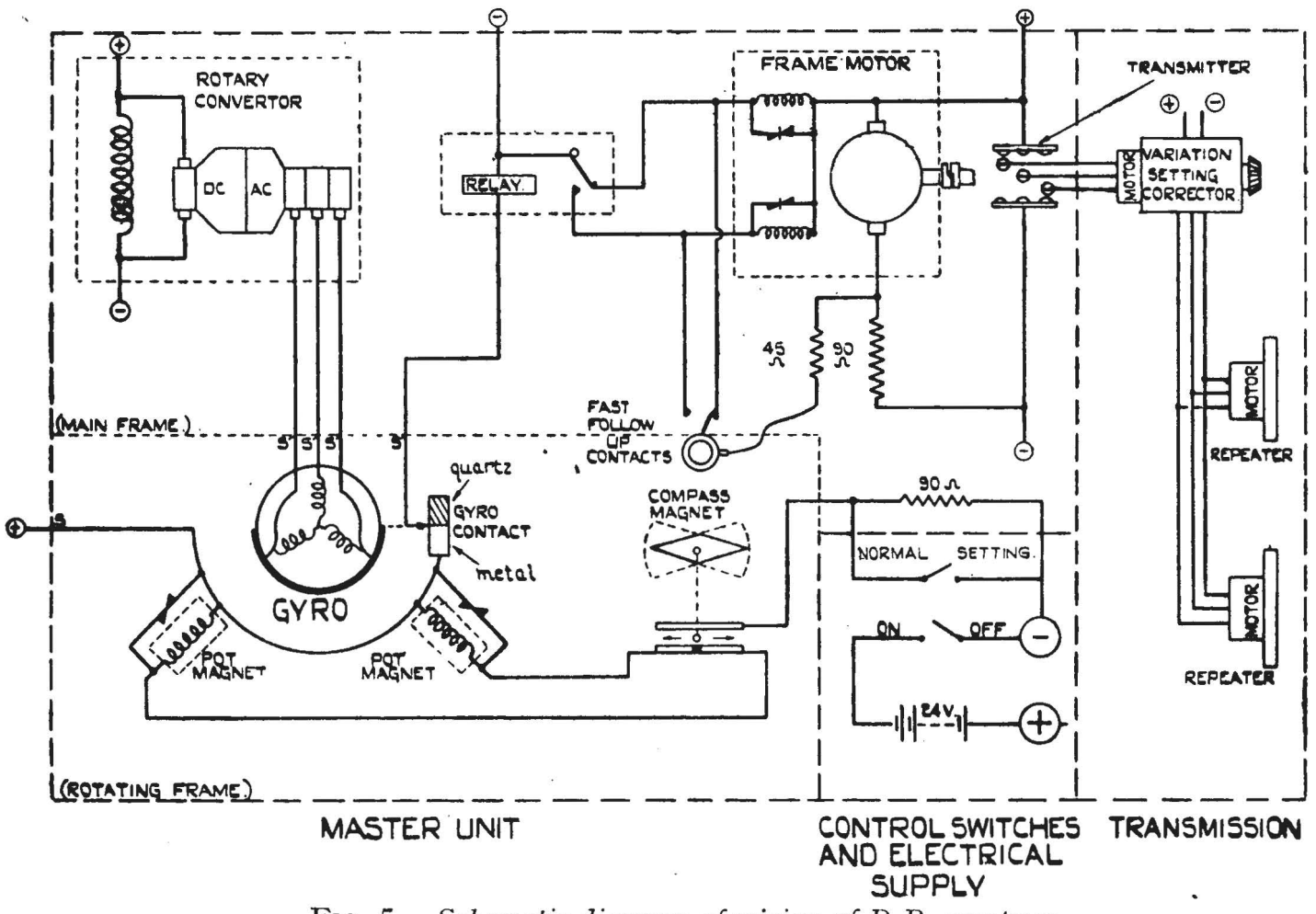


FIG. 5.—*Schematic diagram of wiring of D.R. campass*

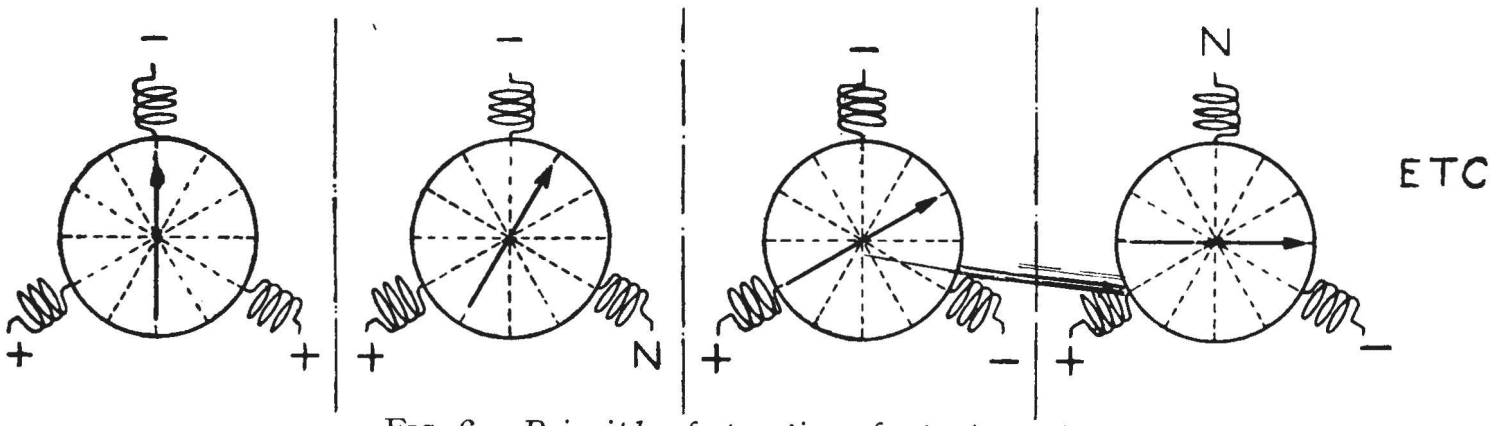


FIG. 6.—*Principle of operation of repeater motor*

Line 1 = − − − *N* + + + + + + *N* − −
Line 2 = + *N* − − − − − *N* + + + + +
Line 3 = + + + + + *N* − − − − − − *N*

Transmission and Repeater System

The heading of the master unit is transmitted to the repeaters on the " step by step " principle commonly known as Admiralty " M " type transmission. The basic item in this system is a small star-connected 3-phase motor with a laminated soft-iron rotor. Referring to Fig. 6 it will be seen that by an appropriate variation of supply polarity and with alternate 2- and 3-phase energization the resultant magnetic field, and hence the rotor, can be made to rotate in 30 deg. steps. The required polarity changes are given by a small transmitter on the master unit, driven by gearing from the inner frame.

The transmitter is shown in Fig. 4 and comprises three cams and a contact spring-set. Space does not permit a description of the transmitter except to state that one rotation of the cam spindle causes the springs to transmit the polarity sequence given in Fig. 6, i.e. for one revolution in twelve 30 deg. steps. The cam spindle is inserted in the gear train between the frame motor and the inner frame such that the ratio is 60 : 1 step up. The repeater motor drives the repeater card through a 60 : 1 reduction gear. Thus when the heading of the aircraft changes the repeater motor moves in 30 deg. steps and the repeater card in $\frac{1}{2}$ deg. steps.

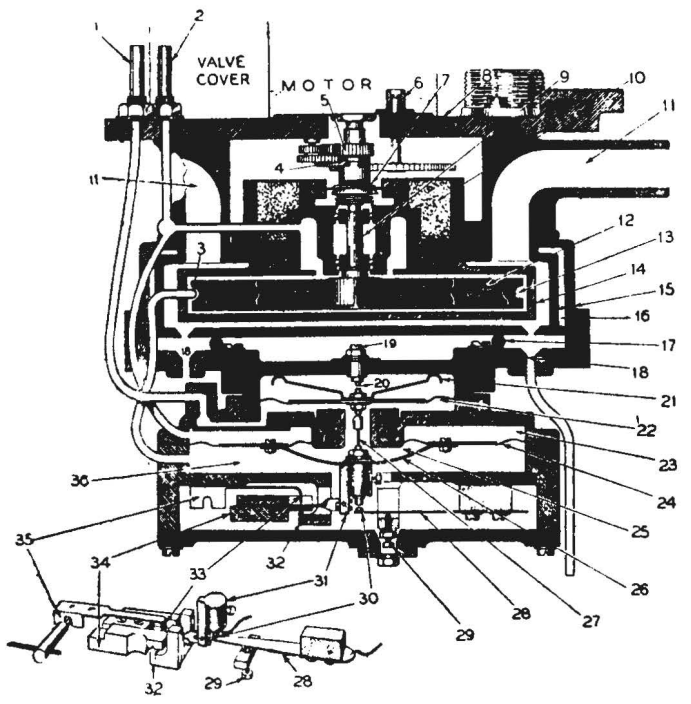
A device which gives 60 deg. back-lash is incorporated between the cams and the cam spindle. This prevents the $\pm\frac{1}{3}$ to $\frac{1}{2}$ deg. hunt on the inner frame from being transmitted continuously to the repeaters.

A diagram of a repeater is shown on the right in Fig. 4. Dual spring loaded intermediate gears are used to eliminate back-lash in the drive. A friction held pointer is carried on the repeater card. This can be set to the desired course and the aircraft then turned until the pointer is parallel to two lubber lines marked on a transparent disc fitted below the cover glass. Repeaters are turned approximately into synchronization with the master unit by means of the spring loaded spindle shown. A key is fitted over the squared upper end, to push the dog on the spindle into engagement with the motor pinion, when the rotor can be turned in 180 deg, steps, i.e. 3 deg. on the card. It will be appreciated that when the motor windings are powered the rotor can be aligned in two positions only, i.e. in steps of 3 deg. on the card. Accurate synchronization can be made after pre-setting the Variation Setting Corrector described later.

The transmission system is accurate and has sufficient torque—about $1\frac{1}{2}$ oz. in.—for driving the gears of light instrument mechanisms. It is also flexible in that, as explained later, repeaters can be easily adjusted in $\frac{1}{2}$ deg. steps to read plus or minus relative to the master unit. This advantage means, however, that the system is not self-synchronous. Consideration of Fig. 6 will show that if power is supplied to the transmission line, the soft iron rotor will turn by the shortest route into alignment wtih the stator field. Thus, the motor itself will re-synchronize only provided that it is not displaced by more than 90 deg., i.e. $1\frac{1}{2}$ deg. on the repeater card. If the correct relative readings of master unit and repeaters differ by more than $1\frac{1}{2}$ deg. the repeaters must be re-set manually.

The Variation Setting Corrector (V.S.C.)

The repeaters are not operated directly from the master unit. Instead the master unit operates a V.S.C. and then any number of repeaters up to maximum of six may be operated from the V.S.C. The V.S.C. is shown in Fig. 4. Its function is to enable the readings of repeaters to



1 PITOT
2 STATIC VENT
3 FAN SCOOP
4 HEAT INSULATION COUPLING
5 GEAR DRIVE
6 COUPLING FOR DRIVE TO A.P.I
7 GRAPHITE AIR SEAL
8 BASE PLATE
9 FAN DRIVING SHAFT
10 COTTON-WOOL HEAT INSULATION
11 AIR COOLING DUCT
12 CENTRIFUGAL FAN
13 FAN SCOOP CLEARANCE
14 METAL FAN CASING
15 HEAT INSULATION CUPS
16 HEAT INSULATION AIR GAP
17 WATER TRAP RING
18 WATER DRAINAGE PIPE
19 ADJUSTMENT SCREW ON LOW A/S CUT-OUT
20 LOW A/S CUT-OUT CONTACTS
21 CONTROL SPRING. LOW A/S CUT-OUT
22 LOW A/S DIAPHRAGM
23 STATIC CHAMBER
24 MAIN DIAPHRAGM
25 PITÔT CHAMBER
26 DOME OF PITÔT CHAMBER
27 PUSH ROD
28 CONTACT BLADE
29 CONTACT ADJUSTMENT
30 MAIN DIAPHRAGM CONTACTS
31 INSULATING CONTACT BLOCK
32 KNIFE-EDGE BEARING
33 ADJUSTABLE SPRING LOADED BEARING
34 BALANCE WEIGHT
35 ECCENTRIC ADJUSTMENT
36 FAN PRESSURE CHAMBER

FIG. 7.—*Schematic diagram of air mileage unit*

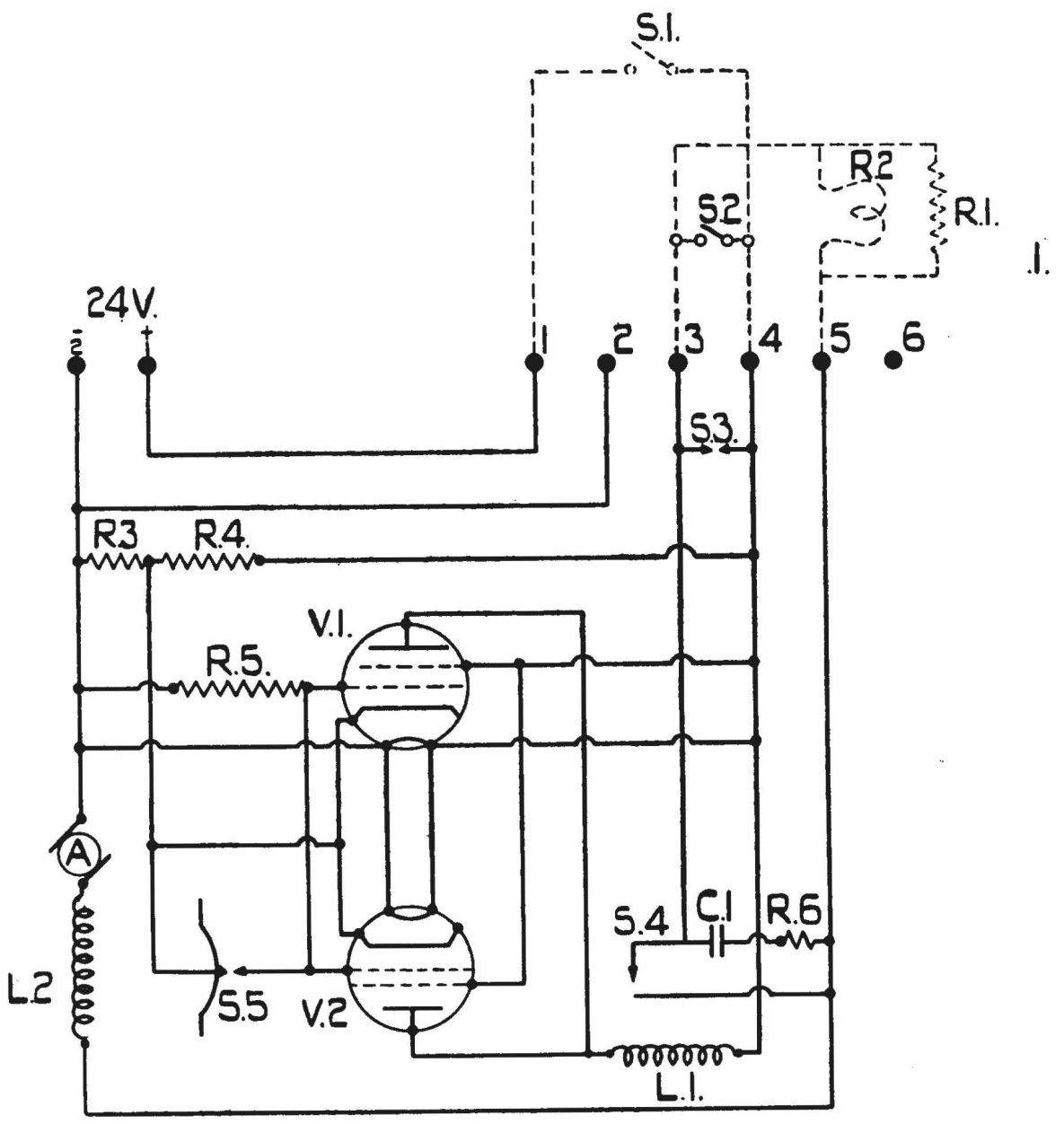


FIG. 8—*Schematic diagram of wiring of air mileage unit with key to components incorporated*

CODE	DESCRIPTION.
R.I.	100Ω GOVERNING RESISTANCE (IN A.P.I.)
R.2.	6 WATT. 24 VOLT LAMP. (IN. A.P.I.)
R.3.	35 Ω RESISTANCE.
R.4.	200 Ω RESISTANCE.
R.5.	100,000 RESISTANCE.
R.6.	25Ω RESISTANCE.
V.I.	OSRAM. (K.T. 33 C.) VALVE.
V.2.	OSRAM. (K.T. 33 C.) VALVE.
S.I.	MAIN SWITCH (IN A.P.I.)
S.2.	GROUND TEST SWITCH (IN A.P.I.)
S.3.	LOW AIRSPEED CUT-OUT.
S.4.	RELAY CONTACTS.
S.5.	DIAPHRAGM CONTACTS.
L.I.	RELAY COIL 1,700Ω + 1,700Ω
L.2.	MOTOR FIELD.
C.I.	2 M.F.D. CONDENSER.

be changed relative to that of the master unit, the objects being: (*i*) to adjust the phase of the transmission so that repeaters can be synchronized accurately with the key previously mentioned, and (*ii*) to adjust the repeaters to read true instead of magnetic heading.

The V.S.C. comprises a repeater motor driving a transmitter. The latter employs an eccentric in place of three cams and although differing in design from that on the master unit, it transmits a similar polarity sequence when the eccentric is rotated. The contact spring-set is rotatable and is located in 30 deg. steps by a detent. The control knob is engaged with the driving spindle to the contact set by a solenoid clutch. This ensures that the contact set cannot be rotated with no electrical supply to the transmission. A 1 : 12 geared scale marked in degrees registers the E or W Variation set on the instrument.

It will be seen that in operation the V.S.C. motor rotates in step with the cams on the master unit transmitter and therefore any change in heading is transmitted from the V.S.C. to the repeaters. However, if the V.S.C. transmitter springs are turned round the eccentric the repeater readings will be changed relative to the master unit, since transmission depends only on relative motion between the eccentric and the transmitter springs.

When the master unit is on a steady heading the repeaters are synchronized to the nearest 3 deg. by means of the key. The V.S.C. initially set to zero, is then operated until the repeaters are heading " master-unit reading plus the 'A' coefficient", this latter correction being made on the repeaters and not on the master unit. The lubber mark on the V.S.C. which is adjustable, is then set to read zero on the scale. Thereafter, any necessary synchronization is made on the repeaters alone by means of the synchronizing key, the V.S.C. being first set to zero. During flight the repeaters can be adjusted to indicate true heading by setting the known E or W Variation on the V.S.C.

The Air Mileage Unit

The airspeed indicator used in aircraft since the earliest days of flying shows the speed of the aircraft through the air only under standard sea level conditions of pressure and temperature; for example, if it indicates 200 knots at 25,000 ft. the true airspeed is about 300 knots. The navigator must compute this true speed from the readings of the airspeed indicator, altimeter and air temperature thermometer, and so derive the distance travelled by the aircraft in a given time. The Air Mileage Unit removes the need for these calculations, and measures the air mileage flown by providing a shaft rotating at a speed proportional to the true airspeed of the aircraft over the range 100–300 knots. The number of revolutions of the shaft in a given time is thus proportional to the air distance covered in that time.

The method of operation of the instrument is best explained with reference to the schematic section shown in Fig. 7. The driving shaft of a 24 volt, series wound D.C. motor is coupled by means of an Oldham coupling to the shaft of a centrifugal fan with twelve radial blades. The fan is housed in a close fitting light-alloy air-tight case, the shaft entering the case through a graphite air sealing gland; this comprises a graphite ring rotating with the shaft against which is lightly spring-loaded a phosphor-bronze washer mounted in a sheet of neoprene which seals the fan case without undue friction on the fan shaft. Two moulded heat-insulating cups surround the fan case and two air cooling ducts pass through these to give access to the outside surfaces of the fan case. Static air pressure, from a special static vent with negligible position error, is applied through a series of holes, at a small radius from the centre of the fan. A stream of air at outside air temperature is induced to flow, from outside the aircraft, through the air cooling ducts and over the metal fan casing. As the fan is insulated from cabin heat the air near the centre of the fan is at outside air temperature and static pressure, i.e. it is at static density. As the fan rotates the air in the fan case will rotate with the blades, and

under centrifugal action will build up a pressure at the periphery. A small scoop, whose orifice faces into the airflow, is built in the side of the fan case and this is used to " pick-up " the centrifugal fan pressure. No air-flow takes place through the scoop and hence a pitot effect occurs at the scoop. If second order terms are neglected the pressure due to the centrifugal effect and the pitot effect are each theoretically equal to $\frac{1}{2}\rho V_F^2$, in which ρ is the static air density and V_F is the velocity of the tip of the fan blades. In practice it is found that the pressure " picked-up " by the scoop is given by the relation :—

$$P_F = S + E\rho V_F^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

In which S is the static pressure applied near the centre of the fan, and E is a constant of the order 0·85 which may be regarded as a measure of the efficiency of the fan.

This fan pressure is led to one side of a diaphragm system of effective area A_1, and to the other side of the diaphragm system pitot pressure from the normal pressure head is applied over an effective area A_2, and static pressure over the difference in area $(A_1 - A_2)$. If compressibility effects on pitot pressure are ignored then :—

$$P_P = S + \tfrac{1}{2}\rho V_T^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

In which P_P is the pitot pressure and V_T is the true airspeed.

Again, if the diaphragm system is considered as mass balanced then for a balance of forces on the system :—

$$P_P A_2 + S(A_1 - A_2) = P_F A_1 \quad (3)$$

or substituting from (1) and (2) into (3)

$$(\tfrac{1}{2}\rho V_T^2 + S)A_2 + S(A_1 - A_2) = (E\rho V_F^2 - S)A_1$$

which reduces to

$$V_T^2 = \frac{2A_1E}{A_2} V_F^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Thus the true airspeed of the aircraft is proportional to the fan blade tip speed (i.e. rate of rotation of fan) irrespective of the static air density.

The motor speed is controlled by means of the diaphragm system so that equation (4) is obeyed and this control is achieved as follows. An electrical contact is mounted at the centre of the diaphragm in an insulating block and it can connect with a fixed adjustable contact mounted on the end of a contact blade. A valve circuit (Fig. 8) is arranged so that when these contacts are open, the grids of two valves (connected in parallel) are biased about 4 volts negative with respect to their cathodes. Under this condition very little current passes through the coils of a relay connected in the anode circuit. When the diaphragm contacts are closed the valve control grids are shorted to their cathodes and sufficient current then flows in the anode circuit to operate the relay. The relay contacts are placed in series with the motor, and a 6 watt, 24 volt lamp in parallel with a 100 ohm resistor are wired across the relay contacts. In flight the following sequence of operations occurs assuming the fan pressure to be initially less than that required by equation (3) :—

(1) The diaphragm contacts are closed, the relay is operated to short the lamp (and parallel resistor) out of the motor circuit, the motor receiving full power will accelerate and the fan pressure will increase until the balance is obtained.

(2) The diaphragm contacts are now open and the lamp (and parallel resistor) is now in series with the motor which will decelerate until the fan pressure decreases sufficiently to allow the pitot pressure to close the diaphragm contacts again.

This cycle is then repeated and the mean motor speed (i.e. fan speed) is governed by equation (4) to be proportional to true airspeed.

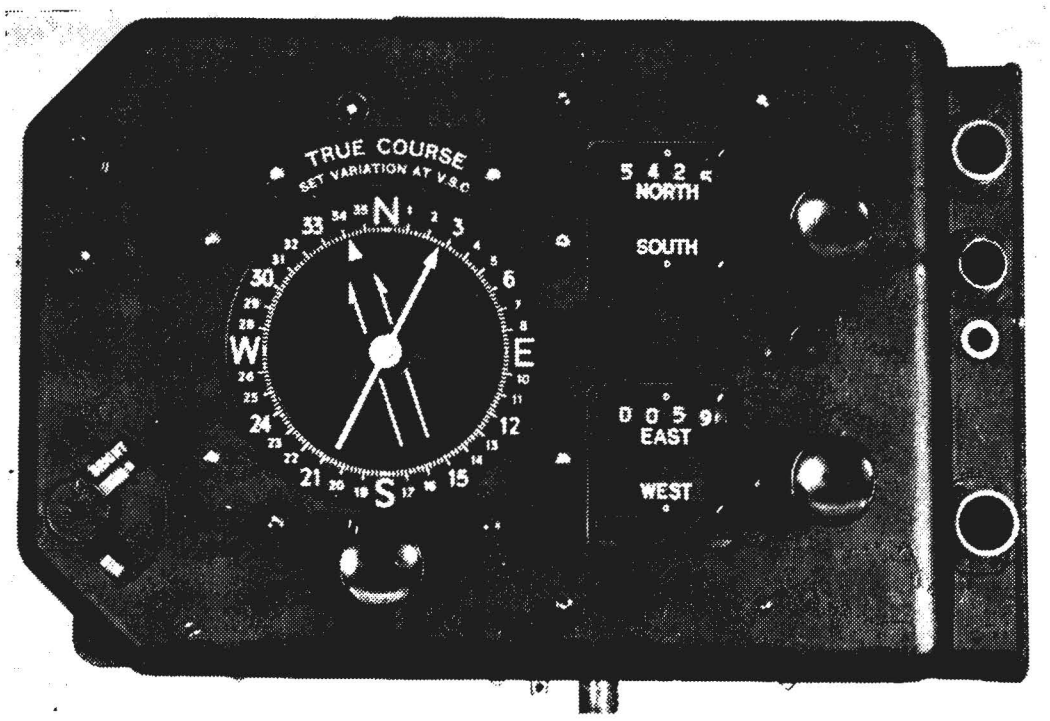


FIG. 9.—*Air position indicator*

The Air Mileage Unit is usually installed under the navigator's table and the lamp is located in the Air Position Indicator which must be conveniently positioned for the navigator. The winking of the lamp gives a visual indication of the nature of the hunt cycle, which is a useful check on the correct functioning of the instrument.

To prevent the instrument running during taxying a diaphragm operated switch, generally termed the low airspeed cut-out switch, is incorporated to cut-off power from the motor circuit until the switch is closed by the pitot pressure at about 70 knots, i.e. " Take-off ". The leaf spring which controls the closing of this switch, is used to provide pseudo-pitot pressure for ground testing purposes. A push-rod, with a cap of insulating material at its end, is screwed into the insulating block on the main diaphragm and its length so arranged that when no pitot pressure is applied the leaf spring pushes the low airspeed diaphragm down into contact with the push rod thus simulating pitot pressure.

When pitot pressure is applied the leaf spring is forced upwards until the connexion between the low airspeed diaphragm and the push rod is broken, leaving the main diaphragm free. For ground testing purposes a push button switch is incorporated in the Air Position Indicator and when operated this shorts the low airspeed cut-out switch. If this switch is operated, since the main diaphragm contacts are held closed by the action of the leaf spring, the motor will accelerate until the fan pressure is sufficient to break the diaphragm contacts against the action of the leaf-spring ; the system then hunts as if pitot pressure were applied.

Referring to equation (4) it will be seen that the ratio between true airspeed and fan speed is $\sqrt{\frac{2A_1E}{A_2}}$ now although E is a constant for any individual fan it varies slightly from fan to fan (Limits 0·82 to 0·86). The ratio is, however, maintained constant for each instrument by adjusting the value of $\frac{A_1}{A_2}$ (approx. $\frac{10}{1}$) by changing the position of the lower diaphragm contact. Screwing in the adjusting screw increases the fan speed for a given pitot pressure by decreasing $\frac{A_1}{A_2}$ and *vice-versa*.

The output is transmitted via a flexible drive to the Air Position Indicator, and the gearing of 50 : 1 from the motor shaft to the flexible drive is such that the latter rotates 24 times for each nautical mile of air distance. The ratio of fan speed to true airspeed is thus 20 r.p.m./knot, i.e. 6,000 r.p.m. at 300 knots, 4,000 r.p.m. at 200 knots, etc.

Accurate correction for the compressibility effect on pitot pressure is not attempted, but a partial correction is applied by biasing the mass-balance weight on the diaphragm system. It should be realized that the absolute velocity of the tips of the fan blades is small compared with the true airspeed and hence although there is a compressibility effect on the fan pressure it is extremely small. With no correction the fan would tend to run fast at high speeds ; the value of $\frac{A_1}{A_2}$ is, however, adjusted to give the correct output at high speed and with perfect mass balance the fan would run slow at low speeds. By means of an eccentric key the point of application of a spring loaded knife-edge may be adjusted along the balance weight to disturb the mass balance. It is thus possible to increase the fan speed at low airspeeds and since a small amount of "out of balance" is not so important at higher speeds the previous adjustment at high speed is not affected. This partial correction is applied at a density corresponding to a mean operating altitude, and if the bias force is denoted by K and the velocity of sound by C the new equation for balance can be shown to be :—

$$\left\{\tfrac{1}{2}\rho V_T^2\left(1+\tfrac{1}{4}\frac{V_T^2}{C^2}\right)+S\right\}A_2 + S(A_1 - A_2) + K = (S + E\rho V_F^2)A_1 \quad \ldots \quad (5)$$

$$\text{or} \quad V_F^2 = \frac{A_2}{2EA_1} V_T^2\left(1+\tfrac{1}{4}\frac{V_T^2}{C^2}\right) + \frac{K}{E\rho A_1} \quad \ldots \quad (6)$$

Accurate correction is also not attempted for the adiabatic heating effect on the cooling air flow, but partial correction is effected by initially setting the ground calibration too slow so that in flight, when the temperature of the cooling air flowing over the fan case is higher than correct outside air temperature, the fan will not tend to run too fast.

The weight of the Air Mileage Unit, including its anti-vibration mounting plate, is 18 lb.

The Air Position Indicator

This instrument (Fig. 9) is designed to combine the indication of total air mileage, provided by the Air Mileage Unit, with the true heading from the D.R. compass, and thus give an automatic and continuous air-plot. The air position is shown in degrees and minutes of latitude and longitude.

Referring to the schematic diagram (Fig. 10), it will be seen that the mechanism includes three infinitely variable gears of the disk, ball and roller type. Two of these are termed the resolving gears and the third the secant gear; the object of the first pair is to resolve total air mileage North–South and East–West, and of the third to convert air mileage East–West into change of longitude.

The input from the Air Mileage Unit drives the disks of the two resolving gears which are mounted on the same shaft. Thus the rotations of each disk are proportional to total air mileage. Each variable gear contains two $\frac{3}{8}$ in. steel balls mounted, in tandem, in a housing whose length is such that, when the balls are in

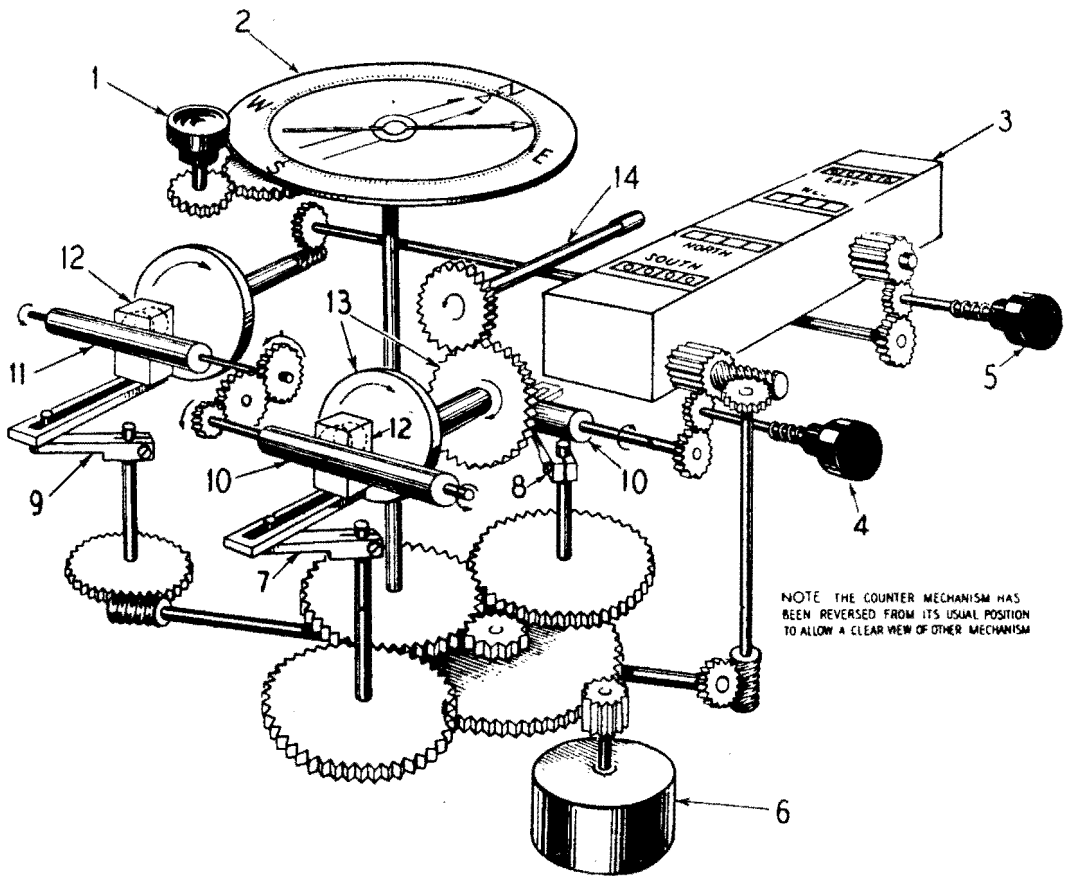
contact, each ball projects slightly out of the housing. Each housing is mounted on a cross-head fitted with a pair of parallel guides in which a crank-pin engages ; the crank pins are rotated by means of direct gearing from a D.R. compass repeater motor which is so arranged that the two cranks are always mutually perpendicular.

A cylindrical roller, hinge-mounted in a frame, completes the variable gears and this is spring loaded, at about 6 lb. loading, towards the disks so that the balls are trapped between the surface of the disk and the roller. The heights of the various components are arranged so that the line through the centres of the two balls passes through the axis of the roller and so that as the cranks rotate the track of the balls across the disk is a diameter. The gear ratio varies directly with the displacement of the balls out along the diameter of the disks and the crank angles are initially adjusted so that in one of the resolving gears (E–W) the balls are at the centre of the disk for a heading of North or South, and in the other gear (N–S) for a heading of East or West. Then for an intermediate heading of θ the displacements are proportional to sin θ and cos θ in the E–W and N–S resolving gear respectively. Thus since each disk is rotating according to total air mileage (M) the rotations of the rollers are proportional to M cos θ in the case of the N–S resolving gear and M sin θ in the case of the E–W resolving gear and these are equal to the air mileage in a N–S and E–W direction respectively. The object of the two balls in tandem is to reduce the torque required from the D.R. compass repeater motor, since, with two balls, as the heading changes the balls rotate and roll along between the disk and roller.

One nautical mile in a N–S direction is always equivalent to a change of latitude of one minute of arc ; hence the output from the N–S resolving gear may be geared directly to a counter to indicate the latitude.

One nautical mile in an E–W direction is equivalent to sec λ minutes of longitude, where λ is the latitude. The output from the E–W resolving gear must be multiplied by sec λ before being passed to a counter to indicate the longitude. This is effected by means of a third variable gear, termed the secant gear. This time, however, the input of E–W air miles drives the roller, which transmits its rotation through the balls to the disk. The crank controlling the displacement of the ball housing is geared from the latitude counter in such a way that the ball displacement from the centre of the disk is proportional to cos λ. For an input of M sin θ nautical miles, the output is thus proportionate to $\frac{M \sin \theta}{\cos \lambda}$ or M sin θ sec λ which is the change of longitude. The output is geared to a counter to indicate the longitude.

The counter mechanism actually comprises four counters two for latitude North or South and two for longitude East or West. Shutters automatically operate to cover the counters not in use and these change over when crossing the Equator or the Greenwich meridian.



1 GRID LINE SETTING KNOB
2 COMPASS DIAL
3 N-S, E-W COUNTER MECHANISM
4 LATITUDE RESETTING KNOB
5 LONGITUDE RESETTING KNOB
6 D.R. COMPASS REPEATER MOTOR
7 E-W RESOLVING GEAR CRANK
8 N-S RESOLVING GEAR CRANK
9 SECANT GEAR CRANK
10 OUTPUT ROLLERS
11 SECANT INPUT ROLLER
12 BALL DRIVE AND CARRIAGE
13 DRIVING DISCS
14 AIR MILEAGE UNIT DRIVE

FIG. 10.—*Schematic diagram of air position-indicator*

At high latitudes the gear ratio in the secant gear increases rapidly and eventually the gear will " slip " ; accurate operation is maintained up to 70 deg. N. or S. latitude.

Manual setting knobs are provided for re-setting the counters ; the action of pressing these disengages the drive from the counters and allows the counters to be re-set by rotating the knobs. The gearing between the latitude counter and the secant gear crank is not affected by depressing the knobs and hence the secant crank angle is always correctly adjusted according to the latitude.

A compass pointer is driven from the D.R. compass repeater motor to indicate true heading. Grid setting lines are provided to enable the navigator to check quickly that any desired heading is being maintained.

The weight of the Air Position Indicator is 20 lb.

Piercy on Elementary Aerodynamics

A Complete Course in Elementary Aerodynamics. By N. A. V. Piercy. [English Universities Press. 21*s*.]

REVIEWED BY DR. W. J. DUNCAN

The author of this book has set himself the difficult task of expounding the principles of aerodynamics over a wide field while using only the most elementary algebra, trigonometry and mechanics. The method adopted is, in outline, to give mathematical proofs and discussions where this is possible with the severely limited stock of mathematical tools permitted, frankly to state some more difficult results without proof, and to illustrate the whole argument by frequent reference to experiment and by the working of numerical examples. In the reviewer's opinion this policy is, in the circumstances, unquestionably wise.

It will be clear from what has already been said that the book is written principally for beginners in aerodynamics who are mathematically weak but who desire more than a merely superficial knowledge of the subject. This class is now numerous and the book will meet their needs more fully than any other known to the reviewer. Anyone who takes the trouble to read and master this book will gain a wide general understanding of aerodynamic phenomena and a base on which to build a greater structure of knowledge when he has learned to use the fine tools of the mathematical mason.

The scope of the book can be indicated by quoting some of the chapter headings:—"Aerostatics, The Nature of the Flow Past Bodies, The Theory of the Model Experiment, Using the Wind Tunnel, Equilibrium in Steady Flight, Propulsion and Airscrews, Stable Flight, Load Factors on Wings, Outline of the Lanchester-Prandtl Theory of Wings." It may surprise many that the discussion of some of these topics should be attempted at all in such a book as this, but the author has had a considerable measure of success in dealing with them. The task is indeed a difficult one, and the reviewer does not believe that the author has reached the limits of what can be done. But he does feel that the author has made a contribution of real value which is likely to be popular and which deserves that popularity.

A book of this kind would be super-human if it did not blend faults with some real virtues. The introduction to the "theory of dimensions" is unsatisfactory, but the proper approach is so simple that any normally intelligent person can understand it. The so-called "physical dimension" of a quantity is not in the least mysterious, but is simply the formula showing the manner in which the size of the unit of measurement for that quantity depends on the sizes of the units of the fundamental quantities (usually taken as length, mass and time). The measure of any quantity is a pure number (nothing but pure numbers and symbols of operation appear in the mathematical equations) which expresses its ratio to the appropriate unit. The measure is therefore inversely proportional to the size of the unit or to the dimensional formula of the unit. When, as usual, a physical equation is true whatever fundamental units are adopted. the dimensional homogeneity of its terms then follows. There are, of course, numerous details which are open to criticism. For example, it is surprising that when discussing longitudinal motion of an aeroplane the author does not point out the simple facts that for a stable machine the rapid oscillations occur very nearly at constant speed of flight while the phugoid occurs at nearly constant angle of incidence. On page 169 it is said: "In order to prevent the flap from developing a torsional vibration in flight, known as flutter . . ." This is misleading as torsional vibration of a flap or control has no vital part in typical flutter; it is the angular movement about the hinge that is important.

The reviewer can sum up his opinion by saying that this book is a bold experiment, whose general conception is sound and whose details are of value, though open to improvement. He predicts that the author will be given the opportunity to make improvements in later editions.

Assessing Control Qualities

The Hystero-Differential Method applied to Elevator Characteristics

By W. E. Hick, M.B., B.S.

IN so far as the behaviour of an aeroplane in flight depends upon the behaviour of its pilot, it is relatively unpredictable, and for practical purposes seems likely to remain so, except from a statistical point of view. It is, however, reasonable to suppose that by making certain simplifying assumptions it will be feasable to regard the pilot as a machine which responds to given situations in definite ways; in other words, to regard him as a form of servo mechanism with characteristics which may be adjusted to fit the average behaviour, though necessarily differing more or less from that of any given individual.

Two major difficulties obstruct the attempt; one is the lack of adequate physiological and psychological data for the construction of an accurate mathematical substitute for the pilot, and the other is the very great arithmetical labour involved in the use of even a crude approximation, and the probability that anything like an exact expression would be unusable in practice. The relatively simple approximation used here is based on practically only one psychological fact—namely, the existence of a time-lag (the reaction time) between a stimulus and the response to it. The assumption, in general terms, is that the control position at any instant is determined by the magnitude of the stimulus one reaction period previously.

This assumption, and the treatment of it by what have been called hystero-differential equations, has been used by Campbell among others for different purposes, but has not, as far as the writer is aware, hitherto been applied to flying controls. There is, however, reason to suppose that, within its severe limitations, it can be made to yield information of value.

Since this article is in the nature of an addition to one outlining an approach to the problem which appeared in *Aeronautics* in July, it is unnecessary to go into psychological detail, except to say that experiment and introspection agree in indicating that responses, whether in flying or in any other activity, do not occur in any such simple and continuous way. What actually happens, apparently, is that, on receiving a stimulus, such as a departure of the aircraft from the desired attitude, the pilot elaborates and sets in motion a response which may be complex, simple, or even totally wrong, according to his skill and knowledge. Having done so, he may voluntarily modify it at intervals of the order of one-third to half a second, but there is no evidence of a continuous conscious adjustment to a changing stimulus.

Probably the assumption of continuous adjustment to the response should be regarded less in the light of an approximation to any particular standard of skill than as a means of estimating the amount of skill required. Though no fundamental difference in viewpoints is involved, an answer is provided to the perfectly valid objections that the assumption is too crude to represent adequately any actual pilot, since even a beginner has resources and deficiencies not implied here, and also, as has been said, does not operate as a continuous servo.

It appears that the method gives most promise of being useful in studying those mechanisms in which the operator is liable to develop oscillations in his endeavour to correct a disturbance. That phenomenon, in the form of pump-handling, is common amongst pupils in connexion with the elevator control, which has therefore been made the basis of the following example.

In assessing the handling qualities of a projected aeroplane independently of pilots' opinions of previous types, it is necessary to assume that the pilot can be replaced by a suitable mathematical expression. The method used here represents one possible and, it is thought, useful, compromise. It assumes, in the case of the elevator, that the control column deflection at any instant is proportional to the deviation, a certain fraction of a second previously, of the aircraft's attitude from that desired by the pilot. It is shown that the constant of proportionality, which may be called the pilot's sensitivity or reactivity, is of a similar order of magnitude for some widely differing types (the criterion being the appearance of a continued oscillation); and may therefore serve as an index of one aspect of the handling qualities.

Notation

S =wing area.
S' =tail area, including elevators.
a $=\delta C_L/\delta\alpha$.
a' = ,, (tail)
k $=\dfrac{\delta C'_L}{\delta\eta}\cdot\dfrac{\delta\alpha}{\delta C'_L}=\dfrac{\delta\alpha}{\delta\eta}$
1 =distance from C.G. to tail C.P.
h =static margin.
H $=h/1$.
$\dfrac{\delta\epsilon}{\delta\alpha}$ =slope of downwash with wing incidence.
k_y =pitching radius of gyration.
i_B $=k^2_y/1^2$=inertia coefficient.
μ_1 $=W/gS\rho 1$=relative density.
T =pilot's reaction time in seconds (taken as 0·3 seconds).
T $=T'\sqrt{\dfrac{2g}{\mu_1 lC_L}}$
η =elevator deflection.
θ =angle between actual and desired attitudes.

It is assumed that the stimulus to which the pilot responds is a change in attitude in the pitching plane, and that he responds by a control deflection proportional to the angular disturbance and in the sense appropriate to correcting it. Hence we may write

$$\eta=K\theta_{t-T}$$

The other components which necessarily exist in any longitudinal disturbance are thought not to be of sufficient relative psychological importance to require inclusion, even were it clear how to deal with them. With large disturbances or a better form of analysis it might be necessary to consider other stimuli, such accelerations normal to the flight path.

In order to put θ_{t-T} into a more tractable form, we make use of a well-known result in the operational calculus. If θ_{t-T} be considered as a function of time and expanded by Taylor's Expansion, writing D for the differential operator, we have

$$\theta_{t-T}=\theta(t)-D\theta(t),\ T+D^2\theta(t)\frac{T^2}{\underline{2}}-,\ \text{etc;}$$
$$=\epsilon^{-DT}\theta(t)$$

It seems justifiable to neglect changes in forward speed, so we can ignore one of the equations of motion, and other simplifications result from assuming horizontal flight and neglecting the less important derivatives. Also, no account is taken of the effect of the aircraft's motion on the elevator. As the result of this drastic pruning, we obtain the following equations (substituting q/D for θ):—

$$w(D-z_w)-q\mu_1=0$$
$$-w(Dm_{\dot{w}}+m_w)+q(D-m'_q-m_\eta K\epsilon^{-DT}/D)=0$$

Non-dimensional derivatives with inertias included have been used. Following more or less the system of R. & M. 1801, the expression used for the derivatives are:—

$$z_w=-\tfrac{1}{2}(a+C_D) \qquad m_{\dot{w}}=-\frac{\delta\epsilon}{\delta\alpha}\cdot\frac{S'a'}{S}\cdot\frac{1}{2\mu_1 i_B}$$

$$m_w=-\frac{H}{2i_B}\left(a+\frac{S'a'}{S}\left(1-\frac{\delta\epsilon}{\delta\alpha}\right)\right) \qquad m_q=-\frac{S'a'}{2Si_B}$$

$$m_\eta=-\frac{\mu_1 k}{2i_B}\frac{S'a'}{S}$$

Since ϵ^{-DT} is merely a formal abbreviation for a series of differential operators, we may assume that the solution of the above equations will be exponential in form, i.e.,

$$q=\Sigma A_n\epsilon^{\lambda_n t}$$
$$w=\Sigma B_n\epsilon^{\lambda_n t}$$

The λ's will be, as usual, the roots of the auxiliary equation

$$\begin{vmatrix} \lambda-z_w & -\mu_1 \\ -(\lambda m_{\dot{w}}+m_w) & \lambda-m_q-m_\eta K\epsilon^{-\lambda T}/\lambda \end{vmatrix}=0$$

which may conveniently be written as

$$\lambda^3+A\lambda^2+B\lambda+CK\lambda\epsilon^{-\lambda T}+EK\epsilon^{-\lambda T}=0$$

the coefficients of which are

$$A=-(m_q+z_w+\mu_1 m_{\dot{w}})$$
$$B=z_w m_q-\mu_1 m_w$$
$$C=m_\eta$$
$$E=m_\eta z_w.$$

For a wholly imaginary root $i\beta$, corresponding to a sustained oscillation, we obtain, by substitution and separation of real and imaginary parts, the pairs of equations

$$-A\beta^2+K(E\cos\beta T+\beta C\sin\beta T)=0$$
$$-\beta^3+\beta B+K(\beta c\cos\beta T-E\sin\beta T)=0$$

Eliminating K,

$$[BE+\beta^2(AC-E)]\cos\beta T+\beta(BC-AE-\beta^2 C)\sin\beta T=0$$

This is an equation from which β can be found by successive approximation. Transposing (1) and putting in the value of β, we are then able to find K:—

$$K=\frac{A\beta^2}{E\cos\beta T+\beta C\sin\beta T}$$

The question now arises as to which of the indefinite number of possible values of β is to be employed. In the first place, it must give a positive value to K; then, since it is the first appearance of instability we are seeking, it must be the one which gives the smallest value of K; and β itself must be real and positive.

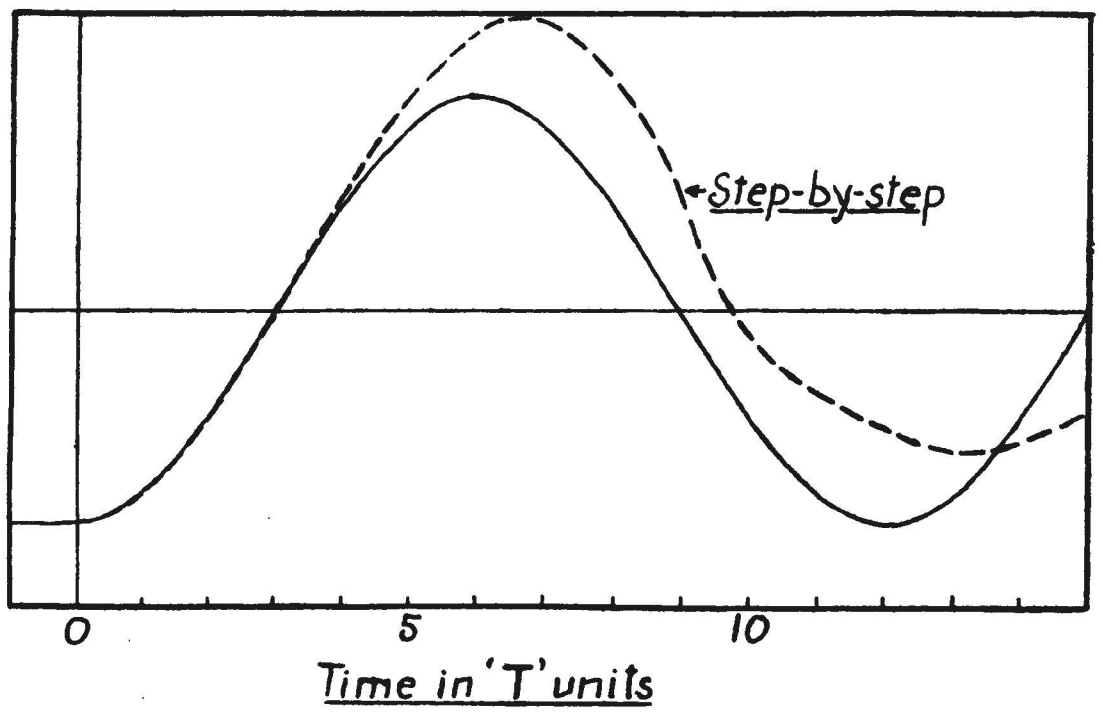


FIG. 1.—*Comparison of the results of continuous and intermittent control movements*

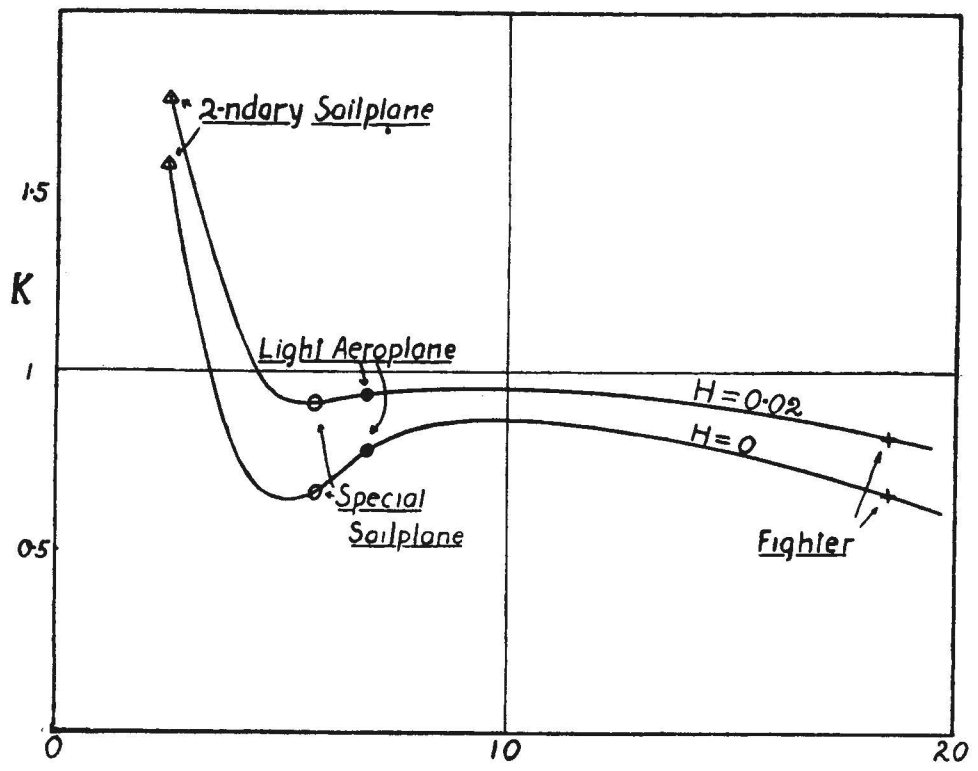


FIG. 2.—*Values of K for a wide range of aircraft and two values of static stability*

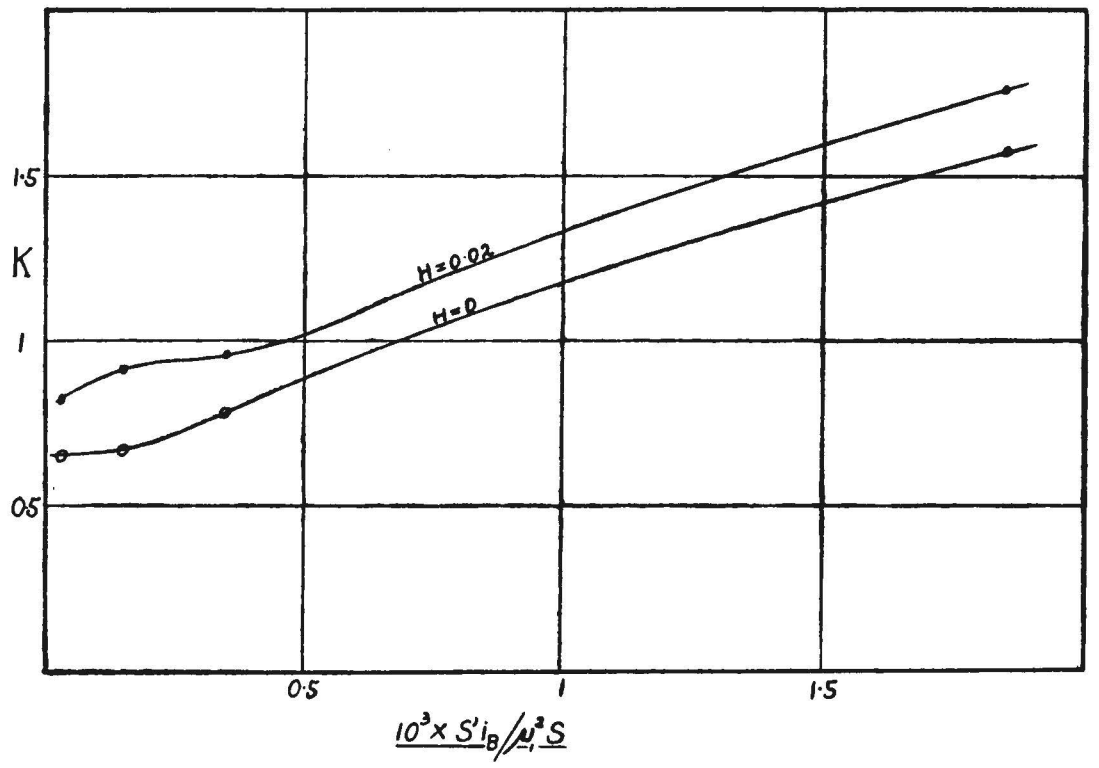


FIG. 3.—*Correction of K with a non-dimensional characteristic*

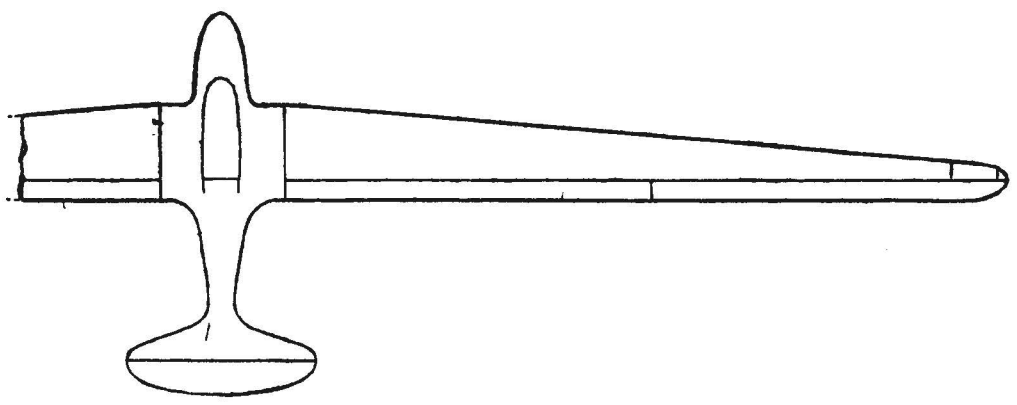


FIG. 4. — *Extreme layout (length 12 ft.) used as example*

Finally β should not correspond to a period of oscillation of less than about 0·7 seconds, because the pilot probably could not take part in more rapid oscillations.

The number K may be considered to represent the sensitivity of the pilot, in a rather special sense. The control movement that a given pilot will consider appropriate to correct a given disturbance depends largely on his previous experience; even a complete beginner, who knows only that he has been told to push the stick forward to depress the nose, is likely to assume, from his experience of other mechanisms, that there will be a more or less vague proportionality between a control movement and its effect. There is no information as to what his constant of proportionality is likely to be, nor does it appear that such information would be of much value if it existed, since it can be so rapidly changed by practice. What seems more relevant to the present point is that the smaller the value of K required by the aircraft, the more likely is the pilot to exceed it, with resultant oscillation. The latter may not, of course, appear obviously as such; owing to the pilot's ability to adapt quickly and in a more complex manner than we have here allowed for, the oscillation may not persist longer than half or one period, and will then amount only to one or two over-corrections.

It seems relevant to mention also the known tendency to overdo small movements, and to commit larger relative errors with them, which may lead to a comparatively experienced pilot performing a small-amplitude oscillation, in circumstances requiring great precision and not allowing time for a sufficiently gradual and careful correction of an error. It seems therefore that, although the actual value of K is not specially informative, it may provide a useful means of comparison between aircraft known to be satisfactory in this respect and proposed designs about which some doubt may arise. Discretion would clearly have to be used in applying it; for instance, it is fairly clear that increased control force makes a machine effectively less sensitive from certain points of view, but it is not clear how this should be allowed for. It would be easy to substitute control force for control deflection in the foregoing treatment, or to include both, but in the absence of knowledge as to their relative psychological importance, nothing would be gained. It may also be mentioned that K, as found here, refers to the control surface; the gearing between that and the control column has an obvious influence on the conclusions arrived at.

As a comparison of the hystero-differential method with what is probably a rather truer, though far more arithmetically laborious, approximation, Figure 1 shows the solution of a sustained oscillation of the equation

$$D^2x = -A\epsilon^{-DT}x - B.Dx$$

Superimposed on it is a curve of the equation

$$x = x_0 - \frac{Ax_{-T}}{B}\left[Bt - \left(\frac{B\dot{x}_0}{Ax_{-T}} + 1\right)\left(1 - \epsilon^{-Bt}\right)\right]$$

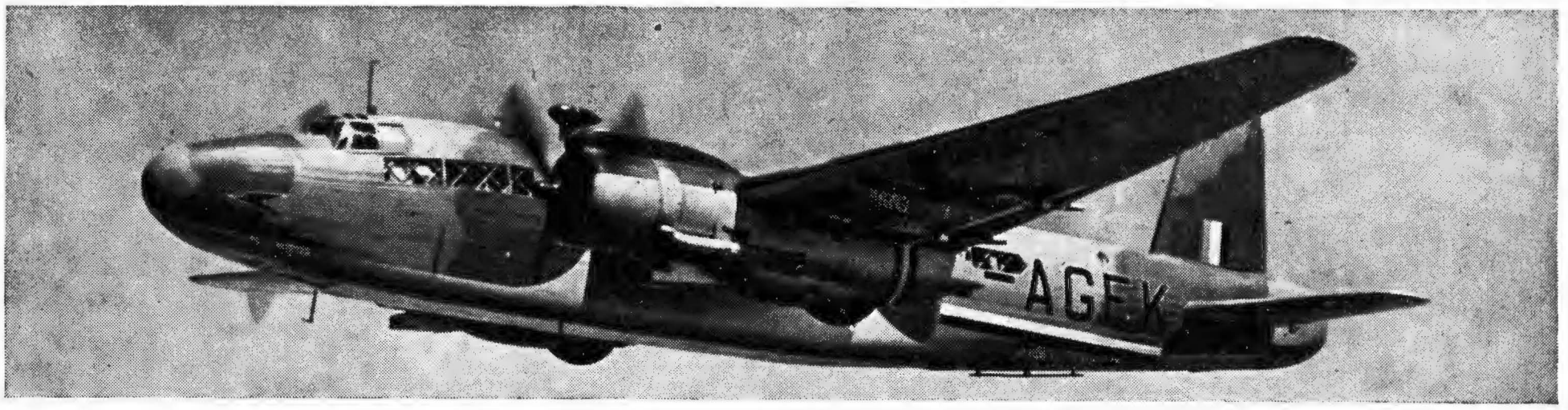
which is the solution of

$$D^2x = -Ax_{-T} - B.Dx$$

The second curve represents a step-by-step calculation, each step being equal to T (the reaction time. x_0 and $\dot{x}_0$ are initial values at the beginning of each step, and x_{-T} is the value of x at the beginning of the *previous* step. A and B have the same values as for the hystero-differential form. It will be seen that this step-by-step method assumes that every T seconds the control is moved instantaneously to a position proportional to the stimulus T seconds before, and is held there for one T period; the control movement is thus a series of jerks. There is, of course, no lack of objections to this assumption, but there is some reason to believe it more nearly resembles the behaviour of a beginner than the hystero-differential, and it is therefore of interest that there is a good deal of similarity between the resulting motions. A better approximation still would make only the muscular force vary in this discontinuous manner, the control movement being continuous.

Figure 3 shows some values of K calculated for four widely divergent types of aircraft, ranging from a single-seat fighter to a somewhat unorthodox sailplane design, with a two-seat light aeroplane and a typical secondary sailplane in between. The conditions were chosen to correspond more or less to cruising speed, and if we assume the control gear ratio to be the same for all, we gain some idea (subject to what was said above) of their relative sensitivity. The oscillation periods range from 1 sec. to 2·36 sec.

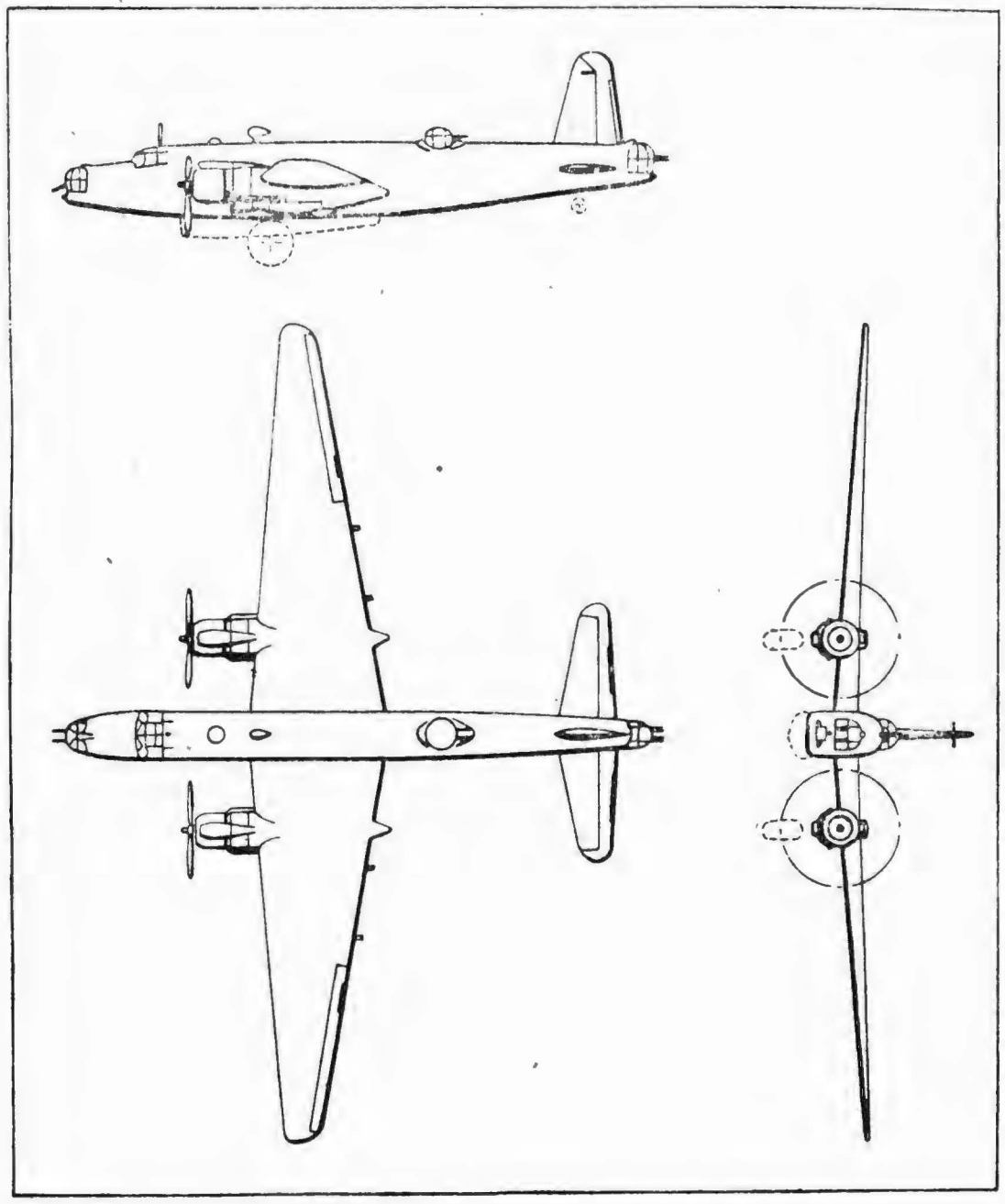
In Fig. 3 the same results are plotted against $S'i_B/\mu^2S$, to show the correlation with this much simpler expression. Since in a calculation of this sort we start from premises of an altogether inferior order to accuracy to those customary in engineering, an expression correlating as roughly as this may be all that is required. As an illustration of what the writer believes to be the practical utility of the method, the special sailplane design (sketched in Fig. 4) is apparently not outside normal limits on this criterion, and therefore might justify further investigation, although on general grounds such a short machine might have been thought very difficult to handle. Needless to say, however, one would not rely on this finding alone.

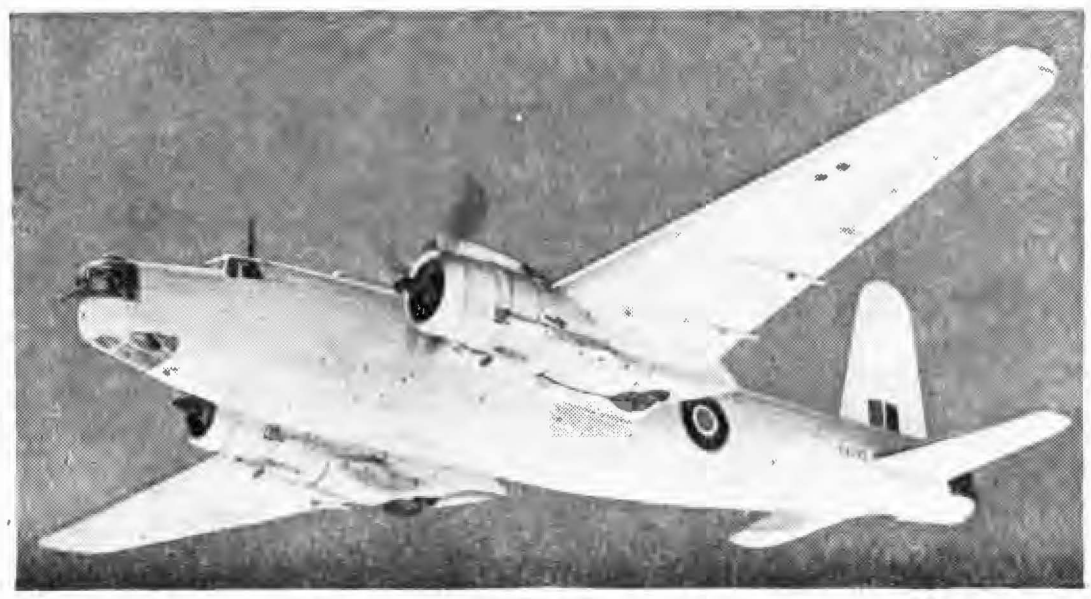


Modern Aeroplane Types

The Vickers-Armstrong Air-Sea Rescue and Transport Command Warwick

(*See p.* 81)





Stability of Tailless Aeroplanes

By A. R. Weyl, A.F.R.Ae.S.

After giving a historical survey of experiments with tailless aeroplanes in the last three issues of AIRCRAFT ENGINEERING, Mr. Weyl now proceeds to discuss the special problems of stability arising from the peculiarities of this type. He starts in this first article with a consideration of longitudinal stability, initially giving an elementary outline of the subject in general as applicable to all types

Introduction

IN a series of articles entitled "Tailless Aircraft and Flying Wings", concluded last month, the evolution of the tailless aeroplane and the flying wing was treated. The different trends of the development were classified, and a short discussion of the difficulties which had been experienced during experimental work given.

In their design, tailless aeroplanes and flying wings present some rather complex problems which sometimes do not seem to be sufficiently appreciated. Moreover, the causes of certain actual difficulties or deficiencies are even to-day not fully clear and need further research.

The knowledge hitherto collected in regard to tailless aeroplanes is by no means as large as it could have been, if the investigators had cared to be more communicative. All investigators, with a very few exceptions, have preferred to keep their valuable experiences and observations to themselves or have been unable to communicate them for the common benefit of aeronautical engineering. Since disappointments have so often been the cause of a discontinuation of experiments with tailless aeroplanes, it seems worth while to emphasize that failures experienced in development work can be as valuable for the benefit of science as successes, if they are made accessible in full so as to contribute to our knowledge and permit of evaluation of the experience at a later date.

It is felt that an outline of some of the main problems of design and a discussion of solutions hitherto attempted or suggested might be helpful, even when such a survey of a vast field of aeronautical intelligence must necessarily be restricted, for various reasons. The outline that follows will, of course, include some of the flying experience collected and made public by the investigators.

As mentioned in the history of the evolution, the attention of the early investigators had already been drawn to the problems of stability. Generally, it has been longitudinal stability that they were concerned about and, even to-day, it is often erroneously assumed that the attainment of satisfactory longitudinal stability presents the critical problem of a tailless aeroplane. During prolonged experimentation in flight most investigators, however, found that while longitudinal stability could be achieved even at or near the stall, the lateral and the directional stability presented major difficulties and problems of control and of balance were acute.

PART I
LONGITUDINAL STABILITY

In general, the longitudinal stability (stability in pitch) forms problems which are well understood and for which satisfactory solutions seem established. However, considerations of longitudinal balance (trim) and effects of compressibility introduce difficulties and, in cases in which high manœuvrability and steadiness are required, it does not seem easy to arrive at a compromise which will give complete stability at small angles of incidence (high speed; dive), and which will satisfy all requirements on stability and manœuvrability.

General Requirements of Longitudinal Stability

Before discussing the problem itself, it will be useful to consider the general requirements on longitudinal stability for conventional aeroplanes. So far, there has been no generally agreed standard, but it seems possible to give a general indication of the qualities expected with modern aeroplanes.

American engineering pilots (1) seem to hold the following views in respect to the desirable qualities of the longitudinal motion:

(1) Positive static stability of such a limited degree that the manœuvrability is not so far affected as to cause the aeroplane to take charge in gusty weather, or such as to give a short and uncomfortable period of oscillation about the lateral axis.

On the other hand, the static stability should not be so small as to permit long wallowing periods of oscillations which produce air-sickness.

(2) A complete longitudinal oscillation should not be longer than 40 sec., nor shorter than 10 sec.

(3) A heavily damped motion is always desirable.

(4) With elevator free, no more than 4 or 5 oscillations should occur before the motion becomes imperceptible.

(5) The longitudinal motion as specified above should not be greatly affected by flying speed and loading; it should be similar with aeroplanes of any size.

S. B. Gates (2) has specified British requirements by stating that pilots want "a little static stability" in all circumstances; so that the aeroplane may be left to itself while cruising in average weather but may also be easily held when trimmed to a different attitude. Considering this and realizing the inability of the designer to provide an equal degree of static stability for all conditions of flight, Gates stipulates:

(6) The free-elevator stability should be at least neutral when climbing with the centre of gravity in its rearmost position.

(7) With the centre of gravity in its foremost position, and at a speed 30 per cent in excess of the top speed and when trimmed for top speed, the force required at the control column should be easily manageable.

(8) With the centre of gravity in its foremost position, the power of the elevator must be sufficient to attain the maximum lift coefficient with the landing flaps in their effective position.

The late A. G. Von Baumhauer stated, in 1939 (3):

Stability has to be positive in the whole range of flying conditions. For blind flying, a minimum amount is necessary in order to prevent overstraining the pilot. It is believed that the maximum is a question of comfort to passengers, especially in bumpy weather. His requirements on commercial aeroplanes refrained from prescribing a degree of stability.

The "Design Requirements for Aeroplanes of the Royal Air Force" (A.P. 970, pre-war edition) lays down no requirements on stability, apart from a reference to conditions imposed on the stability and control of aeroplanes in which automatic controls may be used. The requirements are that no instability should exist at the rearmost position of the centre of gravity, but that, for normal loading, the longitudinal stability with elevators fixed should be as neutral as possible. Stability with elevators free was not required, but there should be no dangerous instability.

This short selection shows how varied the requirements on static and dynamic longitudinal stability are, and how difficult it is to arrive at a satisfactory compromise.

General Conditions Governing Stability

With respect to the needs of the Flying Wing, it is thought advisable to treat the subject of longitudinal stability *ab initio*, since this will elucidate recurring misapprehensions and will facilitate an evaluation of the merits of different categories of Flying Wings. The discussion will be restricted to the range of normal flight, i.e. below the stall.

In order that the flight of an aeroplane shall proceed as a steady stable motion, at any instant three conditions have to be satisfied:

Firstly, the aeroplane must be in a *state of equilibrium;* i.e. all forces and moments acting on it must balance each other. The forces and moments arising are aerodynamic forces and mass forces. It is necessary to establish the condition of trim before any consideration of stability. In the case of the tailless aeroplane, fundamental errors and even accidents have been caused by neglect to examine this.

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The second condition is that of *static stability*. This quality represents the tendency to return to a state of equilibrium after a disturbance. The characteristic is the direction of the reaction the aeroplane sets up under the effect of a disturbance. Static stability does not imply that the state of equilibrium will be aperiodically (i.e. directly) reached. When the disturbance is caused by a permanent change in the position of the elevator (or the trimming tab), static stability implies the return to the new state of equilibrium defined by the changed control position.

In cases of great static (inherent) stability, control manœuvres can be seriously affected, the aeroplane preferring to return to its original state of equilibrium. The Dunne biplanes were said to have suffered from such incontrollability, and the Etrich monoplanes were also infamous for it.

The third condition of stability is that of *oscillatory or dynamic stability*. This concerns the way in which oscillations about an attitude of equilibrium are damped or incited as a result of a disturbance. This condition cannot be considered unless static stability (however small) exists. Dynamic stability and static stability must needs be restricted to small deflections from the state of equilibrium; since at large deflections, even a stable aeroplane may tend towards quite a different state of equilibrium.

Static Longitudinal Stability

Complying with the first condition of stability, let us consider the balance of moments acting about the lateral (Y-axis) through the centre of gravity of the aeroplane. Let us take those moments, M, about this axis (pitching moments) as positive which tend to effect an increase in the angle of incidence, α; i.e. which will tend to depress the trailing edge of the wing.

Then, the condition for static stability is simply:

$$\frac{\partial M}{\partial \alpha} < 0$$

or, for the case of neutral static stability:

$$\frac{\partial M}{\partial \alpha} = 0$$

In a graph of the moment M versus the incidence α, the slope of the curve must, for stability, therefore, be negative; with the angle of incidence increasing, a negative (nose-heavy producing) moment must appear, for the case of stability.

The partial derivatives are required since the position of the elevator is assumed unchanged after the disturbance, for the criterion of stability; further, the angle of incidence is decisive (and not, as sometimes thought, the lift coefficient), for the reason that towards the stall the static stability becomes more and more critical.

For a simple wing system without excrescences (such as fuselage, nacelles, vertical surfaces, airscrews, etc.) which might contribute pitching moments of their own, and assuming the thrust as generated at the centre of gravity, the aerodynamical pitching moment M is formed by the resultant air force acting on the wing (R_w) and its fore-and-aft distance (lever) from the centre of gravity (e).

It is, then:

$$\frac{\partial M}{\partial \alpha} = -\frac{\partial (R_w \cdot e)}{\partial \alpha} = -\left(e \frac{\partial R_w}{\partial \alpha} + R_w \frac{\partial e}{\partial \alpha} \right)$$

Now, with a Flying Wing satisfying our assumptions, the centre of gravity has, for balance (first condition), to coincide with the centre of pressure (i.e. the point of intersection of the resultant air force with the chord line of the aerofoil section), so that:

$$e = 0$$

Hence:

$$\frac{\partial M}{\partial \alpha} = -R_w \frac{\partial e}{\partial \alpha};$$

i.e. for a simple Flying Wing, static longitudinal stability depends upon the sign of $\frac{\partial e}{\partial \alpha}$ and the margin of stability upon the magnitude of $\frac{\partial e}{\partial \alpha}$; since, in normal flight, the resultant air force cannot change its sign.

If $\frac{\partial e}{\partial \alpha} < 0$, static instability exists,

$\frac{\partial e}{\partial \alpha}$ is the travel of the centre of pressure* for the wing system considered. When the centre of pressure travels, with increasing angle of incidence, towards the leading edge (e becoming smaller with increasing α), the system is unstable. (The preceding discussion neglects, for the sake of simplicity, the influence of the vertical position of the centre of gravity.)

Stability Qualities of Aerofoil Sections

The travel of the centre of pressure on aerofoils has always been realized as important for the stability qualities. Sir George Cayley, for instance, stipulated, in 1809, that the centre of gravity should be below the centre of pressure; he was also aware, from his experiments, that at moderate incidences, the centre of pressure was forwards of the geometrical centre of the aerofoil chord, and that its position varied under different conditions of experiment (4).

In 1804, Avanzini published in a paper the results of fluid-force experiments on bodies in flowing water. He found that when a plane surface (flat-plate aerofoil) moved under an incidence in a fluid, the centre of pressure of the resulting hydrodynamic force displaced itself towards the centre of the area when the incidence increased. In 1870, Joessel, confirming the experiments of Avanzini, established without doubt that the resultant force experienced on a plane surface in flowing water not only varies in magnitude and direction when the incidence changes, but that the centre of pressure changed its position so that there was a tendency to counteract an increase of incidence (5).

In accordance with our criterion for static stability, this would mean, for a state of equilibrium, that:

$$\frac{\partial e}{\partial \alpha} > 0$$

i.e. positive static stability.

Model glider tests with aerofoils consisting of flat plates (of no marked thickness) show indeed that they can be (at low Reynolds Numbers) statically stable; i.e. they can exhibit a tendency to return to a given state of equilibrium after a disturbance. According to hydrodynamic theory, a flat plate of infinitely small thickness has a stationary centre of pressure. By placing the centre of gravity below the centre of pressure stability can thus be obtained. The theory, however, takes only pressure forces into account and thus neglects the surface friction which is important for such surfaces.

Flat-plate aerofoils would, theoretically, form a solution for a stable wing system with self-contained devices for longitudinal stability. In 1897, Friedrich Ahlborn, who has already been mentioned in connexion with the Zanonia development, was the first to draw attention to this possibility.

In reality, flat plate aerofoils are, however, an abstraction. The wings of an aeroplane require a finite thickness. The logical consequence is the adoption of symmetrical aerofoil sections which —in hydrodynamic theory—correspond in their relevant aerodynamic properties to flat plates. Tailless aeroplanes have been constructed on this basis. Lippisch has claimed to have been the first to realize this possibility.

Symmetrical aerofoil sections were disregarded for use in aeroplane wings for many years because the pronounced scale effect particular to them made them appear rather inefficient. Wind tunnel investigations at higher Reynolds Numbers gave a different picture. Their maximum-lift coefficients, however, are disappointing, so that their use without appropriate high-lift devices seems unpractical. Symmetrical aerofoil sections do in practice not quite correspond to flat-plate aerofoils. At their best (i.e. thin sections of this kind) they have a stationary centre of pressure within the useful range of incidences. This is strictly in accordance with the results of hydrodynamic theory.

Thicker symmetrical aerofoil sections, such as are preferable for Flying Wings and for cantilever wing structures, however, display an unstable centre-of-pressure travel within the range of very small incidences (high speed and dive). The reasons for this discrepancy from the results of hydrodynamic theory will be discussed below.

It was early seen that flat-plate aerofoils had but a mediocre efficiency (lift/drag ratio). Sir George Cayley observed that birds had cambered wings; he thus subjected cambered aerofoil sections to tests on his whirling arm. On his advice, Henson and Stringfellow adopted cambered sections (1842). In 1874, the brothers Otto and Gustav Lilienthal began to investigate aerofoils with simply-cambered (circular arc) sections. They, again, took this feature from observations of birds. In 1884, Horatio Phillips secured, on the basis of careful experimenting, a patent for a cambered wing section. Having discovered that the air flow in front of the leading edge of a wing assumes an ascending direction, he originated the "dipping" leading edge ("Phillips Entry") of cambered aerofoil sections, a peculiarity with which we shall deal later. For this he obtained a patent in 1891. At about the same time, F. W. Lanchester also recommended cambered wing sections of this kind. In 1884, Goupil published a treatise on aerial locomotion in which he described experiments with cambered aerofoils in an airflow, defining an especially suitable aerofoil section similar to that found in the wings of birds. In 1889, Otto Lilienthal published the results of his whirling-arm experiments in his famous book on Bird Flight and Artificial Flight, emphasizing (Theorem No. 13) that only cambered wings would permit flight. The camber ratio he found most suitable was rather large (1/12th of the chord length).

Otto Lilienthal and his school (Pilcher, Ferber, Chanute, Wright, etc.) convinced the world that cambered aerofoil sections, as exemplified in birds, were essential for flying.

It was with such simply-cambered aerofoil sections that the attainment of longitudinal stability offered problems for the design of tailless aeroplanes.

With all aerofoil sections in which the medium camber line is so curved that the concave side of the camber faces, in flight, the ground, the centre of pressure moves—within the incidences appertaining to normal flying attitudes—towards the leading edge when the angle of incidence increases. In other words, such aerofoil sections have, for a given state of equilibrium (i.e. centre of pressure coinciding with the centre of gravity):

$$\frac{\partial e}{\partial \alpha} < 0$$

Hence they are, for single plain wing systems and a given position of the centre of gravity, without exception unstable; since the resultant aerodynamic force produces a tail-heavy moment when the incidence increases, thus

* The conception of a centre of pressure and the elements of static longitudinal stability seem to have been known to Leonardo da Vinci (about 1490).

aggravating any disturbance from the state of equilibrium.

By reason of this unstabilizing quality, an aeroplane employing a plain aerofoil with cambered sections must either be provided with a tail plane or with a stabilizing aerofoil in front of the wing (tail-first type). Such a tail, be it in front or behind the wing, has to produce aerodynamic moments about the centre of gravity which counteract the unstabilizing moments originated by the air force of the wing. In 1870, A. Pénaud was the first to prove the purpose and necessity of such a tail plane for longitudinal stability.

With a tailless aeroplane employing simply-cambered aerofoil sections and having a fixed centre of gravity, the stabilizing action of a tail plane has to be replaced by aerodynamic means. All these means are, in fact, nothing else than "*tails*" incorporated directly in the wing system.

There are, however, possibilities which should not be left unmentioned, though they have not yet been considered practical. Even with a fixed centre of gravity, stabilizing moments could be produced with the aid of an eccentric (airscrew or reaction-propulsion) thrust. R. Arnoux suggested a variation of the thrust by way of the throttle in order to keep the incidence constant. One could also visualize that the inclination of the thrust line relative to the chord line might be varied, in order to counteract the unstabilizing moment. A second possibility would be to shift the centre of gravity so that the balance of moments would always be restored. Ellehammer's idea of the "live" pendulum was similar. But both these possibilities are not devices of inherent stability. They signify automaticity; i.e. stability obtained by the incorporation of an automatic device. Another possibility would be to have the centre of gravity very much below the wing.

There seems indeed but one practical way to secure inherent stability for such a tailless wing system, without having recourse to the incorporation of a tail. When the centre of gravity is in front of the aerodynamic centre, i.e. far forward, the plain wing with cambered section will have no equilibrium, but static stability. By the introduction of a constant pitching moment other than aerodynamical (as, for instance, produced by a thrust line below the centre of gravity) equilibrium could be obtained. Such a Flying Plank would be obviously stable in powered flight. (Fig. 2.)

The Aerodynamic Centre and its Peculiarities

For further discussion, it will prove helpful to introduce the conception of the "Aerodynamic Centre"—or, as it is often termed in official British statements (contrary to the British Standard Glossary of Aeronautical Terms) the "Neutral Point".

R. v. Mises (6) published, in 1920, a paper on the hydrodynamic theory of wing lift based on the method of conformal transformation, in which he proved that for any aerofoil section a point ("Focal Point") exists for which the moment of the lift force becomes independent of the angle of incidence. This law of hydrodynamic theory is limited to an ideal inviscid flow (potential flow) and to aerofoils of infinite aspect ratio (two-dimensional flow). It is, however, with a fair degree of approximation, also valid for wings of finite aspect ratio having aerofoil sections similar to those in use, at speeds at which compressibility effects are not yet noticeable. In their aerofoil analysis, Birnbaum and H. Glauert have perfected this adoption of hydrodynamic theory to practical purposes of wing design and stability.

An examination shows that, in good agreement with the theoretical deduction of v. Mises, the "Focal Point" coincides with the Aerodynamic Centre by lying close to the quarter-chord point of the aerofoil chord, behind the leading edge. Hence the National Advisory Committee for Aeronautics adopted, in about 1929, the quarter-chord point as a convenient axis of reference for the aerodynamic pitching moment set up by the resultant air force. Previously, this moment had commonly been referred to an axis going through the leading edge of the aerofoil section.

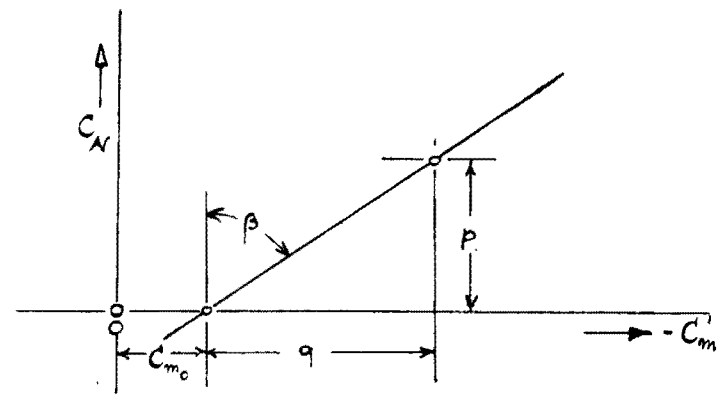

FIG.—1.—*Aerodynamic moment and normal force on aerofoils*

Let us first assume the moment axis to be at the leading edge of the aerofoil section.Then the resultant air force R_w acting on the wing produces the moment:

M'=(Normal Component N of R_w) X (Distance d between the moment axis and the centre of pressure).

Introducing:

c=length of the wing chord (mean chord of wing).

q=dynamic air pressure.

S=wing surface.

We have—

$$M'=N\times d=C'_m\cdot q\cdot S\cdot c$$

where—

C'_m=pitching moment coefficient about the leading-edge axis.

Hence—

$$d=\frac{C'_m}{C_N}\cdot c$$

and, since at incidences well below the stall the normal force can be approximated to the lift,

$$C_N\sim C_L$$

$$d\sim\frac{C'_m}{C_L}\cdot c$$

When discussing stability near the stall (i.e. at take-off and when climbing), it is, however, necessary to introduce:—

$$C_N=C_L\cos\alpha+C_D\sin\alpha$$

In agreement with the law of v. Mises, experience with normal aerofoil sections in average conditions proves that, at incidences well below the stall, the moment coefficient is approximately linearly proportional to the normal-force coefficient (Fig. 1); hence the slope of the moment coefficient versus the normal-force coefficient:

$$a=\frac{dC'_m}{dC_N}=\frac{q}{p}=\text{constant}$$

Consequently the function satisfies the equation:

$$C'_m=C_{m_o}+aC_N$$

or

$$c\cdot C'_m=c\cdot C_{m_o}+a\cdot c\cdot C_N$$

In this, the summand $c\cdot C_{m_o}$ represents a constant value which is independent of the magnitude of the aerodynamical force and thus also independent of the angle of incidence; theoretically, it depends only on the shape of the mean camber line of the aerofoil section.

The summand $a.c.C_N$ is a value which varies in linear proportion with the aerodynamical force and thus, under the conditions stated, with the angle of incidence α.

Referring now the aerodynamic pitching moment to an axis chosen at a distance $x_{a\cdot c\cdot}$ behind the leading edge (our original moment axis), so that:

$$x_{a\cdot c\cdot}=ac,$$

the moment about the axis so defined becomes constant at all angles of incidence (below the stall and at positive values of lift). This axis is called the "Aerodynamic Centre" of the aerofoil section, and the pitching moment about it is:

$$M_{a\,c}=c\cdot C_{mo}\cdot q\cdot S$$

Theoretically, the aerodynamic centre should be fixed at quarter-chord, i.e.:

$$a=0\cdot 25$$

$$(a.c=0\cdot 25c)$$

In practice, however, there are noticeable differences. With conventional aeroplanes, these differences rarely affect the stability qualities much, except at high and at very high flying speeds. With tailless aeroplanes, however, the deviations experienced may have a large bearing on the stability problem. Hence it will be necessary to examine these deviations from hydrodynamic theory more closely.

First of all, it should be noted that the actual aerodynamic centre (which can be defined, for a wing, as the centre of gravity of all the section aerodynamic-centres along the span) generally differs in two respects from that of theory:

(*a*) It is not situated at the quarter-chord;
(*b*) It does not remain stationary within the whole range of the useful incidences below the stall.

The position of the aerodynamic centre depends upon the Reynolds Number and, to a larger extent, upon the Mach Number. Within the range of lower values of the Reynolds Number comparative tests seem to indicate fairly large variations (7). At speeds at which compressibility effects become noticeable, the centre of pressure travels enormously back, due to an increase of negative pressure near the middle and the tail portion of the aerofoil section (8). This means a variation of the position of the aerodynamic centre with the Mach Number. Hydrodynamic theory as extended to compressible fluids is not in agreement with this experimental fact; C. Kaplan (9) found theoretically, in agreement with H Glauert (10), that the effect of compressibility on the centre of pressure is negligible. It seems, however, established that compressibility as well as viscosity and fluid pressure exert a profound influence.

In low-drag (streamline) bodies and in aerofoils of medium and large thickness ratio on which small values of form drag (pressure drag, due to the inertia of the fluid) are experienced, the aerodynamic centre begin to travel; within the range of small incidences, it travels from its original position towards the leading edge. On bodies of the shape of airship hulls, such as modern nacelles and fuselages, the aerodynamic centre can even assume a position in front of the nose of the body (11). This is a well-known phenomenon to which, however, until recently, not much attention has been paid (airship designers excepted); it is indeed the cause of the often observed fact that highly efficient aeroplanes are apt to show (longitudinal or lateral) instability when flying at small angles of incidence or yaw. Moreover, with thicker low-drag aerofoils and near the angle of incidence of no-lift (dive), it is not uncommon to find the aerodynamic centre having proceeded to within 5 per cent of the chord, instead of remaining in the neighbourhood of 25 per cent, where the aerodynamic centre is (theoretically) supposed to remain (12).

The same is valid of aerofoils which have very small aspect ratios (13). This phenomenon may provide a possible reason why the development of the low-aspect ("Disk" category)

aeroplane, as mentioned in the historical survey, has not been further continued. They possibly exhibited undesirable stability qualities in glides and dives, by reason of the excessive (and, probably, unexpected) travel of the aerodynamic centre within the range of small incidences. From this point of view and from that of dynamic stability, the Disk category will offer difficulties.

Fundamentally, the main cause of the deviation from theory seem to be the forces set up by the viscosity of the fluid, i.e. the surface friction. This would explain why bodies and aerofoils of low drag are most affected. This also provides an explanation why stability difficulties at small incidences are experienced only with well streamlined aeroplanes, though it must be conceded that other factors point in the same direction. But it makes one realize why the deficient directional stability of Lippisch's Stork I with a low-drag nacelle was improved by fitting a (shorter) nacelle of higher form drag (Stork II), and why experimenters with tailless aeroplanes so frequently were disappointed by the discovery that stability qualities previously established underwent a change for the worse as soon as the aeroplane was cleaned up aerodynamically.

As long as the influence of surface friction upon the total drag is small, the aerodynamic centre will behave in accordance with hydrodynamic theory, i.e. remain steady near the quarter-chord. When surface friction prevails, it can be safely expected that the aerodynamic centre will neither remain stationary over the whole range of useful incidences nor will it be very close to the quarter-chord point. Aerofoil sections of 30 per cent thickness, for instance, have their aerodynamic centres at about 18 per cent of the chord (14).

Laminar-flow aerofoil sections, which are at present generally preferred, are, in this respect, specially interesting.

Aerofoil sections with a reflexed medium camber line are particularly sensitive to scale effects since pressure changes in the region of the reflexed tail cause a thickening of the boundary layer in this region. Near the zero-lift angle, and at negative angles of incidence, the negative pressure on the reflexed aerofoil-tail is prevented from becoming fully effective, and this causes a travel of the aerodynamic centre. At high Reynolds Numbers, a closer agreement with theory can be expected.

Aerodynamic Centre and Static Stability

Considering now the condition for static longitudinal stability, the problem has very simply become that, *as soon as the centre of gravity is located in front of the aerodynamic centre, static stability exists*. When both centres coincide, the stability is neutral, and when the centre of gravity lies behind the aerodynamic centre, static instability will be experienced.*

Since stability is a conception admissible only for the case of a state of equilibrium, it remains to investigate if the stable position of the centre of gravity fulfils the requirements of balance.

It is thus immediately realized that a tailless wing system of the Flying-Plank category having simply-cambered aerofoil sections cannot have inherent static stability, since both requirements mentioned above cannot be satisfied for the same location of the centre of gravity. When the centre of gravity is located in front of the aerodynamic centre, no balance can be obtained. It is, however, possible to secure a margin of static stability even in this case, by locating the centre of gravity below the aerodynamic centre (or the centre of pressure); thus forming a physical-pendulum system.

It is evident that simply-cambered aerofoil sections can only be applied to tailless aeroplanes when the wing system incorporates the functions of a tailplane providing the balance required for a stable position of the centre of gravity. A swept-back plan shape with wash-out towards the wing tips, for instance, fulfils this requirement. J. W. Dunne was the first to adopt this principle. The plan shape of the inverted arrow (Buzzard category) with wash-in towards the wing tips is another solution for a longitudinally stable wing system embodying unstable aerofoil sections of identical or similar form.

To state a generally valid principle: *Unstable aerofoil sections can always be combined to form a stable wing system, when the wing portion situated forward of the centre of gravity is so arranged that it produces more lift (i.e. has the greater effective angle of incidence) than the wing portion behind the centre of gravity.*

This principle (formulated by Ferber as "Ferber's Theorem", but actually arising from the work of Pénaud) is incidentally also generally valid for conventional aeroplanes, ordinary tandem aeroplanes, and for tail-first arrangements of any kind. It is even, to a certain degree, valid for the "Flying-Slot" category which will be discussed further below.

A convenient measure for judging the degree of static stability, is the moment coefficient at zero-lift (C_{m_o}). A positive value of this coefficient indicates static stability, and the absolute magnitude characterizes the degree of stability or instability. According to hydrodynamic theory, this coefficient should be, for a given aerofoil or aerofoil section, non-variable up to the lift coefficient at which partial stall of the flow begins to set in.

Aerofoil-Section Stability

Since the travel of the centre of pressure is responsible for the stability characteristics of plain aerofoil systems, aerofoil sections having a stationary centre of pressure, i.e. $\frac{\partial e}{\partial \alpha}=0$, would seem to offer a solution for the Flying-Plank category. At such sections, $C_{m_o}=0$. With small static "pendulum" stability, however, secondary instabilizing effects arising from surface friction and/or from excrescences at the wing (nacelle, etc.) would easily render the whole system unstable. Actually, Flying Wings of this type have been attempted, but gave little satisfaction, with the exception of glider models having a low position of the centre of gravity.

Hence modern solutions give preference to two possibilities:

(*a*) The Flying-Plank category embodying aerofoil sections of positive stability, i.e. a plain (cylindrical or tapered) aerofoil having heavily reflexed-camber sections all along the span.

(*b*) A moderately swept-back plan shape with wash-out, mainly constituted of aerofoil sections which have a practically stationary centre of pressure.

Lippisch (15) at first tried an intermediate solution by providing a wing system of the Arrow type with an aerodynamical wash-out instead of the geometrical one, by employing at the wing tips the same unstable basic section *inverted* (convex side of the camber facing the ground). Though it was found that a small geometrical wash-out could not be avoided, in order to secure stability in a dive, it was thought that the low profile drag of this wing system would be superior. The low maximum-lift coefficient, however, made it preferable to choose instead simply-cambered sections which were positively stable in the inverted position, either symmetrical or reflexed sections, in accordance with the arrangement mentioned under (*b*).

Aerofoil sections with a stationary centre of pressure ($C_{m_o}=0$) either have a straight camber line corresponding in theory to a flat plate (symmetrical sections), or they are of the reflexed category, having a point of inflexion near the tail portion of the medium camber line. The symmetrical class of sections has already been discussed with respect to their stability properties.

Reflexed aerofoil sections are in fact the addition of a (stabilizing or balancing) Pénaud tail to a simply cambered aerofoil section. In accordance with the magnitude of the reflexed portion (curvature and range of curvature), any degree of stability may be obtained. This is in good agreement with modern hydrodynamic theory, and so it is quite possible to predict from theory, with a fair degree of accuracy, the sign and magnitude of C_{m_o} from the layout of

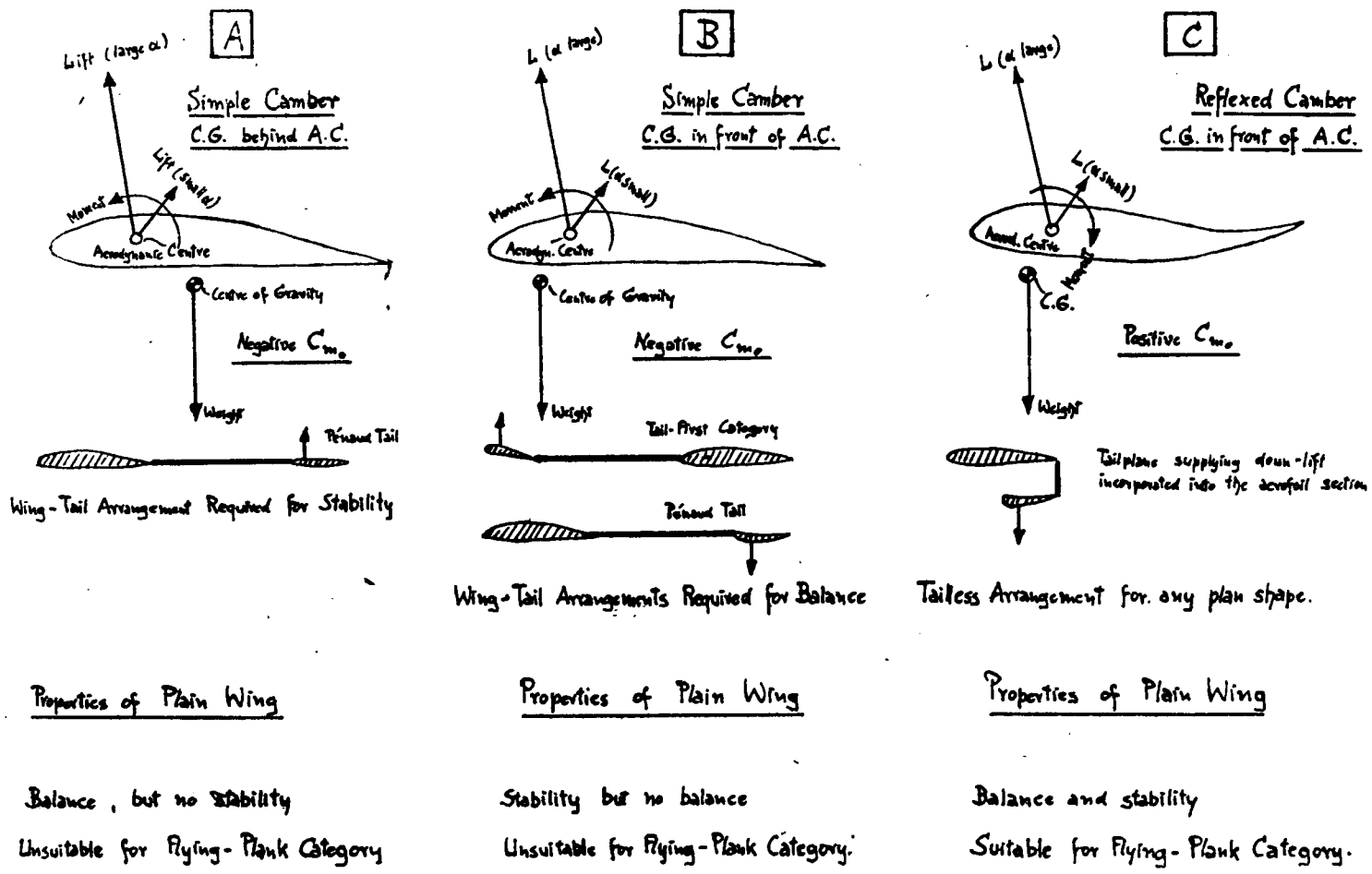

FIG. 2.—*Longitudinal stability and balance on plain wing systems (neglecting the pitching moment arising from the vertical position of the centre of gravity with regard to the wing)*

* This very simple condition for static stability seems to have been formulated first by H. Glauert and S. B. Gates in 1928 (H. Glauert and S. B. Gates, "The Characteristics of a Tapered and Twisted Wing with Sweep-Back", *R. & M.* 1226, p. 7). It neglects, of course, the influence of the vertical position of the centre of gravity with regard to the wing.

an aerofoil section. It is also possible to have reflexed-camber aerofoil sections which will give a stable centre-of-pressure travel (positive C_{m_o} values) over the whole useful range of incidences. The *inverted*, simply-cambered aerofoil section (convex camber facing the ground) is the limit for such stable aerofoil sections.

The history of reflexed aerofoil sections is linked up with the progress in the consideration to longitudinal stability and, hence, deserves mentioning.

The monoplane-project of Pénaud and Gauchot of 1876 (vd. p. 340, December 1944) which belongs to the Flying-Plank category, was the first to be provided with stable reflexed-camber aerofoil sections. In their patent description (16), Pénaud and Gauchot show an aerofoil section of this kind and state:

> ". . . Un équilibre stable d'avant en arrière est obtenu pendant le vol par le retroussement de la totalité ou d'une partie du bord postérieur de la surface de soutien. Cet effect est très important" . . . "Sur nos dessins, les ailes sont légèrement concaves en dessous, à leur partie antérieure, de facon à agir sur l'air à la maniére des hélices marines à pas croissant. . . ."

Twenty-two years later, L. Hargrave, experimenting with such aerofoil sections, established that they gave positive stability. In 1897, Friedrich Ahlborn opposed Otto Lilienthal by condemning simply-cambered sections for their stability deficiency and suggested the use of inverted-camber sections giving stability. For his tailless glider, Ferber employed, in 1901, reflexed sections. In 1907, W. R. Turnbull published extensive research work on reflexed-camber aerofoil sections, emphasizing their superiority for the stability of aeroplanes. One of the earliest stable aerofoil sections investigated in this country was the Modified R.A.F. 6, tested by the N.P.L. in 1913/14.

Heavily reflexed aerofoil sections formed the basis of Arnoux's development of the Flying-Plank category; later they were used by Fauvel and by Abrial. In the earlier years of aviation, however, reflexed sections were not uncommon with conventional aeroplanes. The successful Nieuport monoplanes, for instance, made good use of them. Elastic trailing edges had an identical effect (Etrich, Weiss, Caudron, Voisin, etc.) So there does not seem much novelty about stable, reflexed-camber aerofoil sections.

With the method of conformal transformation, R. v. Mises (6) was able, in 1920, to derive theoretically reflexed-camber sections of any desired degree of stability. In 1922, J. Geckeler (17) continued this work, giving a number of concrete examples for sections with a stationary centre of pressure. R. v. Mises also proved that, for positive stability, i.e. for a location of the centre of gravity in front of the aerodynamic centre which satisfies the condition of balance without necessitating a tail, a reflex in the curvature of the medium camber line is a necessity. M. Munk, basing his investigations on wider and more practical lines, arrived at the same condition of an S-shaped camber line and established a series of useful aerofoil section ("M" series) which have found wide application for all sorts of aeroplanes. From Munk's work, the modern research on stable aerofoil sections has mainly originated.

From the preceding considerations, it is evident that the Flying-Plank category can be realized only with the help of reflexed camber aerofoil sections. It was this condition which imposed upon R. Arnoux the necessity of fitting stops for limiting the downwards deflection of the controllers. Otherwise, the longitudinal stability would have been seriously imperilled. All tailless aeroplanes based on the use of aerofoil section stability must incorporate similar precautions for retaining the degree of static longitudinal stability which is required. On the other hand, it is seen that controllers forming

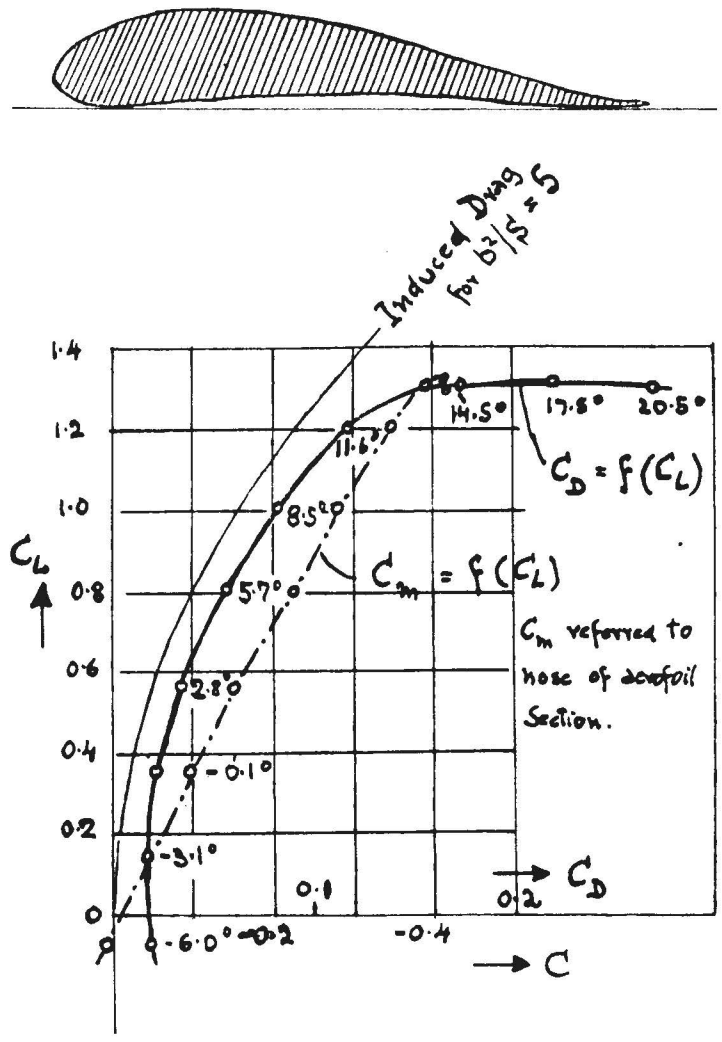

FIG. 3.—*Goettingen No. 716 aerofoil section, developed by Lippisch in 1932. The centre of pressure is theoretically stationary over the whole range of useful incidences, but the wind tunnel test exhibits instability at small angles of effective incidence, due to the appearance of suction below the reflexed tail of the section*

FIG. 4.—*Aerofoil section with stable travel of the centre of pressure (positive C_{m_o}), as employed by Fauvel*

the trailing edge of the wing will, with tailless aeroplanes, always deeply affect the longitudinal stability. In general, the stability will be improved in climb and decreased in a dive. This change in the degree of static stability will also affect the dynamic stability; and this requires special consideration.

Stable aerofoil sections are, however, in their performance qualities, not thought of as very satisfactory. Their main deficiency is that they suffer from low values for the maximum-lift coefficient. This is an inherent deficiency, since the reflexed tail portion is intended to balance the lift produced by the front part; it is actually the down-lift of a tail plane which is produced at the reflexed (bent-up) portion of the aerofoil. One realizes that static stability cannot be gained without a loss of lift and, in this respect, the only course open is to decide if it is more profitable to generate the down-lift, which is required for stability or balance, by way of a tail plane or by way of a reflex in the aerofoil-section camber line.

Incidentally, when considering the tail-first arrangement, this deficiency does not arise. But there is as yet no known equivalent solution for a stable aerofoil section incorporating the tail-first principle.*

Stable aerofoil sections are also generally inferior for take-off and climb. The only superiority, which they formerly seemed to exhibit, in comparison with commonly used sections, concerns the minimum profile drag.

Comparative tests between two related thin sections (18), one with simple camber and the other with a reflexed camber line (R.A.F. 6 and R.A.F. 6 Modified) would indicate a loss of 15 per cent in the maximum-lift coefficient, and an inferiority in the optimum lift/drag ratio of 8 per cent for the reflexed section, while the minimum drag was not less than 25 per cent better owing to reflexing. This result, however, refers to older tests made at relatively low Reynolds Numbers.

Modern investigations have beyond doubt established that aerofoil sections of this kind, like those with stationary centre of pressure, are adversely affected at low Reynolds Numbers. Since this discovery, aerofoil sections with a stationary centre of pressure have found ample use in aeronautics, and to-day they generally seem preferred with conventional aeroplanes.

The National Advisory Committee for Aeronautics has published comparative wind-tunnel experiments in order to establish the influence of a reflexed camber line (19). Unfortunately, the comparison, as made public, was restricted to such an amount of reflexing that only a stationary centre of pressure (i.e. $C_{m_o}=0$) was achieved. The trend of the results tallies quite well with the British tests mentioned above, though the sections investigated had thicknesses between 12 and 14 per cent of the chord. By reflexing, the maximum lift decreased between 9 and 13 per cent. The optimum lift/drag ratio was less affected than before. The minimum drag showed a distinct tendency to decrease, by about 4 per cent. But at higher lift coefficients (above $C_L=0{\cdot}5$), the drag was markedly increased by reflexing.

Very pronounced reflexing such as required for the attainment of positive section stability (positive values of C_{m_o}) will, of course, cause a greater variation in the section characteristics than those quoted.

More recent comparative tests (20) indicate that a reflexed section having a positive C_{m_o} value and 12 per cent thickness gives about 9·5 per cent less lift than the relative simply-cambered section, while the minimum drag is slightly increased, by about 1·2 per cent; the optimum lift/drag ratio is about 1·8 per cent inferior, but occurs at a higher angle of incidence.

From this it would appear—contrary to expectations—that there is some scope for stable aerofoil sections after all, and the performance of the Fauvel tailless lightplane has indeed proved that they are quite competitive. One of Fauvel's sections is shown in Fig. 4.

Lippisch (21) and Stieger (22) have drawn attention to an inherent disadvantage of reflexed sections in respect to control. In connexion with normal controllers, they are apt to promote roughness of operation, and the control will tend to become heavier at higher speeds. We shall return to this peculiarity later.

Stable Wing Systems

Lippisch (23) seems to have been the first to emphasize that a satisfactory solution of the problem of longitudinal stability for single wing systems ought to combine section stability with stability by way of wing shape.

That unstable aerofoil sections can always be employed to form stable wing systems, had already been stated. The discovery of the *Arrow category* was due to J. W. Dunne (1906). Later (24 and 25) it was mathematically proved that only a combination of sweep-back with wash-out could render a wing system longitudinally stable, while either feature alone was useless.

In order to secure static stability and balance over the whole range of useful incidences, however, large degrees of sweep-back and wash-out are required. The Dunne aeroplanes had sweep-back angles of the order of 30 degrees and pronounced wash-out. Glauert and Gates have shown (25) that taper does not affect the stability of wing systems of this kind.

Tailless aeroplanes with wing systems relying solely on the wing shape for stability are disadvantageous. Weight and performance are

* The nearest approach to shapes of this kind would appear to be "Profile No: 5" as calculated by J. Geckeler (17, p. 180).

unfavourable. The drag is high and the maximum lift low. In conformity with theoretical expectations (25), the flying qualities are poor, and structurally, the wing is bound to be heavy, Thus tailless aeroplanes of this kind will generally be inferior to conventional aeroplanes. The experience gained with the Dunne biplanes does not contradict this conclusion. On the whole, any attempt to achieve stability by the expedient of wing shape alone must seem unpromising.

The other extreme, the *Flying-Plank category* relies entirely on section stability. Stable aerofoil sections, as we have seen, need not necessarily be so far inferior to the best common sections as to exclude competition. Practical experience confirms this view, and further research in this direction would seem promising. Structurally, the Flying-Plank is the ideal. Its flying qualities could be very good. Yet there is the inherent disadvantage that this category is very sensitive with regard to the location of the centre of gravity. Thus the problem of trim would appear difficult to solve.

It is true that the sensitivity in the fore-and-aft location of the centre of gravity and in all pitching moments could be somewhat decreased by the choice of small aspect ratios, but this will not always be a welcome remedy. Moreover, for reasons stated above in connexion with "travelling" aerodynamic centres, it is likely to diminish the stability at small angles of incidence. Hence, the Flying-Plank category will seem to offer distinct advantages only for certain very limited applications.

Lippisch's combination between the two extremes has proved generally the most useful solution. It is theoretically possible to start from given aerofoil sections and to define for these the wing shape (sweep-back and wash-out) for any desired degree of static stability. Or, the calculation can proceed from a given wing shape by defining for it the aerofoil sections satisfying the stipulated degree of stability. Wuster (26) has in this way calculated stable wing systems and compared them with wind-tunnel tests. The aerofoil sections for the given plan shape are evolved by the method of conformal transformation, applying the theory of wing lift by v. Mises (6) and the procedure devised by J. Geckeler (17). The section "Focal Points" are then referred to the plan shape given, by the application of the aerofoil theory of Lanchester and Prandtl.* The trend of the procedure is thus not unlike to that followed by Glauert and Gates in their calculation of a tapered and twisted wing with sweep-back (25). The series of stable aerofoil systems calculated by Wuster agree in their stability well with the results of wind-tunnel tests at the corresponding models. This proves that at such complicated wing systems too, the "Focal Points" of the perfect flow correspond practically with the section aerodynamic centres of the real, drag generating flow.

With the aid of a moderate sweep-back and wash-out, it is not necessary to use stable, i.e. heavily reflexed, sections all over the span. Sections with a stationary centre of pressure ($C_{m_o}=0$), i.e. of symmetrical shape or with a slightly reflexed camber line, may be employed for the whole wing system. Or for the major part of the span, aerofoil sections are selected which have very small negative values of C_{m_o}, such as the best modern small-camber sections. In each case, the result will be a combination wing system of the Delta type which is well adaptable for most practical purposes.

* This method (as well as that of Glauert and Gates) is an approximation in so far as the present aerofoil theory neglects to consider the influence of sweep-back on the distribution of lift over the span, while the wash-out is fully taken into account. For small angles of sweep-back, the difference between theoretical and experimental results is small, in comparison with other assumptions of the method, but with pronounced sweep-back, it would seem necessary to apply the classic theory on the basis of an experimentally established distribution of lift over the span.

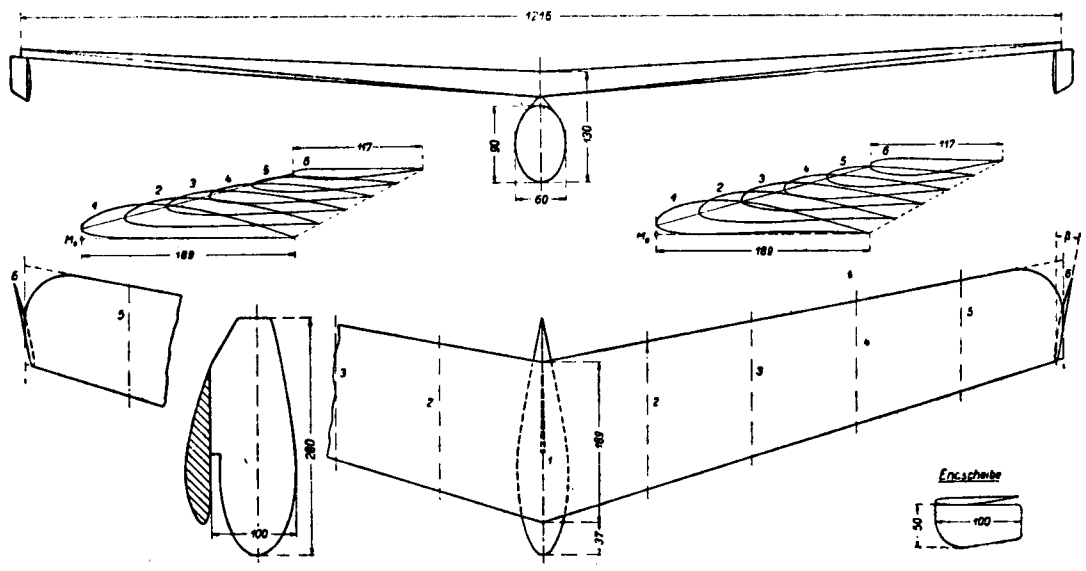

FIG. 5.—*Wind-tunnel models for the development of the earlier Stork types of Lippisch* (β = *angle of slanting of the wing-tip disks*)

The aerofoil sections shown left belong to aerofoil type 1, *those shown on the right to aerofoil type* 2

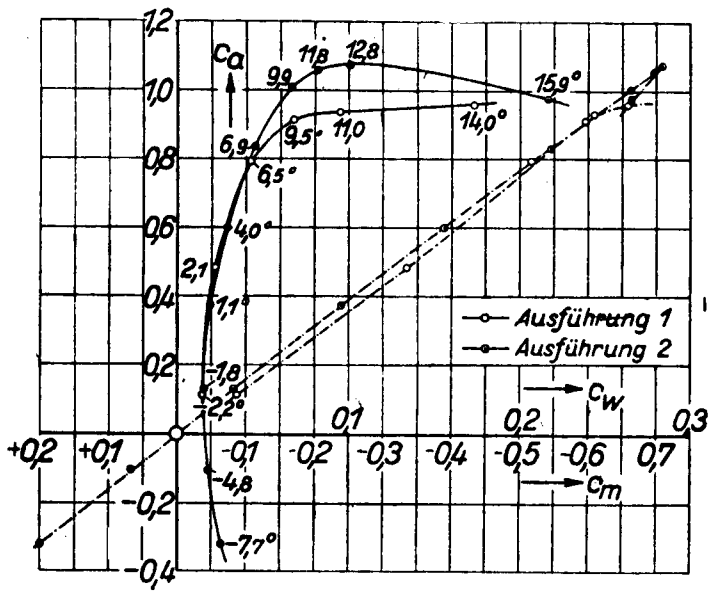

FIG. 6.—*Wind-tunnel test of Stork I without wing tip disks. The moment coefficient* c_m $(=-c_m)$ *is referred to the leading edge at the centre of the wing. Note the differences between the two aerofoil systems shown in Fig.* 5

Ausführung=type; referring to aerofoil types in Fig. 5

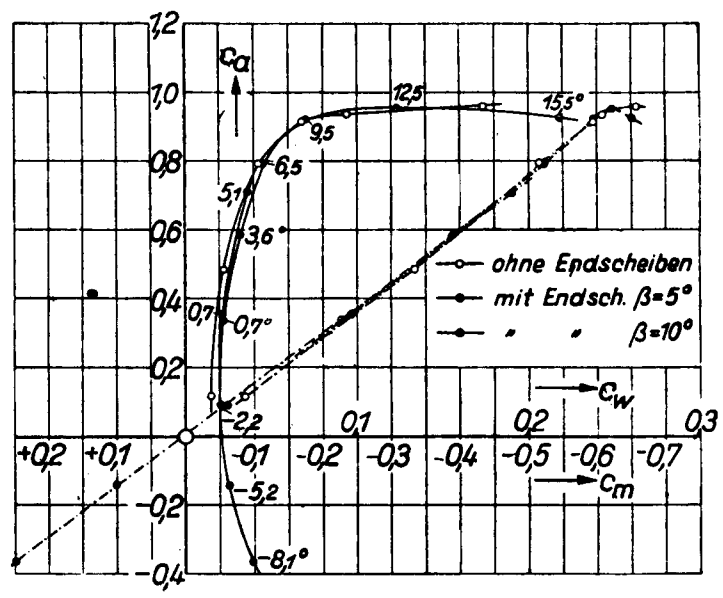

FIG. 7.—*Wind-tunnel tests of Stork I with and without wing-tip disks and under different angles of slanting* β

Ohne and mit Endschiben=with and without wing-tip disks

$c_a=c_o$ $c_w=c_o$

The Complete Aeroplane

Considering a tailless aeroplane other than a genuine ideal Flying Wing, the problem of longitudinal stability becomes involved by reason of excrescences and additional pitching moments. With conventional aeroplanes, additional pitching moments can in most cases either be neglected or be summarily included by adjusting factors, because the pitching moments of wings and tail prevail on balance. This is not so with the tailless aeroplane.

It has already been pointed out that well-streamlined components such as nacelles, fairings, etc., may cause trouble by having their aerodynamic centres not only far forward, but also not stationary. Interference effects may add further complications. Since nacelles (or fuselages) will normally project forward of the leading edge of the wing, the total aerodynamic centre, built up from that of the wing and that of the nacelle, lies more forward. This implies the demand for greater static stability to be supplied by the wing system, since a shifting of the centre of gravity in front of the new total aerodynamic centre will have to be compensated either by greater section stability (greater reflex, for instance, by raising the controller stops) or by an increase in sweep-back and/or wash-out.

Another difficulty which is often felt with designs using tractor airscrews, is due to the airscrew and its slipstream. The effect of the slipstream on parts of the wings is not yet so fully explored that it has become entirely amenable to theory, but it is certain that the slipstream makes the aerodynamic centre travel forward, hence decreasing the static stability (27). According to Gates, the effect disappears at very high speeds, i.e. at those locally approaching sonic velocities, where the pressure distribution fundamentally changes.

Another effect on stability arises from the fore-and-aft position of the airscrew with respect to the centre of gravity. Reaction jets may exhibit certain analogous phenomena.

When an airscrew rotates at an inclination to the relative wind, a force is generated in the plane of rotation which acts perpendicular to the airscrew axis (28). In its effect, this airscrew cross-force is comparable to an aerofoil located in place of the airscrew under a corresponding inclination. It is evident that with tractor arrangements the cross-force produces unstable pitching (or yawing, as the case may be) moments about the centre of gravity, which aggravate any disturbance from the state of equilibrium. These moments are, moreover, greatest in the attitude of climb; i.e. when the inherent static stability of the wing system becomes smallest.

With tailless aeroplanes, especially with those employing airscrews of large diameter, the effect of these unstabilizing moments will be considerable. It follows that pusher arrangements are particularly beneficial for tailless designs (29). Experience seems to have borne this out in practice, though pusher arrangements without transmission gears offer problems of their own.

Quite apart from these effects, unbalancing pitching moments will arise as soon as the thrust line of airscrews, or of reaction jets, is passing above or below the centre of gravity. With the tailless principle, the compensation of such moments would necessitate a different location of the centre of gravity and thus affect the longitudinal stability. It is not surprising to find that all attempts at the conversion of tailless gliders into light aeroplanes by the fitting an engine-cum-airscrew aggregate above the wing (Fauvel, Kupper, etc.) did not meet with success.

The discussion of the static stability of aerofoil systems and its general dependence on the shape of the medium camber line of the aerofoil sections employed, leads immediately to an understanding of the problem of controllers

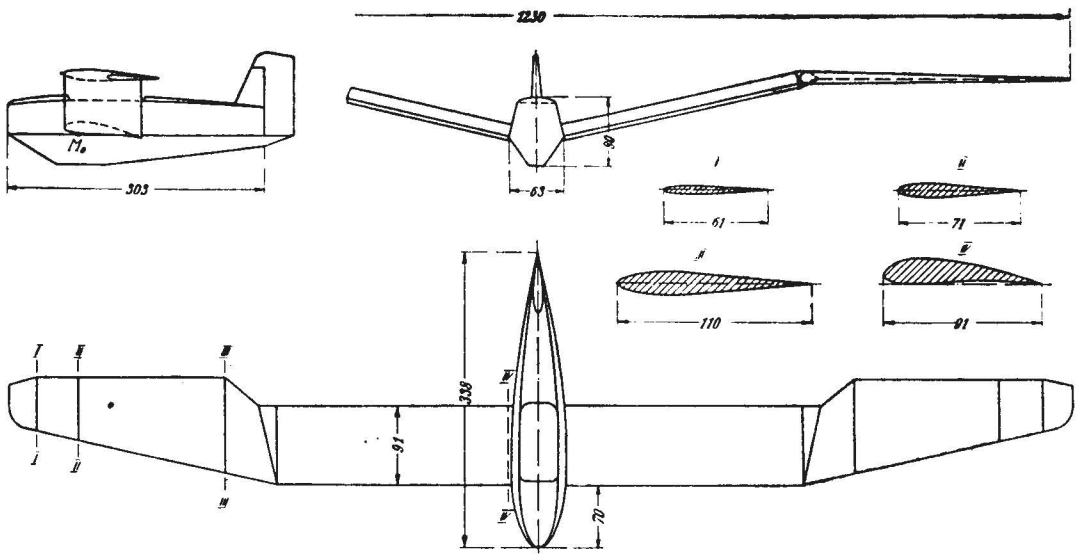

FIG. 8.—*Wind-tunnel model of an experimental Weltensegler two-seater lightplane type V.E.1, designed by F. Wenk*

and other control organs which form movable portions of the trailing edge of the wing. Control surfaces of this kind act through a variation of the effective angle of incidence of the wing portion concerned, as well as by way of a modification of the section camber. Thus, in a raised position, controllers effect a reflexed camber, hence increase the static stability. This means that, in climb, the effect of elevators counteract to some extent the decrease in static stability which is experienced at higher angles of incidence.

Alternatively, when depressed, controllers are apt to render the wing portion forward of them unstable, Considerations of stability will thus, as mentioned above, limit the angle of downwards deflection. Stops, like those provided by Arnoux for his full-span controllers, imply, of course, that the controllers may be employed only for half the range available for the control surface of a conventional aeroplane.

Ways and means to achieve efficient control will be discussed in a later article.

Dynamic Longitudinal Stability

Static stability is a requisite for dynamic stability. The problems offered by the latter seem to-day well understood, though it still appears undecided when and to what an extent dynamical stability of the oscillatory motion is desirable or practicable. Some of the more general requirements have been outlined above. For certain purposes, dynamically neutral and even dynamically slightly unstable aeroplanes have given full satisfaction in service. For large transport or military aeroplanes, however, a certain degree of dynamic longitudinal stability appears desirable and, in connexion with automatic pilots, probably essential. Airsickness would seem to provide certain values for the desirable damping.

The dynamic longitudinal stability requires special attention and would seem to need more attention than has hitherto been paid to this problem. This seems to have been realized early in this country, when the original Pterodactyl types exhibited certain unpleasant flying qualities (30) though it was then assumed that by discarding the floating wing-tip controllers, the problem could be considered as satisfactorily solved. Nevertheless, the research work then done (mainly by H. Glauert and S. B. Gates, both of the R.A.E.) has provided the foundation on which future research in this direction can build.

Aeroplanes having static stability will generally exhibit a longitudinal motion, after experiencing a disturbance, which may be approximated as a superposition of two oscillations which have different periods and different dampings. One of these oscillations, commonly called the short-period oscillation, is connected to variations of the angle of incidence. The other one, called Lanchester's phugoid, or the long-period oscillation, is mainly due to variations of the speed.

Tailless aeroplanes, of course, also experience both these oscillations. But there is an essential difference between aeroplanes of the Pénaud type and of the tail-first type. While with conventional aeroplanes the short-period oscillation is so heavily damped that there is never any reason to investigate the stability of the motion or the amount of damping when dealing with a normally designed aeroplane, the tailless aeroplane may well suffer from a small damping and quick period of this oscillation. Gates and Hirst (30) were the first to point out this characteristic difference.

Damping in Pitch

The main cause for the discrepancy is the difference of damping in pitch which, with a conventional aeroplane, is mainly (about 80 per cent) derived from the tail. With a tailless aeroplane, the main source of air-damping is the wing. Nacelles, etc., may supply contributory damping, but the value of this will be practically negligible.

For the purpose of a short survey of the problem, it will be sufficient to say that the parameter which causes the main difference between a conventional and a tailless aeroplane is commonly denoted by m_q and known as the rotary-derivative coefficient of the pitching moment due to pitching. It is a non-dimensional value defined as follows:

$$m_q = \frac{-M_q}{\rho \cdot S \cdot V \cdot c^2 k_B} = -\frac{k_{mq}}{k_B}$$

where:

M_q = rotary derivative of the pitching moment due to pitching $= \dfrac{\partial M}{\partial q}$

k_{m_q} = dimensionless coefficient of the rotary derivative Mq:

$$k_{m_q} = \frac{-M_q}{\rho \cdot V \cdot S \cdot c^2}$$

k_B = lateral inertia coefficient $= \dfrac{B}{m \cdot c^2}$

B = moment of inertia about the lateral axis

$m = \dfrac{W}{g}$ = mass of the aeroplane

c = geometric mean chord of the wing

ρ = mass density of the air

S = wing area

V = forward speed of the aeroplane

q = angular velocity of pitch

m_q and k_{m_q} are, unfortunately, factors which are not easily amenable to accurate calculation, except for the case of a plain aerofoil under certain simplifying assumptions.

H. Glauert has calculated k_{m_q} for a plain aerofoil (31) and, according to B. M. Jones, these theoretical values are in good agreement with experiment (32). These theoretical results thus may be used for Flying-Plank types. The values of k_{m_q}, i.e. the aerodynamical damping of a wing in pitch, increase when the axis of pitch (i.e. the centre of gravity) shifts towards the leading edge. From this it is evident that the aerodynamical damping increases with increasing static stability. For a tailless aeroplane, which necessarily must have its centre of gravity far forward, this is an important circumstance in favour of dynamic stability.

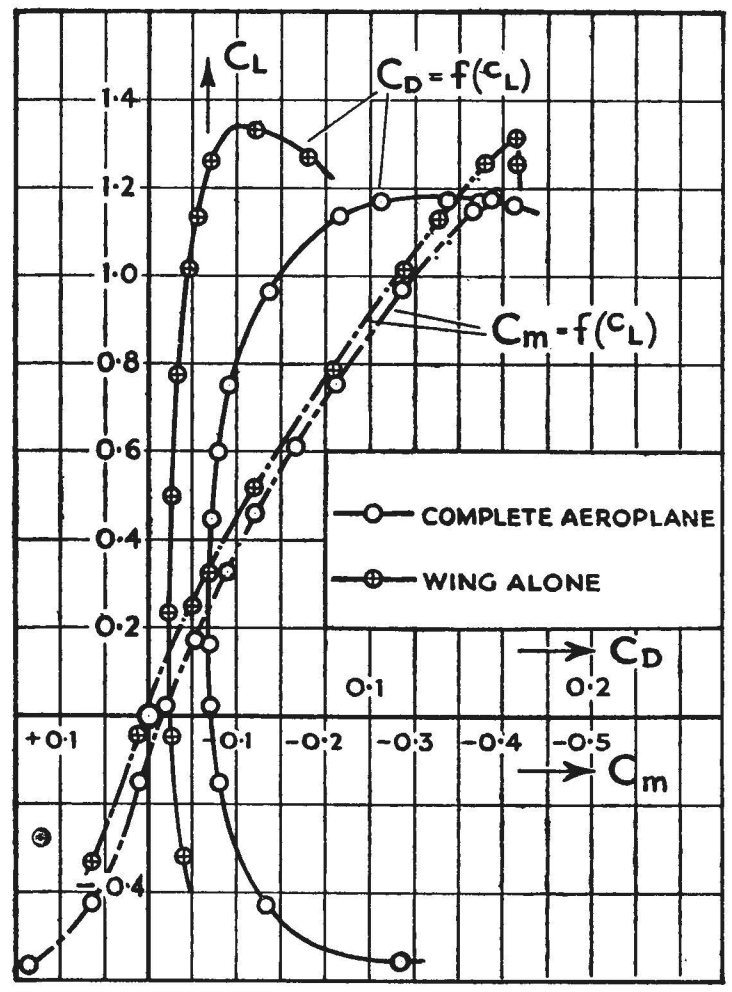

FIG. 9.—*Wind-tunnel tests of Weltensegler V.E.1 two-seater. The moment is referred to an axis which is 19.2 per cent behind the leading edge of the central wing portion. It is seen that the addition of the fuselage renders the system unstable*

Glauert has also shown that, for such positions of the centre of gravity as are likely with aeroplanes of the Flying-Plank category (10 to 20 per cent of the mean wing chord), the magnitude of k_{m_q} varies somewhat with the aspect ratio. The improvement of the aerodynamical damping will be assisted by a corresponding change in the lateral moment of inertia, so that, in general, Flying Wings of a higher aspect ratio may be expected to give better damping in pitch than those of low aspect ratio. It would be interesting to learn if flying experience with aeroplanes of the Disk category has borne out this conclusion.

Glauert and Gates have calculated k_{m_q} for aerofoils with sweep-back, taper and wash-out (25). It needs, however, still to be proved by experiment if the complete neglect of span-wise flow components is admissible in this respect. From the theoretical investigation it follows that taper has not much effect on the aerodynamical damping and that no variation of the wash-out along the span influences the damping; the damping increases greatly with the angle of sweep-back. It seems possible that, when three-dimensional flow is taken into account, the twist of the wing will have a bearing upon the damping.

The coefficient m_q which is characteristic for the total damping of the aeroplane in pitch, can also be written as follows:

$$m_q = \frac{m}{\rho \cdot S \cdot V} \cdot \frac{-M_q}{B} = \frac{W}{S} \cdot \frac{1}{\gamma \cdot V} \cdot \frac{-M_q}{B} = \sim C_L \frac{V}{2g} \cdot \frac{-M_q}{B}$$

where:

γ = specific weight of the air

$\dfrac{W}{S}$ = wing loading

From this, it is seen that m_q depends upon parameters relating to temporary conditions of flight, and on two physical characteristics relating to the design, viz.:

(*a*) the aerodynamical damping in pitch;

(*b*) the moment of inertia about the lateral axis.

Now the aerodynamical damping in pitch is, with a tailless aeroplane, only a fraction of that of a conventional aeroplane. With an aeroplane

of the Arrow category it will be about one-third of that of a conventional type, and with a Flying Plank, it may be only one-eighth. Gates and Hirst (30) assumed for the earlier Pterodactyl (Mk. Ib), a total m_q (i.e. including the effect of the smaller moment of inertia) of only up to half that of an ordinary aeroplane. The aerodynamical sweep-back of this type was approximately 25 degrees.

It is also seen that the designer cannot do much to improve the aerodynamical damping. The only thing he can do with reasonable effect is to increase the angle of sweep-back. But by doing so, he is also increasing the moment of inertia, and soon an optimum will be reached, beyond which an increase of the sweep-back will only result in a deterioration of the dynamic stability. The Dunne biplanes seem to have formed good examples of this.

More may be done for an increase of the damping coefficient m_q by keeping the inertia about the lateral axis to the lowest limits which the general arrangement permits. It would seem that with many of the hitherto constructed tailless aeroplanes, this point has not been given sufficient attention. The Dunne biplanes have most obviously not been designed with this point in view, and many of the subsequent tailless attempts seem also to have suffered from the same deficiency. Past tailless gliders and sailplanes must have been far better in that respect. It has already been mentioned that a satisfactory compromise between the aerodynamical damping and the moment of inertia will define the most suitable degree of sweep-back. Wing-tip disks and/or heavy controllers located near the wing tips, large fore-and-aft distances between concentrated masses such as engines and crew, etc. will render the damping poor.

When discussing the problem of the moment of inertia about the lateral axis, two arguments may be raised in favour of a large inertia. It may be said that a disturbance (gust) will not be apt to take charge of the aeroplane as quickly when the inertia is large, and that small gusts will thus remain ineffective. However, the small aerodynamic damping of a tailless aeroplane and the fact that there is no tail upon which a gust can exert a large pitching moment, will imply that gusts should have a far smaller effect on the attitude of the aeroplane. What counts for the dynamic behaviour of an aeroplane is not so much an up-and-down motion of the centre of gravity as pitching moments affecting the incidence and the speed directly. From the up-and-down movement of the centre of gravity, secondary pitching moments arise with the tailless aeroplane, but it is safe to suppose that the pitching moments directly applied by a tailplane are, by comparison, far larger.

It may, further, be said that a large inertia will make control easier. It is true that a small inertia will require sensitive control organs which act without lag and back-lash. But it cannot be seen why, with control having these qualifications and with sufficient static stability and facilities for trim, the control of a tailless aeroplane should be more difficult when the fore-and-aft inertia becomes a minimum. This seems to agree with the flying experience collected during the evolution.

The Short-Period Oscillation

The classic stability biquadratic can be approximately factorized into two quadratics representing the two oscillations which were mentioned above. Conditions for the factorization are that the aeroplane is in steady flight and that it possesses positive or at least neutral static stability.

The solution for the short-period oscillation makes it a condition for damping of the oscillation that the sum of certain stability coefficients is negative. This condition will always be fulfilled, but the degree of damping will, with a tailless aeroplane, be far smaller than with a conventional aeroplane, because the magnitude of m_q is so much smaller.

Of the other stability coefficients contributing to the damping, one is practically of no importance owing to its small magnitude; the remaining one depends largely upon the slope of the lift curve and on the drag. So the designer cannot do much about it.

Another, and possibly more serious, effect of the decreased damping concerns the period, With a tailless aeroplane, the period will be somewhat quickened and the oscillation will last longer until it is damped down to imperceptibility. It has been mentioned that the short-period oscillation is mainly connected with change in incidence. Quick oscillations of this nature may have aerodynamic consequences in the airflow over the wing which necessitate special consideration. In this case, the common methods of investigating the dynamic stability need amplification and further experimental research.

Two phenomena connected with a rapid oscillation of the incidence might have profound influences upon Flying-Wing design. When the angle of incidence of a wing is suddenly increased, a dynamic lift is experienced and the maximum lift is temporarily increased, since the separation of the flow from the suction side of the wing is delayed. This phenomenon would influence the strain on the wing structure, and might also have a bearing on the problem of flutter. It might occur with large disturbances, when a quick period is combined with a progressive and large damping.

The other phenomenon is the Katzmayr effect*. With this, a diminished or negative drag can be created when an aerofoil changes its angle of incidence periodically from a positive to a negative value. The lift is very little affected. But as the drag has a large influence upon the stability and damping of the oscillations, a decrease of the drag due to the short-period oscillation following a disturbance would affect the damping of the phugoid too.

The Phugoid Oscillation

The long-period oscillation is the only one which can cause trouble with conventional aeroplanes. Gates and Hirst (30) have investigated the influence of a suppression of the stability derivative coefficient m_q on this oscillation. They found that in this case, the phugoid damping will not be affected at high speed (small C_L values) and will even be increased at stalling, while the damping will be much reduced at medium speed. The period of the oscillation will decrease with m_q, except at stalling.

With the phugoid, the interrelation between the single physical characteristics determining its nature is not so simple as with the short-period oscillation. Hence it is, without having recourse to mathematical aids, not easy to form an opinion on the import of the single factors upon the motion. Stated in general terms, the period and the damping factor (or the time required for damping the oscillation to one-half amplitude) depend mainly upon: lift and drag coefficient; the slopes of the lift and of the drag in respect to the incidence; the moment derivative of the pitching due to pitch; the moment derivative of the pitching due to normal velocity; the lateral moment of inertia; the wing loading; the air density (or, the altitude, respectively); the flying speed. How far with tailless aeroplanes, forces and moments due to angular accelerations and incidence variations will need to be considered, requires further investigation. It will appear that, with tailless aeroplanes, stability values which are commonly considered as being of secondary importance and even negligibly small for conventional aeroplanes, may be found quite important.

Adapting the treatment on the subject by Ch. H. Zimmermann (34), to the needs of tailless aeroplanes—an approximation which might require justification—the short survey of the problem can be simplified by stating that the damping of the oscillatory motion is mainly influenced by two dimensionless parameters. One of these, the rotary-derivative coefficient m_q, here termed "rotational damping factor", has already been considered above. Its decrease in value quickens the period of the phugoid.

The Static-Stability Factor

The other parameter, termed the static-stability factor μm_α also influences the period (but not the damping) of the short-period oscillation to some extent, since it is interrelated to the moment derivative of pitching to normal velocity. The static-stability factor is constituted as follows:

$$\mu m_\alpha = -\frac{m}{\rho \cdot S \cdot c} \cdot \frac{1}{2k_B} \cdot \frac{dC_{m_{c.g.}}}{d\alpha} = -\frac{W}{S} \cdot \frac{1}{\gamma} \cdot \frac{m \cdot c}{2B} \cdot \frac{dC_{m_{c.g.}}}{d\alpha}$$

where:

$\frac{dC_{m_{c.g}}}{d\alpha}$ = slope of the pitching-moment coefficient as referred to the centre of gravity, in respect to the angle of incidence.

The slope of this pitching-moment coefficient is a measure of the margin of static stability for the whole aeroplane. If it is negative, it indicates the presence of static stability; if it is zero, neutral stability will exist*. The magnitude characterizes the margin of static stability. $C_{m_{c.g.}}$ has to take into account all pitching moments arising from the normal-force and tangential-force components of the resultant aerodynamic force and also all pitching moments arising from parts other than the wing. It will be found that with tailless aeroplanes, especially with those of the Flying-Plank category, the vertical location of the wing relative to the centre of gravity may have marked influence. High-wing arrangements may be preferable. But, in the first place, the value of $dC_{m_{c.g}}:/d\alpha$ depends on the distance of the centre of gravity in front of the aerodynamic centre.

The damping of the oscillation depends largely on the magnitude of the static-stability factor. The latter affects the lag in the angle of incidence with regard to the change in the angle of flight-path, following a disturbance. The larger the periodic delay in the incidence variation, the more probable is the occurrence of dynamic instability. The interaction of the rotational damping factor with the static-stability factor, therefore, gives a measure of the dynamic instability and the amount of damping. At the same time, both parameters give an indication of upon which main characteristics the problem of dynamic longitudinal stability rests.

The margin of static stability alone is in no way decisive. S. B. Gates (27) has stated that though static stability is conditional for the damping of the phugoid, it does not follow that the damping as such is in a direct relation to the amount of static stability. In fact, it cannot be presumed that the damping will improve when, for instance, the centre of gravity is shifted forward into a position giving greater static stability. Although this improves directly the

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* More correctly termed, the Knoller-Betz effect, since R. Knoller and A. Betz independently from one another, discovered and explained this phenomenon 10 years before Katzmayr proved its existence experimentally. (33)

* It is necessary to note that the moment coefficient $C_{m_{c.g.}}$ refers to the centre of gravity as the axis for the pitching moment, and not to the aerodynamic centre (as C_{m_0} does).

aerodynamic damping provided by the wing, it is yet theoretically possible that the oscillation will increase (negative damping) with the centre of gravity lying well ahead of the aerodynamic centre; this has occasionally been observed.

It is necessary to take note of this somewhat queer fact when considering the dynamic stability of tailless aeroplanes as it is still frequently assumed that, as a tailless aeroplane is bound to have static stability, the question of dynamic instability does not arise. Model tests also indicate that acute instability can exist.

Zimmerman (34) concludes, on the basis of his simplifying investigation that, when the original value of the static-stability factor is small, an increase of the static stability will be detrimental, while, beyond a certain value, such an increase will tend to obviate dynamic instability.

In general, low-drag, i.e. efficient, aeroplanes are more liable to exhibit dynamic instability of the phugoid, since the drag is one of the most efficient physical characteristics to decrease the amplitude of oscillations and to increase their period. Flying Wings should thus be more exposed to trouble in this direction than other aeroplanes.

Some Results of Flying Experiences

Few experimenters have cared to relate in detail their impressions of longitudinal stability. And the few impressions recorded are, often enough, neither very intelligible nor very truthful, an understandable fact in view of the urge of the experimenter to forge ahead and to secure better assistance by not mentioning deficiencies in stability and control.

It is difficult to assess to-day how far major crashes experienced with Arnoux aeroplanes have been caused by deficient longitudinal stability, but it may have been a contributory factor in at least one of them. The reason has become clear through protests Arnoux raised at the time: the stops limiting the downwards deflection of the full-span controllers had been removed by pilots who were ignorant of the stability quality. In normal flight, however, and with limited controller angle, these Flying Planks seem to have performed quite well.

This is in good agreement with 1/3rd scale-model tests made by Lippisch (35). He had originally assumed that with the Flying-Plank category, there would be no damping of oscillations. Nearer insight, however, convinced him that, since the disturbing moments were of equal magnitude as the damping ones, dynamic stability might well exist. The models indeed flew steadier than equivalent tailless glider models of the Arrow category. The models tested had symmetric aerofoil sections; in order to obtain a margin of static stability, the centre of gravity was placed below the centre of pressure.

The flying qualities of the Fauvel monoplanes were repeatedly reported upon. Fauvel himself claimed (36) that according to his flying experiments with the A.V.3 glider and the A.V. 10 light aeroplane, the dynamic longitudinal stability did not constitute a difficult problem. Flights in gusty weather proved positive stability. In his opinion, the action of gusts on an aircraft of his design is small because the wing only is affected, and not a system consisting of a wing plus a tail plane which is acted upon at an interval corresponding to the distance between wing and tail plane; the smaller inertia about the lateral axis is a contributory factor. Moreover, he states that oscillations are always damped because of the static stability, which is required by the Flying-Plank category (having the centre of gravity between 12 and 22 per cent of the chord aft of the leading edge), and because of the concentration of masses. The A.V. 10 was officially tested by the French authorities and approved for air-worthiness (37); it indeed proved entirely satisfactory in respect to longitudinal stability, at all speeds and at all permissible positions of the centre of gravity. The same has been stated with regard to the tailless sailplane A.V. 33 which a number of pilots have tried. The small effect of gusts was commented upon. From all this it would appear that—to say the least—the stability qualities of the Fauvel monoplanes cannot have been unsatisfactory.

But even if there were no remedy to improve the dynamic stability of more efficient aeroplanes of the Flying-Plank category by reason of poor damping qualities, devices seem conceivable which would permit, either by aerodynamical effect or by artificial means (for instance, by gyroscopes), to improve upon the natural damping of a plain wing.

The Arrow category as already been mentioned. The damping of longitudinal oscillations by way of sweep-back has been emphasized by J. W. Dunne in his 1909 patents; he also assumed that a gradual wash-out would help in this respect. The Dunne aeroplanes suffered most probably from excessive sweep-back and from a great moment of inertia. They have been described as "too stable" and "uncontrollable." Lack of control efficiency may be as much the consequence of too great an inherent stability as of deficient dynamic stability which, in gusts, necessitates constantly changing control manoeuvres without immediate and apparent direct effect. Incidentally, theory and flying experiment seem to indicate for the Arrow category, that the dynamic stability is superior with a biplane arrangement, owing to the greater aerodynamic damping. Wind-tunnel tests (38) have otherwise shown that the static stability of a swept-back biplane is slightly less than that of a monoplane with equivalent sweep-back.

Hill (39) reported after a first series of flights with Pterodactyl Mk. 1A that the aeroplane possessed static stability with free controllers, and that it exhibited a rather quick period of oscillation (guessed to be about 9 sec., at 40 m.p.h.); the damping appeared rather less than normal. Further investigation of Pterodactyl 1B, which had a more powerful engine, higher speeds and a higher wing loading, established that this type was rather deficient in dynamic stability. Hill had already observed that his aeroplane was sensitive to gusts and more affected by them in pitch than laterally. Subsequent tests proved that the type showed "vicious instability in bumpy weather" (40), was somewhat difficult to handle and distinctly unpleasant to fly; while take-offs and landings in bumpy weather proved difficult. The main cause, however, was found to be the influence of the large and heavy floating controllers at the wing tips; an improved and sensitive control as required by the low air damping of the wing and the small lateral moment of inertia, would have rendered the early Pterodactyl innocuous. Subsequent Hill Pterodactyls were equipped with more conventional controllers and seem to have exhibited satisfactory longitudinal-stability qualities with approximately equivalent plan shapes of the wing, though these qualities have unfortunately not been thoroughly investigated (40) and though minor control-gear troubles interfered with observations in flight.

The Stork series of Lippisch gave some rather interesting results. The first Stork was found to have satisfactory longitudinal stability provided that the controllers were not moved to extreme positions (41). Lippisch has explained this by the circumstance that these controllers acted simultaneously as ailerons and elevators; he blamed the unsymmetrical (inverted) aerofoil sections employed at the tip for the unpleasant flying characteristics (42), changing them in the Stork II/III to symmetrical sections, and abandoning the skewed controllers. Of Stork III/IV, Lippisch stated (43) that the pitching motions were "short and hard" and, though this was not considered unpleasant, an increase of the angle of sweep-back for greater damping and inertia was felt practical. Delta I was commonly reported to possess satisfactory longitudinal stability, and the flying exhibitions certainly gave no indication of pronounced longitudinal oscillations. Concerning the subsequent Lippisch types, no further details have become known.

The Horten brothers reported that they noticed with Horten I that the pitching motion following gusts was rather "fast," but that the sailplane was stable and could be flown with hands off (44). When commenting upon their subsequent Flying Wings, longitudinal stability was not further mentioned. So it seems that there were no outstanding peculiarities about it (45). Of the Soldenhoff arrow-type monoplane, it was claimed that, while being fairly insensitive to the effects of "little gusts," it was deemed advisable to leave the aeroplane to itself when oscillation occurred, as otherwise control manoeuvres were apt to incite the longitudinal oscillations further. This would seem consistent with the dynamical peculiarities of the Arrow category, to which attention has already been drawn.

(To be continued)

Modern Aeroplane Types

The Warwick

(*See p.* 72)

THE Warwick is the third type to be built entirely on the Wallis principle of geodetic construction and is palpably an enlarged version of the ubiquitous Wellington. In addition to the increased dimensions and engine power the fuselage lines have been slightly refined.

Few details of the Warwick have yet been released, but it has been disclosed that there are at least two versions: the Air-Sea Rescue one, armed with three turrets, and a Transport with a faired nose and tail.

It is in the installation of the Pratt and Whitney Double Wasp engines that the Warwick shows most difference from its predecessor. The nacelles are long, projecting aft of the wing, and are underslung to improve the air flow over the wing—the Wellington engines, it will be recalled, are mounted in rather high nacelles. The engine installations include a large air intake with a filter on top of the cowling and an oil cooler beneath it.

The A.S.R. version is fitted to carry an airborne lifeboat under the bomb bay. The boat is designed to be pulled up on the bomb slips against the closed bomb doors, so as to present an even surface to the air flow.

The transport aeroplane has neat fairings at the nose and tail, although the latter must still be blunt enough to result in considerable drag. The geodetic structure is excellent for the easy fitting of windows—of which there is an ample number—since it is only necessary to replace sections of fabric covering by clear plastic sheet.

The only information released at present is for the transport version, and is:—

Span	96 ft. 8 in. (29·5 m.)
Length	70 ft, 6 in. (21·5 m.)
Height	18 ft. 6 in. (5·64 m.)
Wing area (gross)	1,006 sq. ft. (93·45 sq. m.)
Gross weight...	45,000 lb. (20,430 kg.)

Books Received

Engineering Research. R. A. Collacott. 24 pages. [Crosby Lockwood, 1*s.* 6*d.*]

An Introduction to Differential Equations. S. L. Green. 138 pages. [University Tutorial Press, 7*s.* 6*d.*]

Refrigeration in the Engineering Industry. 69 pages, typescript. [O. W. Roskill & Co. (Reports) Ltd., £2 2*s.* 0*d.*]

List of Selected Translations

APPLICATIONS for the loan of copies of translations mentioned below should be addressed to the SECRETARY (R.T.P.3), MINISTRY OF AIRCRAFT PRODUCTION, LONDON, S.W.1, *and copies will be loaned as far as availability of stocks permits. Suggestions concerning new translations will be considered in relation to general interest and facilities available. Lists of selected translations have appeared in* AIRCRAFT ENGINEERING *since September,* 1938

LIST No. 78

Translation No. and Author — *Title and Reference*

Aero and Hydrodynamics

(2387)
VUSKOVIC, I. ... *Experiments on the Influence of Air Content on Cavitation and Corrosion in the Case of Water Flow.* (Escher Wyss Mitt., Vol. 13, 1940, pp. 83-90.)

(2389)
BILHARZ, H. ... *Notes on a Controlled Type of Unidimensional Motion.* Z.A.M.M., Vol. 22, No. 4, Aug. 1942, pp. 206-215.)

(2392)
MULTHROPP, H. *The Calculation of the Lift Distribution of Aerofoils.* (L.F.F., Vol. 15, No. 4, 6.4.38, pp. 153-169.)

(2393)
HARTMANN, W. *Discharge Tests and Force Measurements on the Stationary Blading of a Single-Stage Experimental Turbine in the Air Test Plant.* (Forschungsheft No. 397, July-Aug. 1939.)

Engines and Thermodynamics

(2380)
SEMONOFF ... *The Theory of the Combustion Process.* (Z. f Physik, Vol. 48, 1928, pp. 571-582.)

(2382)
ZEMAN, J. ... *Recent Development of the Two-Stroke Engine, II (Design features).* (Z.V.D.1, Vol. 87, No. 13-14, 3.4.43, pp.177-182).

Plastics

(2391)
STAUDINGER, H. *High Polymer Compounds—(The Laws of Viscosity of High Polymer Compounds).* (Helv. Chim. Acta., Vol. 15, 1932, pp. 221-230.)

(2396)
PETZ, A. ... *Modern Plastics as Raw Materials for Adhesives.* (Kunststoffe, Vol. 32, No. 2, 1942, pp. 49-54.)

(2399)
STAUDINGER, H. LEUPOLD, E. O. *An Isoprene and Rubber—on Homologues of Hydro-Caoutchouc.* (Helv. Chim. Acta., Vol. 15, 1932, pp. 221-230.)

Elastic Theory

(2373)
VOLKERSEN, O. *The Distribution of Forces on the River in Stretched Joints with Constant Strap Cross Section.* (L.F.F., Vol. 15, No. 1-2, 20.1.38, pp. 41-47.)

(2394)
WEWERKA, A. *Notch Effect.* (Maschinenabu, Vol. 8, No. 2, 1929, pp. 33-37.)

Meteorology

(2383)
SCHNAPAUF, W. *Aerological Investigation in the Region of the Atlantic Doldrums.* (Veroff. des. Met. Inst. der Univ., Berlin, Vol. II, No. 4, 1937, pp. 5-34.)

(2385)
JAW, J. ... *The Thermodynamics of the Trade Surface Current.* (Veroff des. Met. Inst. Univ., Berlin, Vol. II, No. 6, 1937, pp. 4-24.)

Mathematics

(2388)
BERGER, E. R.... *Harmonic Analysis of Discrete Numerical Series.* (Z.A.M.M., Vol. 22, No. 5, Oct. 1942, pp. 269-272.)

(2397)
BECK, W. ... *The Kurzbach Method for the Graphical Analysis of Natural Torsional Oscillations.* (M.T.Z. Vol. 5, No. 8-9, Sept. 1943, pp. 242-248.)

Instruments

(2386)
SILBER, R. ...
OUDART, A. ... *Torque Meter for Power-Driven Aircraft Models in the Wind Tunnels.* (Bull. des. Services Techniques, No. 84.)

N. A. C. A. Technical Memoranda

Technical Memorandum No. 1068. Heat Transfer in a Turbulent Liquid or Gas Stream. By. H. Latzko. ("Der Wärmeübergang an einen turbulenten Flüssigkeitsoder Gasstrom." [Abstract of a Dissertation presented to the Phil. Faculty of the Univ. of Vienna.] *Z.f.a.M.M.*, Vol. 1, No. 4, August, 1921, pp. 268-290.)

The theory of heat transfer from a solid body to a liquid stream could hitherto be presented only with limiting assumptions about the movement of the fluid (potential flow, laminar frictional flow).

For turbulent flow, the most important practical case, previous theoretical considerations did not go beyond dimensionless formulae and certain conclusions as to the analogy between the friction factor and the unit thermal conductance. In order to obtain numerical results, an experimental treatment of the problem has been resorted to, which gave rise to numerous investigations because of the importance of this problem in many branches of technology. However, the results of these investigations frequently deviate from one another. The experimental results are especially dependent upon the overall dimensions and the specific proportions of the equipment.

In the present work, an attempt is made to develop systematically the theory of the heat transfer and of the dependence of the unit thermal conductance upon shape and dimensions, using as a basis the velocity distribution for turbulent flow set up by Prandtl and Von Kármán.

Technical Memorandum No. 1071. Determination of the Actual Contact Surface of a Brush Contact. By Ragnar Holm. ("Eine Bestimmung der wirklichen Beruhrungsflache eines Burstenkontaktes." *Wissenschaftliche Veroffentlichungen aus den Siemens Werken*, Vol. 17, No. 4, 1938, pp. 43-47.)

The number of partial contact surfaces of a brush-ring contact is measured by means of a statistical method. The particular brush is fitted with wicks—that is, insulated and cemented cylinders of brush material, terminating in the brush surface. The number of partial contact surfaces can be computed from the length of the rest periods in which such wicks remain without current. Resistance measurements enable the determination of the size of the contact surfaces. The pressure in the actual contact surface of a recently bedded brush is found to be not much lower than the Brinell hardness of the brush.

Technical Memorandum No. 1072. The Surface Structure of Ground Metal Crystals. By W. Boas and E. Schmid. ("Über die Struktur der Oberflache geschliffener Metallkristalle." *Naturwissenschaften*, Vol. 20, Nos. 22/24, May 27, 1932, pp. 416-419.)

The changes produced on metallic surfaces as a result of grinding and polishing are not as yet fully understood. Undoubtedly there is some more or less marked change in the crystal structure, at least, in top layer. Hereby a diffusion of separated crystal particles may be involved, or, on plastic material, the formation of a layer in greatly deformed state, with possible recrystallization in certain conditions.

For s systematic investigation of the grinding effect the roentgenographic method, briefly described in thefollowing, seemed suitable. The method consists of the recording of Laue-reflection diagrams with X-rays of specially long wave lengths—that is, X-rays suitable for the study of the structure of thin sections. (See reference 4.) If, in addition, diffractions lie at great angles of deviation for the characteristic radiation of the employed anticathode, the same arrangement makes it possible to detect fine-grained layers or such with ordered texture by the appearance of Debye-Scherrer concentric rings or layer lines. In this manner the grinding effect can be followed by a series of records after etching with varying degree of severity.

Professional Publications

Under this heading are given each month the principal articles of aeronautical interest appearing in the current issues of the Journals of the leading Professional Societies and Institutions.

The Institute of the Aeronautical Sciences

AERONAUTICAL ENGINEERING (MONTHLY)

Vol. 3, No. 11, November 1944.

"Daylight Training of Pilots for Night Flying." J. G. Beebe-Center, L. Carmichael and L. C. Mead.
"Lightweight Magnetic Direction Indicators." G. M. Giannini.
"Lubrication Ceiling." P. H. Schweitzer.

Vol. 3, No. 12, December 1944.

"The Trend of Wood Use in Aircraft." R. W. Hess.
"Application of the Variable Ratio V-Belt Principle in the Design of a Constant-Speed Propeller." Ll. H. Leonard.
"New Wrought Aluminium Alloys for Aircraft and New Temper Modifications of Present Alloys." D. A. Lawless.
"Aero-Economics." J. B. Kendrick.
"The Correlation of Aircraft Take-Off and Landing Characteristics with Airport Size." A. L. Morse.

The Society of Automotive Engineers

S.A.E. JOURNAL (MONTHLY)

Vol. 62, No. 12, December, 1944.

"The Intercooling Problem in Airplane Design." A. B. Dickinson.
"Recent Trends in Airplane Ice-Prevention Technique." L. A. Rodert.
"Propeller and Gear Ratio Requirements for Aircraft Designed for Airway Operation." R. S. Schairer.
"Relation of Intake-Charge Cooling and Engine Performance." E. A. Droegemueller, D. S. Hessey and W. A. Rukel.

Vol. 63, No. 1, January 1945.

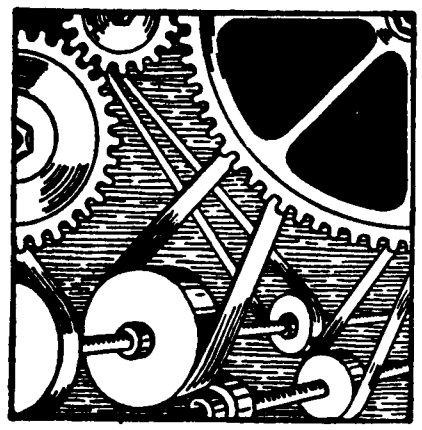
"Possibilities of Aircraft Structures in Ground Vehicles." M. Short.
"Difficulties with Engines Installed in Civil Aircraft." S. H. Rolle.

The Royal Aeronautical Society

JOURNAL (MONTHLY)

Vol. 49, No. 410, February 1945.

"Notes on Power-Operated Controls for Large Aircraft." A. Gouge.
Discussion on Civil Aviation.
List of Council and Committees.
List of Branches.
The Society's Prizes.



Workshop and Production Section

The Strength of Riveted Joints

The Results of a Statistical Analysis of Test Data

by I. G. Bowen, B.Sc.

Introduction

A CONSIDERABLE volume of data on the strength of typical aircraft rivets in joints of Alclad (D.T.D. 390) sheet, has been published in the M.A.P.'s Scientific and Technical Memorandum series. The need for such an investigation arose from the use by the stress offices of different aircraft manufacturers, of strength figures which showed little unanimity even when identical riveted joints were compared. The result was that fixed conditions of manufacture; of the proportions of the joint; of methods of testing and finally of analysis led to a body of data which gives a fairly representative basis for practical design.

The examination of this data, using the methods of statisical analysis, leads to a number of important conclusions relating to the variation of strength inherent in the process of riveting. The method of analysis adopted in the M.A.P. series of reports, results in tables of strength for different combinations of rivet diameter and plate thickness. Variation was catered for by the adoption of a reduction factor to the average strength figures. It is the purpose of the present article to examine the significance of these reductions and to make an exhaustive examination of the causes of variation by means of statistical methods. The final picture should provide the designer with a knowledge not only of the safe limit for design calculations but with a reasonably sound conception of the hazards involved in the choice of higher figures.

The method of approach is briefly as follows :—

(*a*) The controlled and uncontrolled factors are first of all enumerated.

(*b*) Then follows the selection of test data suitable for analysis.

(*c*) For the purpose of those who are unfamiliar with the various statistical tests, a brief account will be given of the meaning and purpose of these tests. Definitions of " levels of significance " or " points of probability " will also be given and these will be adhered to throughout the analysis.

(*d*) The analysis of each type of rivet will then be attempted. In the first instance the calculations will be given in some detail but for subsequent rivets, abridged results only will be given. Conclusions will be drawn from each separate set of rivet data.

(*e*) A general survey of the conclusions reached for the different types of rivets, will provide further information on the interaction of the uncontrolled factors in the riveting process.

Factors in the Riveting Process

We are first of all interested in the degree of control exerted on the factors that are known to influence the strength of riveted joints. It is difficult to assess the degree of control but an attempt will be made to present an ordered list in which the highest degree of control appears at the head of the list and in which uncontrolled factors appear at the bottom. For this purpose reference is made to M.A.P. S. and T.M. No. 21/43, where the following information is made available :—

(1) *Type of rivet.*

For each investigation the type of rivet remains the same and is as specified by the relevant S.B.A.C., A.G.S. or manufacturer's standards. This means that the shape of head and size and length of shank are accurately dimensioned although there are two further factors which are uncontrolled. These are the practice of the firms making the riveted samples of cutting down long rivets to suit thin plates and secondly the varying physical properties of the rivet material within the specification limits. Both these factors are discussed later in the list.

(2) *Identification.*

Identification of samples was very strictly controlled and with successful results. These were only one or two isolated examples where chemical analysis had to be resorted to in order to check the identity of obviously wrong figures.

(3) *Type of joint.*

A single-riveted pair of lapped plates was used throughout the tests and the dimensions of the plates were fixed for all sizes of rivets. The holes at the ends of the specimen were jig-drilled. The efficiency of the joint to develop the full shearing strength of the rivet or the full bearing strength of the plate was demonstrated for all sizes and strengths of rivet investigated.

(4) *Test procedure.*

This was standardized throughout.

(5) *Plate material.*

The strength of the material used for the plates influences the strength of the resulting joint. To eliminate this factor it was decided to reduce the strength of joints which failed by tearing of the plate to correspond with the minimum specified tensile strength of the plate material. This was effected by testing the ultimate tensile strength of four samples from each sheet of D.T.D. 390 used in the preparation of rivet specimens. The conditions of these tests were standardized.

Where failure occurred in the rivet no reduction in the strength figues was effected. It was considered that the effect of the small variations in strength of the plate do not cause serious variations in the associated bearing pressure on the rivet shank. This assumption is probably reasonable.

(6) *Formation of hollow rivets.*

These were set by means of standard tools and riveting " techniques" are less apt to cause variation.

(7) *Drill size.*

For the solid rivet series, three out of four manufacturers of riveted samples followed the usual technique of drilling clearance holes for placing the rivets. The usual assumption is that the rivet subsequently expands and fills the hole completely. The remaining manufacturer drilled holes to suit the size of shank. (Supplier H.P.) In the three firms special drills were set aside for this work.

(8) *Thickness of plate.*

This was taken to be equal to the average of those measured for the four control tensile tests mentioned above (5). There is likely to be variation over the whole sheet of an unkown amount. This has an effect on the associated bearing pressure on the rivet for the same nominal thickness of plate.

(9) *Manufacture by different firms.*

Samples were obtained from different firms using different methods of placing the rivets. For example three firms used pneumatic riveting with three different types of guns (suppliers, B., F. and H.P.), whilst the fourth used hand tools (supplier, F.R.). Where heat treatment was called for, however, the usual practice was followed and this factor may be deemed to be controlled.

(10) *Strength of Rivet.*

This factor is considered to produce more variation than any other and attempts to control it, from the correlation of hardness with strength, failed. From the design point of view, there are advantages to be obtained from this lack of control since the resulting scatter of figures gives the designer an idea of what variation to expect in practice. Owing to manufacture at different places, it is to be expected that different batches of rivets were chosen.

Investigation at the different suppliers showed that rivets were cut down whenever a shortage of supply of rivets of the exact length occurred.

Selection of Data for Analysis

In the combination $\frac{1}{8}$ in. diameter rivets in 18 S.W.G. plates each manufacturer made approximately twenty test samples. These results form a basis for a statistical analysis of the importance of the riveting factors and in general these figures form the basis of the following analysis. In some instances additional results in other combinations also appear and these are welcomed since they give an estimate of the variation when the ratio of rivet diameter to plate thickness is altered. In all cases reference is made to the individual M.A.P. report, when the data for analysis are presented. In the solid rivet series the manufacturers who assisted in the preparation of samples for convenience are identified by the following symbols :—

B.
H.P.
F.
F.R.

Statistical Methods Employed

Analysis of the results of the $\frac{1}{8}$ in. $\times$ 18 G. combinations in different rivets leads to a nearly similar statistical treatment for each type of rivet. For the benefit of those who are unfamiliar with the tests employed a brief account is now given of their purpose and application. The problems of the various stages of analysis are first set and then we proceed to apply the relevant statistical test. There are four main stages :—

(*a*) *Consideration of the whole data.*

We have at our disposal approximately eighty tests from four suppliers. We are interested in the distribution of the strength figures about the mean of this sample of data and our first step is to calculate the mean and standard deviation. This accomplished we can next attempt to fit a normal probability curve to the data, the probability function having the same mean and standard deviation as the given data.

By a process of " graduation " we can calculate the theoretical frequencies and compare them with those observed. We now have at our disposal sufficient data to proceed with what is known as the χ^2 (chi-squared) test. This is a test enabling us to verify (on a probability basis) our hypothesis that the observed distribution was a sample from normal universe with mean and standard deviation equal respectively to those of the sample. The test is applied by a calculation of the quantity χ^2, reference then being made to a table of standard values of the quantity corresponding to different probabilities (P).

As in all probability tests, we have to draw a line to distinguish significance from non-significance.

For this purpose we follow Fisher's suggestion who prefaced his tables of the χ^2-test with the statement: "In preparing this table we have borne in mind that in practice we do not want to know the exact value of P for any observed value of χ^2 but, in the first place, whether or not the observed value is open to suspicion. If P is between ·1 and ·9 there is certainly no reason to suspect the hypothesis tested. If it is below ·02 it is strongly indicated that the hypothesis fails to account for the whole of the facts. We shall not often be astray if we draw a conventional line at ·05 and consider that higher values of χ^2 indicate a real discrepancy."

Consideration of the facts on the above lines enables the designer to obtain a convenient and fairly accurate picture of the frequency distribution of strength in the particular combination. He is in a position to state the attendant risks of the use of higher values than those recommended in the reports.

(*b*) *Variances produced by different manufacturers.*

As we have already seen, the consideration of results from different manufacturers involves the variations due to the use of different batches of rivets and different methods of riveting. It is important to determine whether the variances in the resulting test data are significantly different for different suppliers.

This can be tested by use of Fisher's z-test. For this purpose we need estimates of the variances of the samples from each supplier. We calculate the ratio of any two estimated variances and by use of tables we determine the significance of the divergence of the observed ratio from unity. This divergence is the crux of the test. We use Snedecor's tables (from his book "Statistical Methods," U.S.A.) which involve less calculation than those of Fisher. The latter's variable z is related to Snedecor's variable F by $F=e^{2z}$. The reasoning is briefly this:—

If for $P=·05$ (or ·01) the observed value of F as computed from the samples, is larger than F_0, the hypothesis is to be rejected and the conclusion is that the samples come from universes with different variances.

We draw a conventional line at the point $P=·01$, smaller values of F indicating the correctness of our hypothesis and larger values indicating that the samples come from universes with different variances.

The test enables one to make comparisons of the dispersion of strength due to use of different riveting technique and different batches of rivets, together with the other uncontrolled factors.

(*c*) *Differences in mean strength from different suppliers.*

From the standpoint of practical application we are very much interested in the question of the significance of the differences in mean strengths achieved by different suppliers. For this purpose we assume that the two samples compared come from universes with equal variances. This will have been tested by the z-test mentioned above in (*b*). Logically, we can compare only those samples which comply with our assumption.

The test of the significance of difference between two means is known as the t-test. The method of application is summarized thus:—

Let $\bar{x}_1$ and $\bar{x}_2$ be the means and s_1 and s_2 the standard deviations of two independent samples of N_1 and N_2 variates from a normal universe with mean $\bar{x}$ and variance σ^2. We calculate the quantity,

$$t=(\bar{x}_1-\bar{x}_2)\left\{\frac{N_1\,N_2}{N_1+N_2}\times\frac{N_1+N_2-2}{N_1S_1^2+N_2S_2^2}\right\}^{\frac{1}{2}}$$

and enter Fisher's table at $n=N_1+N_2-2$ to determine the probability P of a greater difference between the means than that observed. That is, Fisher's tables give us the probability P of occurrence of deviations outside $\pm t$.

We shall draw a line of significance at the level given by $P=·05$ corresponding to a value of $t=t_0$. Smaller values of t than t_0 indicate a significant difference in the mean strengths; greater values than t_0 indicate no significant difference in the means.

(*d*) *Summary of statistical analysis.*

We are now in a position to translate the results of the statistical analysis into purely technical terms. This is done for each type of rivet investigated.

On completion of the analyses for all the rivets under consideration, a survey of the conclusions will yield further information. For example it will be possible to compare the coefficients of variation produced by the *same* manufacturers operating on rivets of different materials. This is of value since considerable interest has been shown elsewhere on the dispersion of strength inherent in different structural materials. The net result here is that we have at our disposal experimental data to compare the dispersion of strength inherent in the riveting process as applied by different manufacturers using different materials.

Duralumin Snaphead Rivets

Experimental data.

The relevant data are obtained from M.A.P. S. and T.M. Nos. 22/43 and 6/44. The results and preliminary statistical calculations are given in Tables I and II.

TABLE I

Combination $\frac{1}{8}$" dia. × 18 S.W.G. plates (failure by rivet shear)

Supplier	B.	H.P.	F.	F.R.	All Data
No. of tests (N) ...	19	19	20	20	78
Mn. strength (x) lb.	504	496	517	505	506
Std. dev. (S) lb.	13·0	16·9	17·5	38·1	24·9
Coeff. varn. V $(s/\bar{x})\times 100$	2·58	3·41	3·39	7·55	4·93
Estimd. variance	180·	302	323	1,527	628

TABLE II

Combination $\frac{5}{32}$" × 22 g. (failure in plate).

Supplier	N	$\bar{x}$	S	V
F.R.	20	560	25·1	4·48

Fitting the normal curve.

We now fit a normal curve to the data of Table I, the function having the same mean and standard deviation as that given in the last column of Table I. The observed frequency distribution and the process of obtaining the theoretical frequencies are shown in Table III. Intervals were taken at distances of 10 lb. apart.

TABLE III

Central Value	Observed frequency (f)	Boundary	t	$A=\int_{-\infty}^{t}$	ΔA	$N\Delta A=(\bar{f})$	$\frac{(f-\bar{f})^2}{\bar{f}}$
		-- ∞	− ∞	0			
	13				·1469	11·5	·196
		479	−1·05	·1469			
484	6				·1110	8·7	·839
		489	−·65	·2578			
494	13				·1434	11·2	·289
		499	−·25	·4013			
504	11				·1583	12·3	·137
		509	·15	·5596			
514	14				·1492	11·6	·496
		519	·55	·7088			
524	11				·1201	9·4	·272
		529	·95	·8289			
	10				·1711	13·3	·759
		∞	∞	1·0000			
Totals	78				1·0000	78·0	$\chi^2=$ 2·988

The column headed $N\Delta A$ gives the theoretical frequency $\bar{f}$. We now test our hypothesis that the observed distribution was a sample from a normal universe with mean and standard deviation equal to those of the sample. The necessary calculation is performed in the last column of Table III from which we see that $\chi^2=2·988$, and we enter Fisher's table with $n=7\text{-}1\text{-}2$ (=4) degrees of freedom. We find that the probability P associated with these values of χ^2 and n, exceeds 0·5 and we conclude that there is no reason to suspect the hypothesis.

In technical terms we say that for the combination considered ($\frac{1}{8}$ in. × 18 g.) the distribution of strength can be referred to a normal probability scale with mean and standard deviation equal respectively to 506 and 24·9 lb. Comparing this result with the recommended design figure of 450 lb. we are able to assess the probability of obtaining a sample whose strength lies below 450 lb. The corresponding value of t is 56/24·9=2·25. From tables of the normal probability scale we see that the required probability is ·012 (or approximately once in 80 trials).

In practice it is not likely that rivets would be used singly and as an example it is assumed that a group of five rivets is taken at random from the normal distribution of mean strength 506 lb. and standard deviation 24·9 lb. The designer is concerned with the probability of the mean strength of the group (assuming equal distribution of load) falling below any specified figure. Take the figure 470 lb. as the desired design value. We want to know the chances of the mean strength of the group falling below this level. We use the well-known result that the standard deviation of a random sample of n components from a normal universe of standard deviation σ is given by $1/\sqrt{n}$ times σ. Thus the standard deviation of the mean of the strength of five rivets is $\frac{1}{\sqrt{5}}$ times 24·9, or 11·1 approx. The value of t corresponding to 470 lb. and standard deviation 11·1 lb. is 36/11·1 = 3·24. From tables of the normal probability scale we see that the probability of the mean strength of the group falling below 470 lb. is 0·0006 (or approx. once in 1,670 trials).

Thus provided the rivets in the group are (1) selected at random from the above distribution (irrespective of batch and manufacturer), and (2) the load is distributed uniformly over the group, we are at liberty (on a probability basis) to accept a design value of 470 lb. without prejudicing the safety of the joint. In fact, accepting the same odds as for the single rivet (once in eighty trials) we are at liberty to adopt a higher design figure still. It can be verified that for a joint of five rivets the odds will be equal if we design to a failing load of approximately 480 lb.

At this point it is patent that such a procedure would not always be safe in practice. Consider the possibility of such design action being taken by the supplier H.P. First of all there is the probability that on any particular occasion the rivets used for the group of five will all come from the same batch. This is contrary to our assumption that they are random choices and it is evident that loss of safety will ensue if the batch happened to be uniformly low in strength. Secondly, it is noted from Table I that the mean strength of samples supplied by H.P. is lower than the mean of all the data. These two considerations alone make the selection of a "safe" design figure a little more involved than the simple treatment given above.

In any particular case, however, the designer has in the figures of Table I, a useful set of data from which to draw his conclusions. It is manifestly impossible to demonstrate every possible design contingency and further application of the data is left for the consideration of the user.

Differences in variances from different manufacturers

For a comparison of the variances produced by different manufacturers we require estimates of these quantities and these are given in Table I. Attention is paid to the significance of the difference in the variances from two suppliers, as given by Fisher's z-test (but using Snedecor's tables). The calculations and conclusions are given in Table V.

TABLE IV

Comparison of	$F=\frac{u^2}{v^2}$	$n_1=N_1-1$	$n_2=N_2-1$	Conclusion about diff. in variances
B. & H.P. ...	1·68	18	18	Diff. not significant
B. & F. ...	1·79	19	18	Diff. not significant
B. & F.R. ...	8·49	19	18	Diff. is highly significant
H.P. & F. ...	1·07	19	18	Diff. not significant
H.P. & F.R.	5·06	19	18	Diff. is highly significant
F. & F.R. ...	4·73	19	19	Diff. is highly significant

Thus the variances produced by the three suppliers B., H.P. and F. are not significantly different from one another. Any comparison of one of these, however, with supplier F.R. results in highly significant differences.

A technical interpretation of this may be attributed to the fact that the rivets from supplier F.R. were closed by hand tools and that the process involves a greater variation in strength about the mean than does the use of pneumatic tools. This conclusion can be checked by appeal to the results of other rivet data to be treated subsequently. A subsidiary conclusion is that the use of different pneumatic guns (and possibly "technique") does

not produce any significant changes in the variations of strength of the joints.

Differences in mean strengths from different manufacturers.

A consideration of practical importance is the test to determine the significance of differences in the mean strengths produced by samples from different suppliers. Values of t are calculated from the data of the three suppliers B., H.P. and F. As stated earlier the t-test can be applied logically to these results. The calculations and conclusions are given in Table V.

TABLE V

Comparison of	t	$n = N_1 + N_2 - 2$	P	Conclusion about diff. in means
B. & H.P.	1·59	36	>·10	Difference not significant
B. & F.	2·55	37	<·02	Diff. is significant—not highly so
H.P. & F.	3·71	37	<·001	Diff. is highly significant

Thus of all the mean strengths only that of the supplier F. is significantly different from the others. It is too early to form conclusions about the performance of the riveting process at this manufacturer's since the high values of strength may be attributed to the selection of rivets of high strength and not to superior technique.

Summary of conclusions reached.

1. The distribution of strength for the combination $\frac{1}{8}$ in. dia. × 18 g. can be referred to a normal probability scale with mean and standard deviation equal respectively to 506 and 24·9 lb. On this basis the odds in favour of the choice of a rivet with strength less than 450 lb. (the recommended design value) are approximately one in eighty.

2. The variances of the figures for the suppliers B., H.P. and F. do not differ significantly amongst themselves. When any one of these variances is compared with that of supplier F.R. there is, however, a significant difference.

Tentatively we conclude that the pneumatic guns produce less dispersion than riveting by hand, although this opinion may be qualified by inspection of data on other rivets.

3. The supplier F. produces samples with mean strength significantly higher from those of H.P. and B. There is no significant difference in the means of the latter two.

4. The dispersion of strength produced by the same manufacturer using a higher ratio of rivet diameter to plate thickness, is no greater than for the $\frac{1}{8}$ in. × 18 g. combination.

Analysis of M.G.5 Snaphead Rivets

Experimental data.

This is obtained from M.A.P. S. and T.M. Nos. 23/43 and 6/44. Results and calculations are given in Tables VI and VII.

TABLE VI
Combination $\frac{1}{8}$" dia. × 18 g. plates. (Failure by rivet shear.)

Supplier	B.	H.P.	F.	F.R.1	F.R.2	All Data
No. of tests N ...	20	20	20	30	20	110
Mean strength $\bar{x}$	414	369	379	423	396	399
Std. devn. S ...	15·5	14·7	5·65	16·0	11·5	24·4
Coeff. varn. V	3·74	3·98	1·49	3·78	2·91	6·12
Estimated variance	254	228	33·6	270	139·2	601

TABLE VII
Combination $\frac{5}{32}$" dia. in 22 g. plates.

Supplier	Type of failure	N	$\bar{x}$	S	V	Estimated variance
F.R. 3 ...	In plate	9	554	30·0	5·42	1,013
	Rivet shear	11	559	10·3	1·84	117
	All data	20	557	21·7	3·90	496

The standard deviation given in Table VI for all test data was obtained from a 10 lb. interval frequency distribution by means of Sheppard's corrections. Exact calculations for the first four columns gives a standard deviation of 26·5 lb. corresponding to a mean of 400 lb.

It will be noted that Table VII enables us to study the behaviour of joints with different values of the ratio of rivet diameter to plate thickness, although additional data from other suppliers would have added more confidence to the conclusions to be formed.

Two series of tests are given for the supplier F.R.; the rivets being presumably from different batches.

Conclusions.

1. The frequency distribution of strength in the $\frac{1}{8}$ in. × 18 g. combination is not well represented by a normal probability-scale with mean and standard deviation equal to those of the whole sample of data. A drawing of the theoretical and observed frequency distributions is given in Fig. 1. The discrepancy is attributed to the relatively large variations of strength possible in the M.G.5 rivet. The samples chosen by the different suppliers are not random samples but probably emerge from the same batch of rivets from stock. This selective process leads to uniform dispersion but not necessarily to equality of mean strength. The net result is a non-normal frequency distribution.

If we accept the representation of the data by a normal probability curve we find that the odds in favour of the selection of a rivet with strength less the recommended design value (360 lb.) are approximately one in 18 trials (P=·057).

The results obtained do not conflict with the physical properties of the material. Duralumin rivets are normalized before placing and tests show that this tends to eliminate the effects of work hardening. M.G.5 rivets, however, are not subject to heat-treatment at any stage of the riveting process and they are therefore possibly more susceptible to accumulative work hardening effects.

2. Variances produced by the suppliers B., H.P., F.R.1 and F.R.2 are not significantly different when comparison is made of any two. Comparison of any one of these suppliers with F. leads to a highly significant difference. For the same manufacturer using different batches of rivets (F.R.1 and F.R.2) the variances do not differ significantly.

3. The above conclusions refer to the $\frac{1}{8}$ in × 18 g. combinations. The small amount of evidence at our disposal for the $\frac{5}{32}$ in × 22 g combination shows that the dispersion of strength for failure in the plates is greater than that where failure occurs by shear of the rivet. This could be accounted for by the variations of size of the formed head. Or combining the data, the degree of dispersion is not appreciably higher than that obtained by the same manufacturer using the $\frac{1}{8}$ in. × 18 g combination. This lends support to the view adopted in the M.A.P. series of reports that the $\frac{1}{8}$ in. × 18 g combination produces dispersion of the same order as other combinations of rivet diameter and plate thickness.

4. Comparison of mean strengths indicates significant differences for all suppliers of the $\frac{1}{8}$ in. × 18 g combination. A summary of the mean strengths obtained is given in Table VIII.

TABLE VIII

Supplier	B	H.P.	F	F.R.1	F.R.2	All Data	Std. Dev.
$(\bar{x}/\bar{X})\times 100$	103·8	92·6	95·0	106·1	99·3	100	6·12

Analysis of Duralumin 120° Countersunk Rivets

Experimental data.

The relevant data appears in M.A.P. S. and T.M. No. 3/44 and is summarized in Table IX.

TABLE IX
Combination $\frac{1}{8}$" × 18 g.

Supplier	B.	H.P.	F.	F.R.	All Data
N	20	20	20	20	80
$\bar{x}$	472	468	449	455	461
S	27·4	21·7	20·8	40·8	31·0
V	5·80	4·64	4·63	8·97	6·73
Estd. variance	791	495	455	1,753	1,012

Conclusions.

1. The frequency distribution can be represented by a normal scale with mean and standard deviation equal respectively to 461 and 31 lb. The odds in favour of choosing a rivet with strength less than the recommended design value (415 lb.) are approximately one in 14 trials. These odds are greater than for Duralumin and M.G.5 snap head rivets and may be attributed to the difference in shape of head. Differences in the depth of countersinking would cause variations in the associated bearing pressure on the rivet shank resulting in different shearing strengths.

2. Differences in the variances produced by the three suppliers, B., H.P. and F. are not significant. The variance from supplier F.R. is significantly different from either H.P. or F. but not from B. As stated earlier, this may be the result of using hand as opposed to automatic tools.

3. Differences in the mean strengths from a comparison of F. with B. or H.P. are significant. There is no significance in the difference between B. and H.P. or B. and F.R. A summary of the mean strengths obtained is given in Table X.

TABLE X

Supplier	B.	H.P.	F.	F.R.	All Data	Std. Dev.
$(\bar{x}/\bar{X})\times 100$	102·4	101·6	97·6	98·8	100	6·73

Analysis of M.G.5, 120° Countersunk Rivets

Experimental data.

The data in Table XI are obtained from M.A.P. S. and T.M. No. 2/44.

TABLE XI
Combination $\frac{1}{8}$" × 18 g.

Supplier	B.	H.P.	F.	F.R.	All Data
N	19	20	20	19	78
x	320	·336	274	305	308
S	11·3	24·5	12·8	11·0	28·0
V	3·53	7·29	4·67	3·61	9·09
Estd variance	135	632	173	128	795

Conclusions.

1. The observed frequency distribution may be referred to a normal scale with mean and standard deviation of 308 and 28 lb. The odds in favour of choosing a rivet with strength less than the recommended design value (280 lb.) are approximately one in 6·3 trials.

2. The variances are not significantly different if we exclude the supplier H.P. Unlike the three previous analyses, the supplier F.R. produced the least variance although as stated, this quantity is not significantly different from that of B. or F.

3. Mean strengths are all significantly different. A very low value of 274 lb. is recorded for supplier F. and no practical reason could be found to explain this. It is possibly a result of the wide variations in material strength inherent in the M.G.5 material. Summarizing the means we obtain Table XII.

TABLE XII

Supplier	B.	H.P.	F.	F.R.	All Data	Std. Dev.
$(\bar{x}/\bar{X})\times 100$	103·8	109·2	88·9	99·1	100	9·09

Analysis of D.T.D.327 Snaphead Rivets

Experimental data.

This was obtained from M.A.P. S. and T.M. No. 11/44. The results are given in Table XIII.

TABLE XIII

Combination	Supplier	N	$\bar{x}$	S	V	Estimated Variance
$\frac{1}{8}$" × 20 g	B.	20	461	19·5	4·2	400
	H.P.	20	481	27·2	5·65	779
D/t = 3·47	F.	20	415	29·7	7·2	928
	F.R.	26	467	20·7	4·4	445
	All Data	86	457	34·4	·7·5	1,200
$\frac{1}{8}$" × 18 g	B.	19	446	19·3	4·3	393
	H.P.	20	486	29·0	6·0	886
D/t = 2·61	F.	20	449	8·9	2·0	83
	F.R.	40	487	25·8	5·3	683
	All Data	99	471	29·7	6·3	892
$\frac{1}{4}$ × 14 g	B.	20	1,760	57·0	3·2	3,420
D/t = 2·40	F.R.	14	1,709	24·8	1·5	663
	All Data	34	1,739	49·3	2·8	2,510

Conclusions.

1. *Consideration of all the data.* For the combination $\frac{1}{8}$ in. × 20 g, the results may be referred to a normal probability scale with mean and standard deviation of 457 and 34·4 lb. The odds in favour of obtaining a rivet with strength less than the recommended value (405 lb.) are approximately one in 15 trials.

For the combination $\frac{1}{8}$ in. × 18 g, the data are not well represented by the normal curve which fails to take account of all the facts. Later inspection by other statistical methods, confirms that the samples drawn by the separate suppliers possess widely differing mean strengths with relatively small dispersion about these means. If the results *are* referred to a normal scale the odds in favour of the choice of a rivet of strength below the recommended value (425 lb.) are approximately one in 16 trials.

2. *Differences in variances.* Comparing the variances for the $\frac{1}{8}$ in. × 20 g and $\frac{1}{8}$ in. × 18 g groups of data it is found that there is no significant difference between the two. In other words the ratio of D/t has no significant influence on the dispersion of strength for this size of rivet. For the $\frac{1}{4}$ in. diameter rivets the coefficient of variation is well below that for either of the $\frac{1}{8}$ in. diameter groups. The general indication is, therefore, that up to $D/t = 3{\cdot}5$ the dispersion of strength is independent of the rivet size and is not likely to exceed 6 or 7 per cent of the mean strength (this measure being the coefficient of variation).

For the combination $\frac{1}{8}$ in. × 20 g, a comparison of the variance of supplier F. with either B. or F.R. shows significance although this is somewhat doubtful. For the purpose of testing the significance of the differences in the means it will be assumed that none of the variances are significantly different.

In the combination $\frac{1}{8}$ in. × 18 g, variance of supplier F. differs significantly from all others. There is a somewhat doubtful significant difference between B. and H.P., but comparisons between the remainder yield no significant differences.

In the $\frac{1}{4}$ in. diameter group the dispersion produced by B. is significantly different from that of F.R.

3. *Differences in mean strengths.* The $\frac{1}{8}$ in. × 20 g and $\frac{1}{8}$ in. × 18 g groups have mean strengths which differ significantly. This has been recognized in the design values by assigning different strengths to the combinations.

In the $\frac{1}{8}$ in. × 20 g combination the supplier F. had mean strength significantly lower than any of the others. Supplier H.P. produced the highest mean strength and is significantly different from both B. and F.R. Between the latter two there is no significant difference.

In the $\frac{1}{8}$ in. × 18 g combination, suppliers H.P. and F.R. produce mean strengths significantly higher than B. and F. Between each of these pairs there is no significant difference.

Summarizing the data we have the mean strengths as given in Table XIV.

TABLE XIV

Combination	Supplier	B.	H.P.	F.	F.R.	All Data	Std. Dev.
$\frac{1}{8}$ × 20 g	$\frac{\bar{x}}{\bar{X}} \times 100$	100·8	105·2	90·8	102·2	100	7·5
$\frac{1}{8}$ × 18 g		94·7	103·2	95·4	103·4	100	6·3
$\frac{1}{4}$ × 14 g		101·3	—	—	98·2	100	2·8

Analysis of D.T.D.327, 120° Countersunk Rivets

Experimental data.

This has been obtained from M.A.P. S. and T.M. No. 13/44 and is summarized in Table XV.

Conclusions.

1. *Consideration of all the data.* It must be remembered that the object of replication of tests in the above table was to give an estimate of the dispersion of strength as between different suppliers and different combinations. The data given in Table XV are more complete than any of the previous series which was analyzed. The evidence from the 7/32 in. and $\frac{1}{4}$ in. diameter series strongly indicates that the dispersion of strength (as measured by the coefficient of variation) gets progressively smaller with decreasing D/t. This is not contrary to what one would expect from practical considerations. At relatively high values of D/t (thinner plates for the same size rivet) variations in the depth of countersinking cause corresponding variations in the associated bearing pressure. In the extreme (very high D/t), failure would occur in the plate and variations in the size and shape of the rivet head will

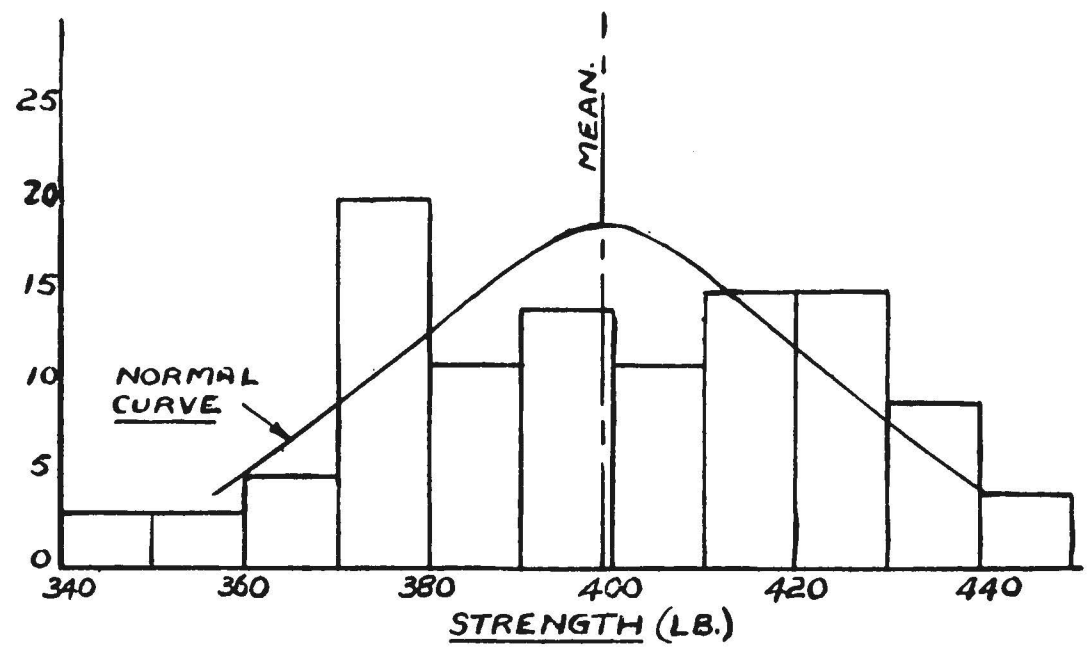


FIG. 1

TABLE XV

Combination	Supplier	N	$\bar{x}$	S	V	Estimated Variance
$\frac{1}{8}$" × 20 g	B.	20	315	21·2	6·7	473
	H.P.	6	324	28·6	8·8	982
	F.	20	361	72·6	20·1	5,540
	F.R.	20	329	31·8	9·7	1,065
	All Data	66	334	49·0	14·7	2,440
$\frac{1}{8}$" × 18 g	B.	20	348	17·4	5·0	319
	H.P.	20	356	24·3	6·8	622
	F.	20	309	21·2	6·9	473
	F.R.	20	329	31·8	4·9	1,065
	All Data	80	335	30·3	9·0	930
$\frac{7}{32}$" × 16 g	F.R.	11	989	91·3	9·2	9,170
× 14 g	F.R.	12	993	59·1	6·0	3,800
× 12 g	F.R.	12	1,225	26·7	2·2	777
× 10 g	F R.	12	1,371	25·3	1·8	698
$\frac{1}{4}$" × 14 g	B.	20	1,469	56·0	3·8	3,300
	F.R.	40	1,539	64·9	4·2	4,320
	All Data	60	1,515	75·2	5·0	5,750
$\frac{1}{4}$" × 12 g	F.R.	12	1,735	41·5	2·4	1,880
× 10 g	F.R	12	1,826	27·5	1·5	825

have a profound effect on the load which can be induced in the plate before tearing out of the rivet head takes place.

Countersunk rivets are more susceptible to variation in strength for the above reasons and the results bear out this conclusion. The choice of a reducing factor is left until a consideration of the variances in the two $\frac{1}{8}$ in. diameter series is made.

2. *Differences in variances.* We compare the results of the two $\frac{1}{8}$ in. diameter series and find that the variances produced are significantly different. This means that the higher D/t ratio (3·5 approx.) has the effect of increasing dispersion and from a practical standpoint we cater for this by evaluating the odds corresponding to a mean of 334 lb. and standard deviation 49·0 lb., these being compared with recommended reducing factor of 10 per cent of the mean strength. We find that the odds in favour of the choice of a rivet below the 90 per cent level of strength are approximately one in four trials. These odds are high when compared with other rivet analyses. The odds compare favourably with the observed data (18 results out of 66 fell below the 80 per cent level of strength for the $\frac{1}{8}$ in. × 20 g combination).

Maximum dispersion in $\frac{1}{8}$ in. × 20 g series was produced by supplier F. and this differs significantly from all other suppliers. These latter did not differ significantly among themselves. In the $\frac{1}{8}$ in. × 18 g series, maximum dispersion was produced by supplier F.R., but this does not achieve significance except in a comparison with B.

3. *Differences in mean strengths.* A comparison of the two $\frac{1}{8}$ in. diameter series shows no significant difference in mean strength. Thus a change in the bearing pressure from $D/t = 2{\cdot}61$ to 3·47 has no appreciable effect on the failing load. This is contrary to what was anticipated in the M.A.P. report where different design figures are quoted for the two thicknesses.

In the $\frac{1}{8}$ in. × 20 g series, maximum mean strength is achieved by supplier F., but does not differ significantly from F.R. In the $\frac{1}{8}$ in. × 18 g series, supplier F. recorded the lowest mean strength and this differs significantly from the other three suppliers; supplier F.R. achieved mean strength significantly different from B. or H.P., but the latter two do not differ significantly from each other.

Summarizing the mean strengths we have the results given in Table XVI.

TABLE XVI

Combination	Supplier	B.	H.P.	F.	F.R.	All Data	Std. Dev.
$\frac{1}{8}$" × 20 g	$\frac{\bar{x}}{\bar{X}} \times 100$	94·2	96·9	108·1	98·5	100	14·7
$\frac{1}{8}$" × 18 g		103·8	106·3	92·2	98·2	100	9·0
$\frac{1}{4}$" × 14 g		97·0	—	—	101·6	100	5·0

Interaction of Above Results and General Conclusions

We now have the results of six analyses of solid rivets from which we may discuss their interactions. This enables us to form conclusions on points which were omitted from the detail analyses or else were put forward only in speculative form.

(A) *Consideration of reduction factors.*

From the practical standpoint this is probably the most important consideration of all. The method adopted throughout the M.A.P. series of reports was to fix the design level at 90 per cent of the strengths obtained from smooth curves through the means of test points. The relation between this factor and the dispersion of strength in the riveting process was demonstrated by replication of tests in certain combinations of rivet diameter and plate tests. In other words the reports suggest—

(i) that the dispersion of strength is sufficiently well represented by the results for $\frac{1}{8}$ in. × 18 g and $\frac{1}{8}$ in. × 20 g combinations, and

(ii) that the adoption of a fixed reducing factor (10 per cent of the mean strength) will cover most practical contingencies.

Examination of the six types of rivets leads one to suppose that a more rational presentation of design data can be achieved. Firstly, the results of the DTD327, 120° countersunk rivet series gives a strong indication that the dispersion of strength increases with increasing D/t. This is brought out more or less consistently in all the other reports where the experimental data is adequate.

Secondly it is felt that the reducing factor should be based on a probability basis. More explicitly, we should calculate the reducing factor from a fixed (arbitrary) probability of the strength of a *single* rivet falling below the design value. In view of the fact that rivets are not used singly (thereby enhancing our chances of achieving a higher mean strength) it is considered that this probability may be increased from the usual 0·05 probability level to 0·0667, which corresponds to odds of one in 15 trials for the choice of a rivet below a certain fixed level (1·5 standardized deviations below the mean). In the majority of analyses we found that the observed data could be sufficiently well represented by a normal probability scale, and it is now proposed to tabulate—

(i) the chances of obtaining a rivet of strength below the 90 per cent design level proposed by the M.A.P. reports and

(ii) the reduction factor which would have to be applied to maintain these chances at the one in 15 basis.

The results are given in Table XVII together with the relevant data.

TABLE XVII

Type of Rivet	Combination	D/t	V	Odds for Choice below 90% of mean	Reduction Factor for 1 in 15 (%)
L. 37 snap.	$\frac{1}{8}$ × 18 g	2·61	4·93	1 : 47·2	7·4
D.T.D. 303 snap	$\frac{1}{8}$ × 18 g	2·61	6·12	1 : 19·6	9·2
D.T.D. 327 snap	$\frac{1}{8}$ × 20 g	3·47	7·53	1 : 10·9	11·2
	$\frac{1}{8}$ × 18 g	2·61	6·31	1 : 17·6	9·5
	$\frac{1}{8}$ × 14 g	2·40	2·84	1 : 5000	4·25
L. 37 c'sk.	$\frac{1}{8}$ × 18 g	2·61	6·73	1 : 14·5	10·1
D.T.D. 303 c'sk	$\frac{1}{8}$ × 18 g	2·61	9·09	1 : 7·37	13·6
D.T.D. 327 c'sk	$\frac{1}{8}$ × 20 g	3·47	14·7	1 : 4·04	22·0
	$\frac{1}{8}$ × 18 g	2·61	9·04	1 : 7·44	13·6
	$\frac{1}{8}$ × 14 g	2·40	4·96	1 : 45·5	7·4

From this table we note:—

(*a*) **The** dispersion of strength in the countersunk **series of rivets is** higher than in the corresponding **snaphead types.** As stated earlier, this result would be **expected** from physical considerations.

(*b*) **For a** fixed combination ($\frac{1}{8}$ × 18 g), the dispersions of strength for the D.T.D. 303 and D.T.D. 327 series are approximately the same, and exceed that of the L. 37 series. This result is again what one expects from a consideration of the heat-treatment given to the L. 37 rivet. This tends to reduce dispersion. The D.T.D. 303 and 327 rivets are not, in general, given heat-treatment before placing. These conclusions, it should be noted, hold for both the snaphead and countersunk types.

(*c*) The data given is insufficient to predict the relation existing between dispersion (as measured by V) and the ratio *D/t*. That such a relation does exist, however, is clearly shown from the results of the D.T.D. 327 investigations.

Bearing in mind the points made above, we are now in a position to give estimates of the reducing factors for the various types of rivets. For the $\frac{1}{8}$ in. × 18 g combinations it is clear that reductions, as given in Table XVII, will provide the designer with a reasonable margin of safety. However, at high values of *D/t* it would be necessary to increase those factors. In the absence of sufficient data it is suggested that the following factors could be applied without prejudicing safety considerations or being unduly pessimistic :—

Type	*Head*	*Reduction factor from mean strength* (%)
L. 37 (heat-treated)	snap.	10·5
D.T.D. 303 & 327	snap.	12
L. 37 (heat-treated)	120° c'sk.	12·5
D.T.D. 303 & 327	120° c'sk.	17

The consideration of the strength of any particular joint is usually complicated by the unequal distribution of load among the different members of the rivet group. It must be emphasized therefore that the odds on which the above factors are calculated, are not of an order that would permit the designer to adopt higher strength figures.

(B) *Dispersion produced by different riveting processes*

A point of subsidiary interest is whether the different riveting processes differ in their effect on dispersion of strength. Various conclusions have been reached for each analysis attempted and these have not always been consistent. There is also the possibility that in a particular instance, the manufacturer may have used rivets from different batches for the production of the 20 specimens used for the study of dispersion. This was, however, not the general case, and we may assume that rivets come from the same batch for one supplier.

Consideration of the six analyses shows that in general, the dispersion from supplier F.R. (hand tools for placing) exceeded that of any of the other suppliers (pneumatic guns for placing). Between these latter there is probably little to choose ; supplier H.P. produced slightly more dispersion than B. or F., but it is doubtful whether these results are of significance.

(C). *Mean strength produced by different suppliers*

The failure of any particular supplier to maintain a superiority of mean strength over the others, suggests that the basic strength of the rivet material is a factor which is just as important (possibly more so) as the type of riveting process used. Reviewing the results for all types of rivets we see that the only results which are consistently on the low side come from supplier F. In general the greatest mean strengths are obtained from supplier H.P.

These results are important since the whole object of the tests was to select a representative sample of the quality of aircraft riveting. In the main, it is concluded that the selection has not been made with undue bias, and confidence may be had in application of results.

Electrical Equipment in Aircraft

To the Editor:

SIR:

Really, Mr. Kearns,

Someone ought to tell him that:

(*a*) Quite a lot of us were schooled in the same 'heavy brigade as he was, and threw the same bricks about years ago. Ask Farnboro!

(*b*) The S.B.A.C. are on the track, and he *should* see the results of a standard scheme on his firm's next new venture.

(*c*) 24 Volts D.C. is *not* the answer, and A.C. has come to stay.

(*d*) Joints *are* permissible as a repair scheme, but would naturally not be encouraged on a new installation.

(*e*) A number, to denote the carrying capacity of a cable, is the answer to the non-technical man's prayer.

(*f*) Most of these cables are now up-rated.

(*g*) P.V.C. is ousting rubber.

(*h*) Soldering, so far as contractor firms are concerned, will soon become obsolete. (See S.B.A.C. Standard Electrical Scheme).

(*i*) 'Earth return' is already here, and will survive.

(*j*) The fact that earth return is used does not mean that one can use the other wire ad lib. The saving in weight, due to the fact that items of equipment are usually 'earthed' at the nearest junction, is only 25 per cent to 30 per cent on large aircraft.
The question of 'doubling up' in case a lamp (or other equipment) should fail, is as old as the industry itself, and I would recommend that he 'tries it on' his own Chief Designer. His reaction will be a shock.

(*k*) Saving of weight, so long as efficiency is not impaired, has always to be uppermost in the aircraft electrical engineer's mind, and this, together with the fact that each contractor firm carries an engineer who has his own pet version (like Mr. Kearns) of what constitutes the ideal installation, has led to the Standards Committee being formed.

Mr. Kearns will find if he stays in the industry that this Committee is representative of the best brains in this country, drawn from the air-minded Manufacturers, Contractors, and M.A.P.

(*l*) His four years' experience in the aircraft industry, especially under 'make do' conditions of wartime, is not necessarily a qualification for his opinions, and I, for one, shudder at the thought of distribution engineers handling aircraft installations. I can almost 'smell' their cast-iron boxes with porcelain fuses, and china switches with knobs on—brass ones.

A. BALL

50 Castle Street,
Beaumaris, Anglesey.

19th February, 1945

British Standard Specifications

Copies of the following Specifications may be obtained, at the prices indicated, from the British Standards Institution, 28 Victoria Street, London, S.W.1.

B.S. 1100, *Pt.* 2, 1944.—*Production Control in the Small Factory.*

This booklet is the second of three (the first of which, *B.S.* 1100, *Part* 1: *Principles of Production Control*, was summarized in AIRCRAFT ENGINEERING Vol. XV, November, 1942, p. 333) dealing with Production Control and, as its title indicates, is designed to advise on production control technique in the small factory, with the over-riding object of stressing the need for control if production is to be economically increased and waste of time and effort eliminated.

The booklet may be found of greatest use in a factory employing 50 to 200 people, but it is recognized that for production control purposes a factory employing 200 people may be simpler than one employing 50 if the type of product in the former is less complex than in the latter.

The text of the booklet epitomizes recommendations for the simple control of the issue of quotations, of purchasing, of the flow and volume of work, of production instructions, of timekeeping and of costs; and is illustrated with specimen schedules, cards, record sheets and a comprehensive order flow chart which shows the various stages through which an order will pass.

Price 2s, post free.

B.S.S. No. 57: 1944—*B.S. Bolts, Screws, Nuts and Washers.*

A revised edition of the British Standard 57 relating to B.S. bolts and nuts has recently been issued by the British Standards Institution. The previous issue of this specification, which has been in force since 1920, was limited to the dimensions of the heads of the various types of screws and to ordinary nuts. The present edition has been extended in its scope to include requirements defining the dimensions of the complete screws and bolts and nuts. In addition to ordinary nuts, the dimensions are given for lock nuts, and two series of washers are standardized.

This new edition of B.S. 57 is published as a war emergency British Standard and gives effect to the instructions issued by the Ministry of Supply by recognizing only certain types and sizes of bolts and screws as standard for wartime production. It has nevertheless been considered desirable to retain on record the dimensions of the other types of B.A. screws which appeared in the previous edition of the specification, and these have been incorporated in an appendix.

Price 2s., post free.

Twist Drill Control

The Ministry of Supply announces that in view of the greatly improved supply position of High Speed Steel Twist Drills, it has been decided that there is now no longer any necessity to continue the Control of Machine Tools (Twist Drills) (No. 1) Order, and, accordingly, this Order has now been revoked.

It has also been decided that there is no longer any necessity to continue the operation of the Twist Drill Allocation Centre which was set up to work in conjunction with the Licensing Scheme. This Centre, therefore, ceased to function on the 16th February, and on and after 17th February, 1945, buyers might revert to their normal sources of supply with which they were accustomed to deal prior to the inception of the Centre.

Magnetic Crack Detection

By J. E. D. Bell

(*Concluded from p.* 60)

PART II

DEFECTS AND METHODS OF DETECTION

In Part I the elementary principles of magnetic crack detection have been discussed, and an endeavour made to explain the elements of a system which has been satisfactorily applied to the inspection of aero-engine components.

It is the purpose of this second part to describe the common defects which can be revealed by this system, and the machines and jigs used in their detection.

The types of defects which can be revealed by magnetic crack detection are roughly classifiable as follows:—

(*a*) Grinding cracks.

(*b*) Forging cracks or defects.

(*c*) Inclusions.

(*d*) Cracks caused by faulty heat treatment or other process.

(*e*) Fatigue cracks or cracks caused by damage.

Defects (*a*) to (*d*) are likely to be present on any other new components, whereas defects (*e*) are most likely to be found on engine parts which have been run.

In Figs. 1 to 6 inclusive, an endeavour has been made to illustrate typical examples of the above defects, and it is hoped that these will prove to be useful illustrations of the formation and locality of various types of defects.

Grinding cracks need particular care in inspection, as these are often very fine and difficult to locate, while being of a very serious nature.

It is possible with this system to reveal defects which are just below the surface of the metal. In such cases the indications visually have a rather blurred appearance.

Particular care should be taken when inspecting components having nitrided surfaces, as indications are less clear on components hardened in this manner.

Any defects revealed should be clearly marked with red or blue pencils by the inspector, and put on one side for investigation by the charge-hand or foreman in charge of crack detection.

FIG. 1.—*Severe grinding cracks on gear teeth*

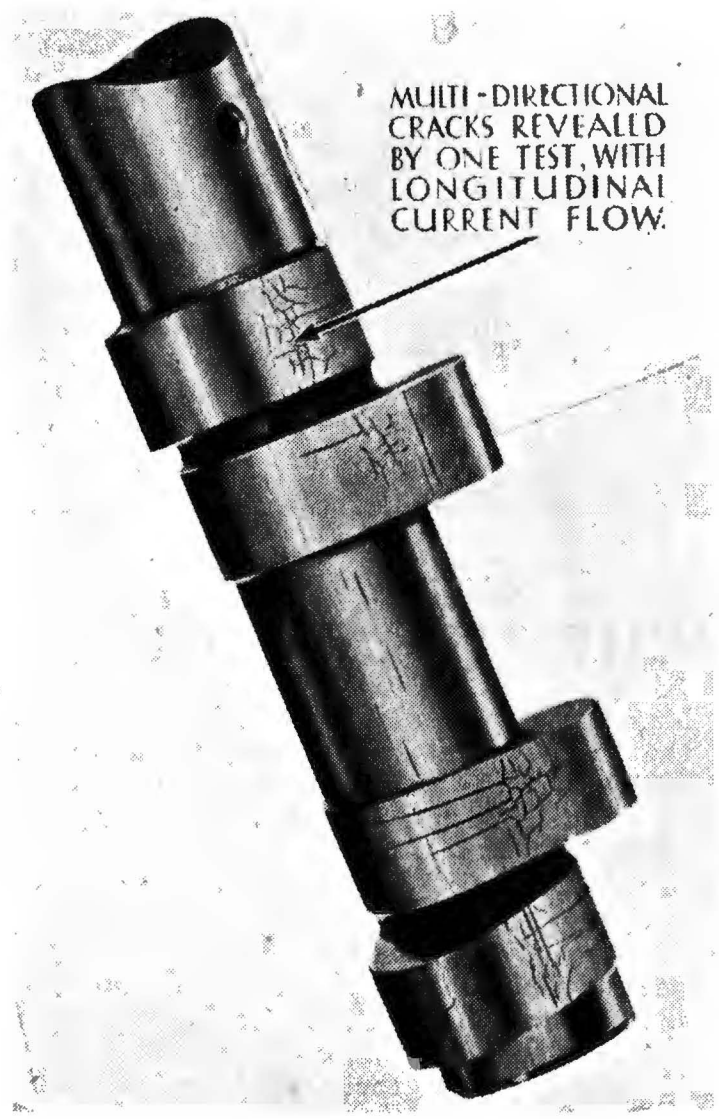


FIG. 2.—*Typical example of crazy pattern grinding cracks*

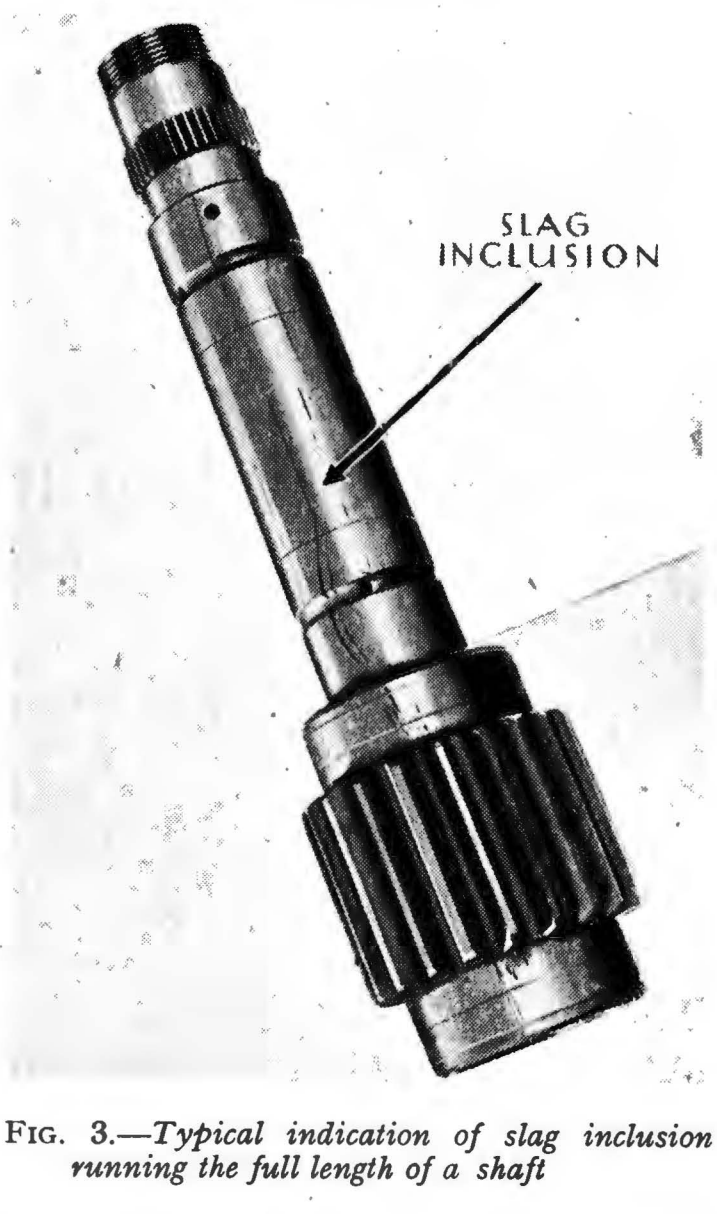


FIG. 3.—*Typical indication of slag inclusion running the full length of a shaft*

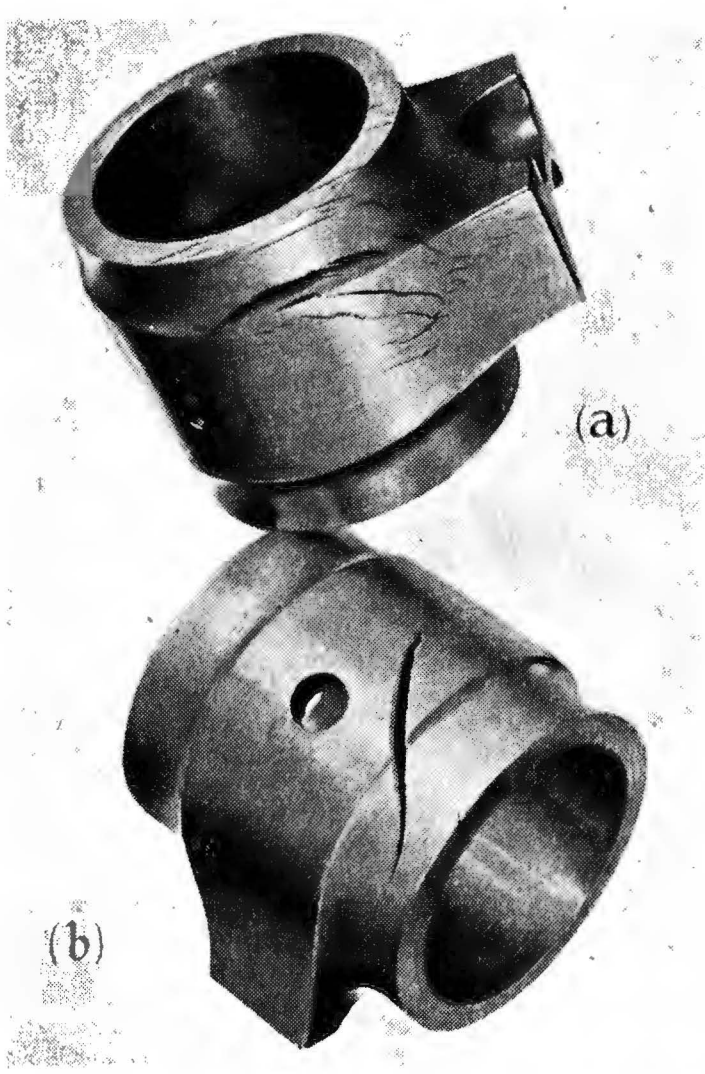


FIG. 4.—*Indications of* (a) *extraneous slag and* (b) *forging defect*

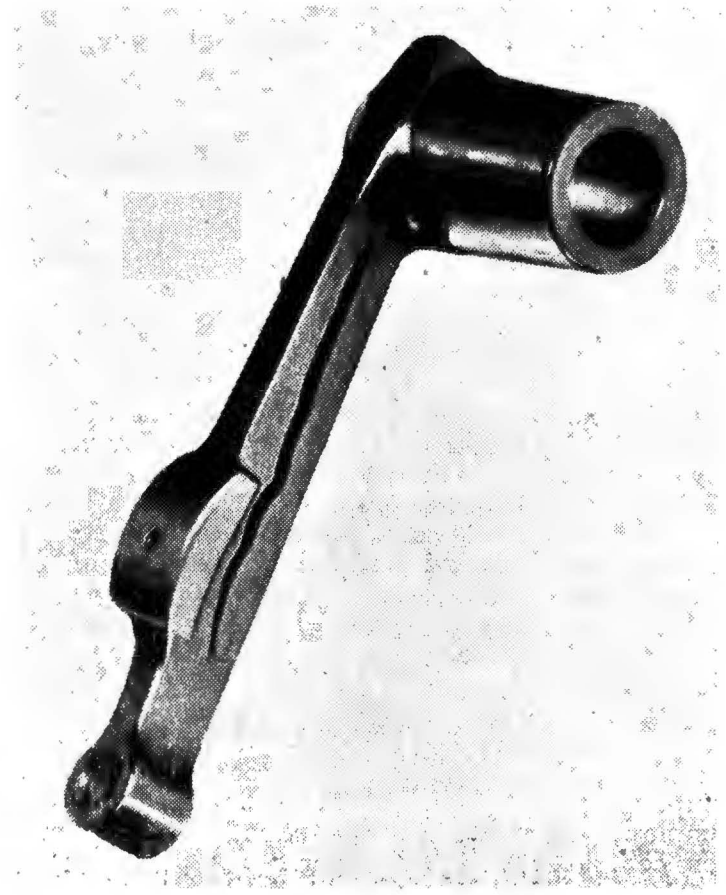


FIG. 5.—*Indication of forging lap*

FIG. 6.—*Indication of crack due to faulty heat treatment*

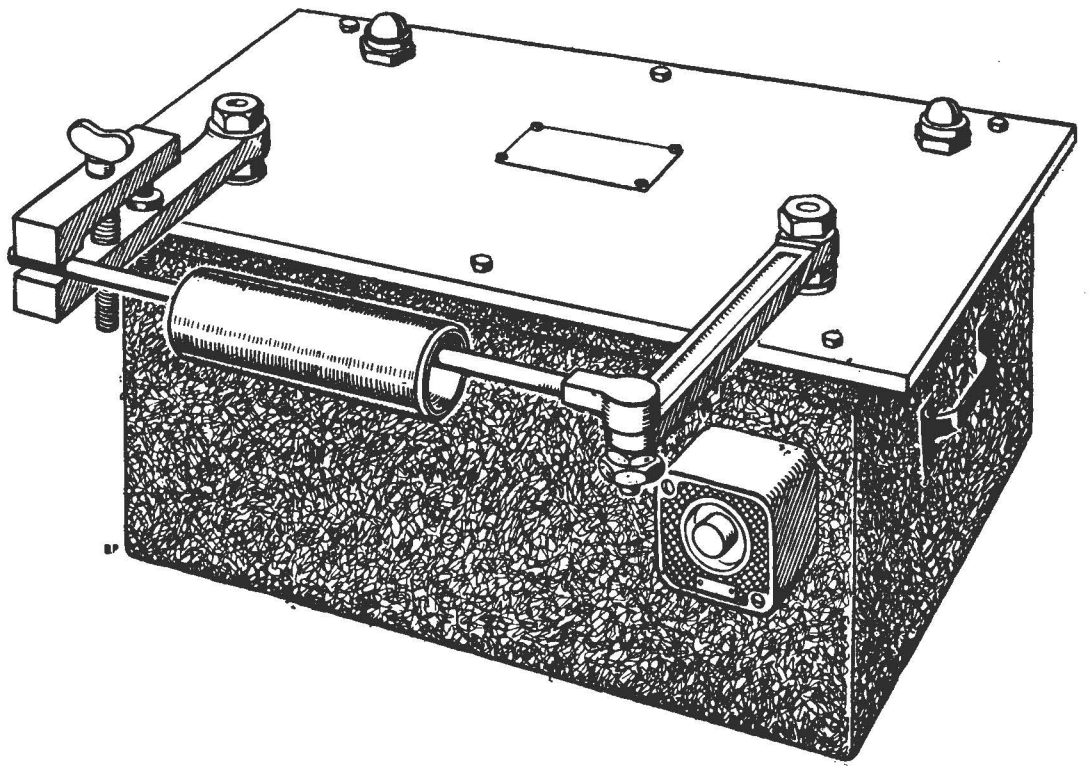


FIG. 7.—*Bar jig mounted on bench-type machine*

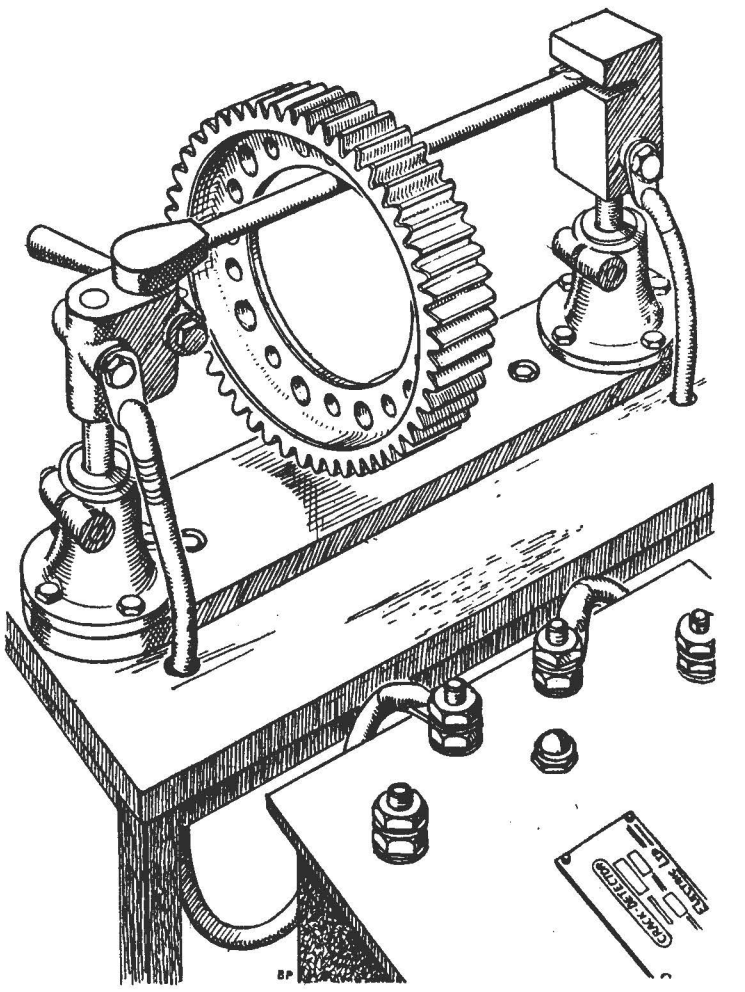


FIG. 8.—*Bench-mounted bar jig testing large gear wheel*

These should be the only personnel responsible for allocating defective parts to scrap or salvage.

Although these last points seem very simple, they are extremely important in the maintenance of a foolproof system of inspection. If marking is not strictly enforced, or if any inspector is allowed to allocate his own components to scrap, there is a danger of faulty parts slipping through, leading to confusion and a breakdown of the confidence built up in the magnetic crack detection system.

No attempt has been made here to discuss acceptance standards for components which are to be magnetically crack tested. These standards will be a matter for the production engineer, or some equivalent authority, to decide upon, and will be peculiar to individual manufacturers according to the type of components being produced. It is a great asset, however, if some simple code of acceptance standards can be devised, for circulation to crack detection operatives. This is particularly useful where components manufactured by sub-contractors are crack tested before despatch to the parent firm. In such cases fixed standards are essential for maintaining high quality production.

The jigs which are described and illustrated in this article, are of the simplest type, and yet have proved to be highly satisfactory in dealing with the large variety of aero-engine components, which are subjected to magnetic crack detection.

The type of jig which is perhaps one of the most widely used, is the simple bar jig (see Figs. 7 and 8). This comprises a copper bar of from $\frac{3}{8}$" to 1" diameter, mounted on a heavy copper swivel at one end, while the other end fits in a tapered or spring loaded grip contact. This may be a separate jig or mounted directly on the secondary output terminals of the crack detector.

Components such as small gear wheels, gudgeon pins, etc., are threaded on this jig for test, the flow of current along the bar inducing magnetism into the components.

Several components can be threaded on the bar together, but care should be taken not to load the bar too heavily and allow components to touch one another. Large gear wheels can also be tested on this jig, but in this case it is advisable to rotate the gear wheel once round the bar slowly, while the current is flowing. A slight increase in the time of current flow is permissible in such case, to allow time to rotate the gear.

This principle of induced magnetism is employed in another type of jig which has been specially devised for testing cylinder liners. Here the copper bar is twisted into a spiral coil of approximately 5" diameter. Four strips of insulating material are laid along the outside of the coil to support the liner, which is simply slipped over the coil for test. Heavy current passing down the coil creates a strong magnetic field which is induced into the liner.

Another type of jig which can be used to test a large variety of components, is the telescopic clamp. (See Fig. 9.) This is also of very simple construction, consisting of two copper plates (round or pear shaped) insulated from one another. One plate is fixed while the other is actuated by a rack and pinion, allowing it to move up or down approximately 15 ins. Each plate is connected by heavy cable to the crack detector output terminals. The plates are padded with several layers of copper gauze to make good contacts.

These jigs can be used for testing components from large gear wheels down to small studs. An

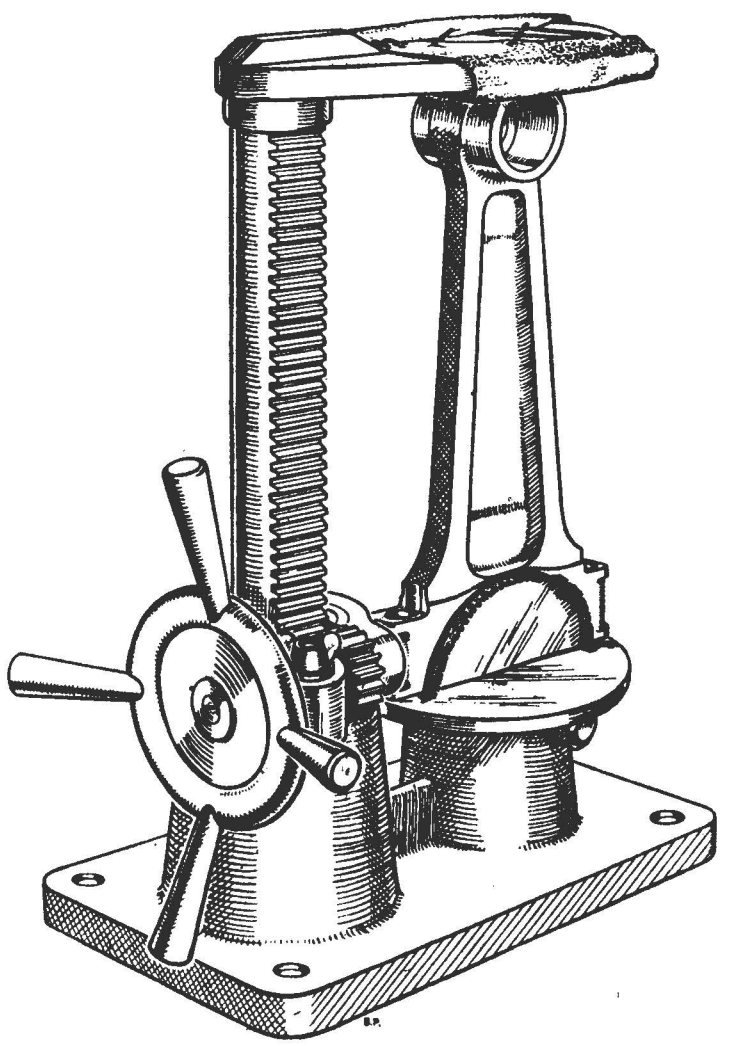


FIG. 9.—*Telescopic clamp*

improved version of this type of jig is incorporated in one of the latest type machines described later in this article.

Simple Vee blocks and half round blocks are extensively used in the testing of various types of shafts. These can be made in several sizes according to the types of shaft to be tested. The surface of the Vee or half round block on which the shaft is to rest, should be covered with several layers of copper gauze for good contact. It is a good plan to fix the blocks on to a sliding bed, so that the distance between the blocks can be varied to suit the length of shaft on test. The half round type of jig is especially useful for testing very large shafts, such as crankshafts. It is well worth while to allocate one or two sets of half round blocks especially to crankshaft test. In such cases, the half round can be accurately machined to match the diameter of the shaft, so that the shaft will bed well down on to the gauze in the half round, ensuring the best possible contact. It may even be advisable to have an upper and lower half round block, which can be clamped together by means of thumb screws or some simple looking device, so gripping the shaft firmly at each end.

Extra heavy leads should be used for connecting these blocks to the crack detector, to minimize current drop.

For long shafts of small diameter, such as camshafts, a spring loaded angle block jig is most suitable. This jig consists of two L-shaped copper blocks of substantial proportions, which are usually mounted on a sliding bed in such a manner that they can be easily locked at any distance apart up to 3 ft. 6 in. One block is spring loaded and actuated by a lever in order to maintain pressure contact on the component under test. The contact faces of the blocks are concave and lined with copper gauze, so that the end of the shaft under test will bed well down when the spring pressure is applied. This prevents burning at the ends of the shaft under test.

The jigs described above aré typical examples of the methods by which a variety of components can be set up rapidly for magnetizing. These are only intended as illustrations of what can be done in a very simple manner; manufacturers will of course devise jigs to suit their own particular requirements. Some may even find it more beneficial to use Universal type crack detection machines, where 3 classes of jigs are incorporated as an integral part of the machine. Most of the jigs described above are designed for bench mounting and are connected to "Floor Type" crack detection machines having three sets of output terminals.

This "Floor Type" model (see Fig. 10) is an ideal machine for dealing rapidly with a large variety of components. It is compact in construction and stands about 3 ft. high and is also portable. It is the most suitable machine for standing at the end of an inspection layout described in the previous article. There are three pairs of output terminals, LOW, MEDIUM and HIGH, giving approximately 1,000, 2,000 and 3,000 amps. respectively, depending upon the resistance of the part undergoing test, thus being capable of magnetizing practically any component from an aero-engine.

This type of machine will take a maximum current of approximately 60 amps. from a.c. supply mains of 200/250 volts 50 cycles. This peak current will be flowing for a period of approximately one second while the machine is in operation. A red warning light shows when the machine is live to the mains supply, while each pair of output terminals has its associated green pilot light, which is illuminated while the component is being magnetized.

Where the variety and size of components for test is limited, a small bench model machine is very suitable. This type of machine is easily portable, it can be readily lifted by one man. There is only one pair of output terminals, the maximum output current being in the region of 2,000 amps. depending on the resistance of the component under test. The machine takes approximately 30 amps. from 200/250 volt a.c. supply mains. Red and green pilot lamps are employed, as on the "Floor Type" machine described above. (See Fig. 7.)

Light components such as gudgeon pins, bearing housings, or small gear wheels can be very rapidly and effectively tested on this type of machine.

A bar jig can be mounted directly on to the output terminals of the machine or alternatively, an external jig such as a telescopic clamp can be connected up by heavy cables if so desired.

Where very large numbers of small components such as studs, bolts or nuts, etc., need to be tested very rapidly, there is a desk pattern crack detection

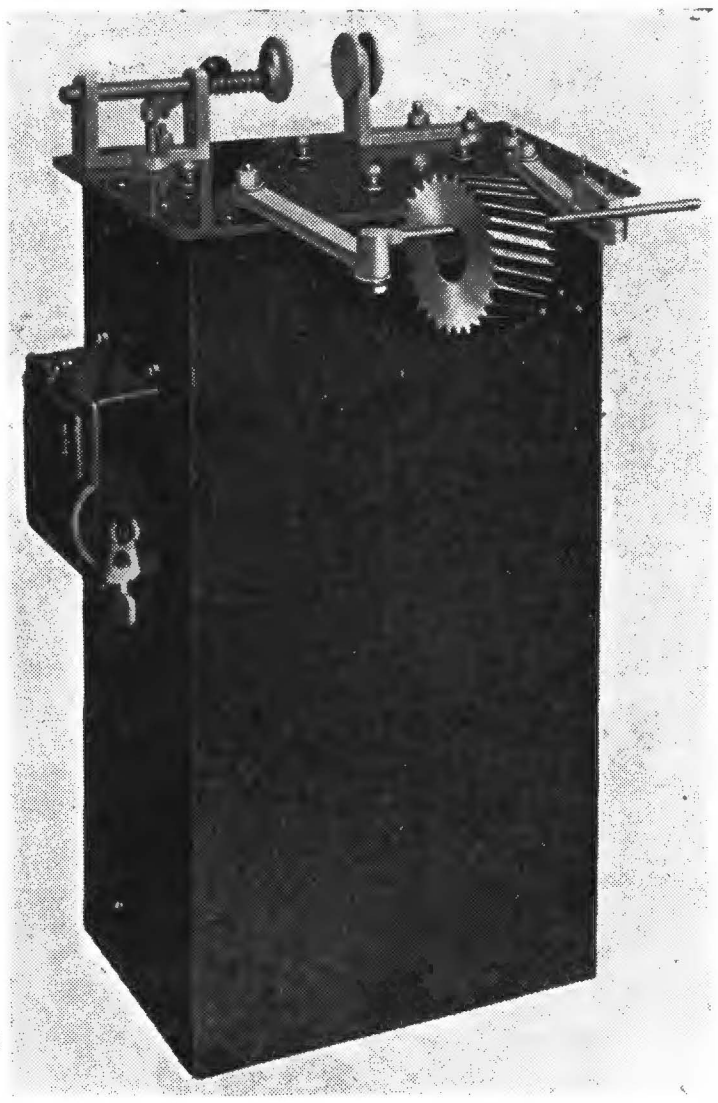


FIG. 10.—*Floor type machine*

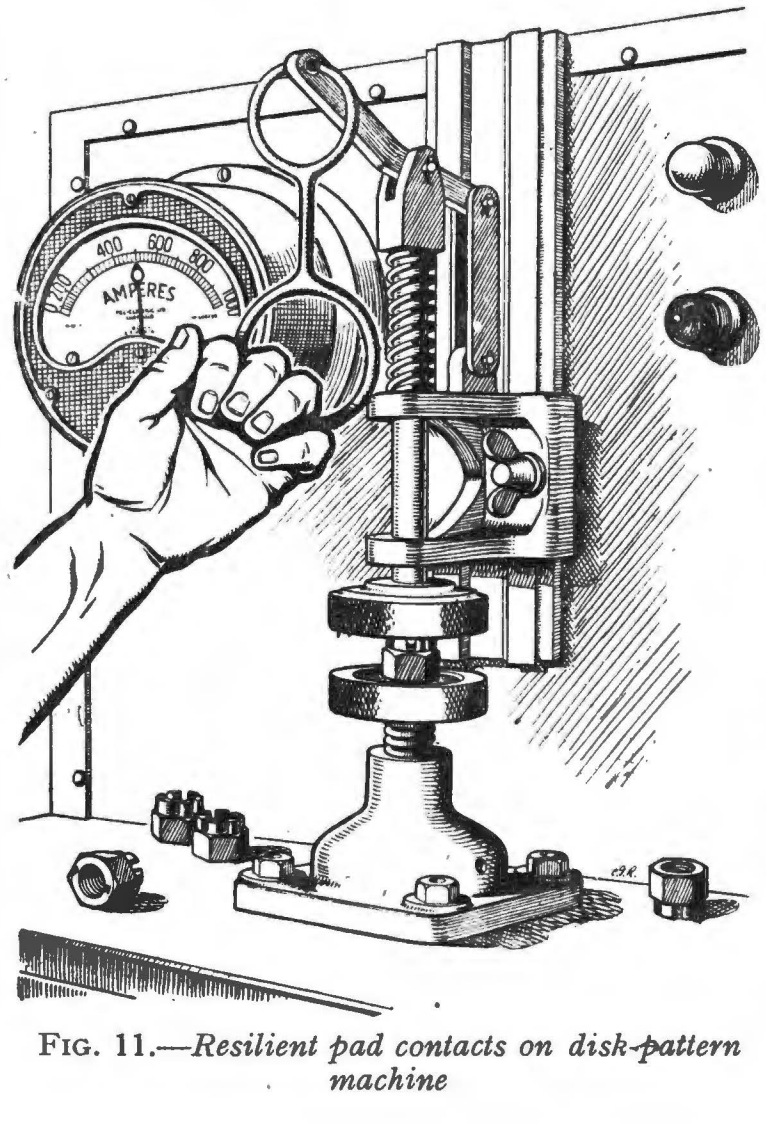


FIG. 11.—*Resilient pad contacts on disk-pattern machine*

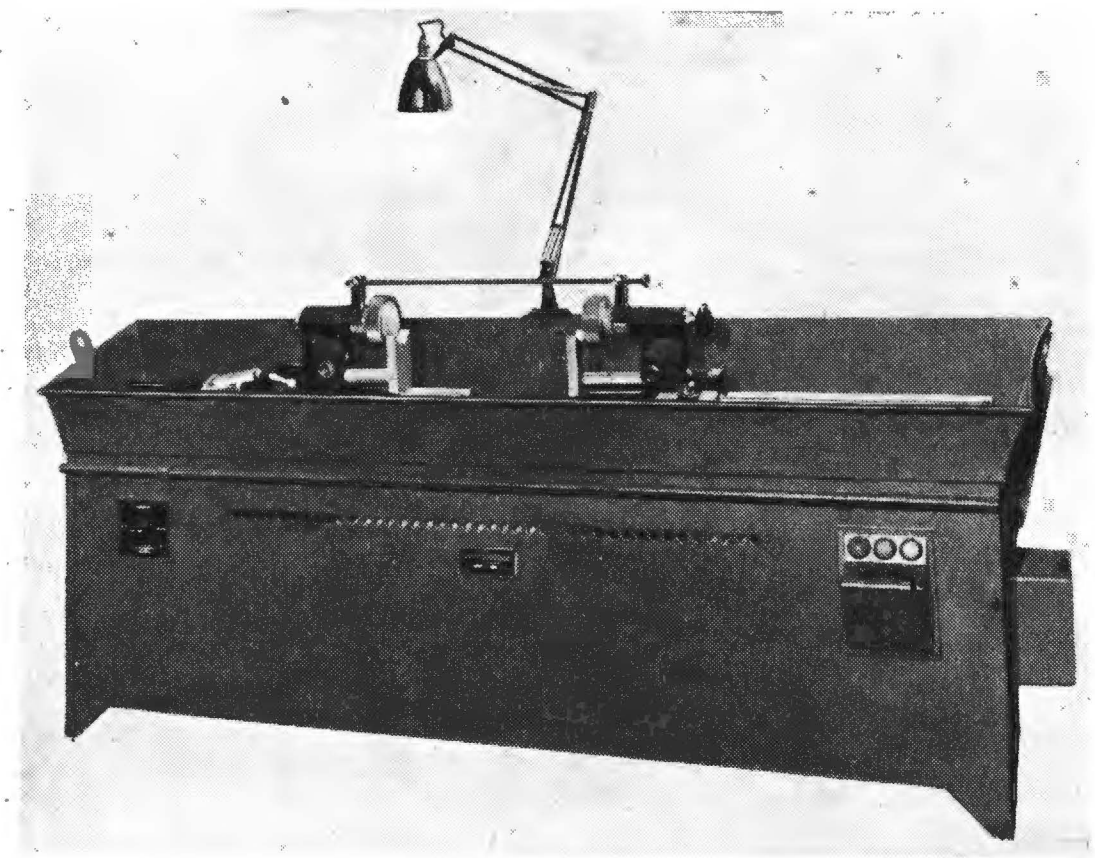


FIG. 12.—*'Universal' floor mounting machine*

machine which has been specially designed for such purposes.

This versatile machine, which is a floor mounting pattern, incorporates a set of contact pads mounted on a vertical slide and actuated by a hand lever.

The contact pads comprise a shallow brass cup, externally threaded, into which fits a domed pad of synthetic rubber. Over the rubber pad are fitted several disks of copper gauze. These disks are approximately the same in diameter as the brass cap, and cover the whole area of the rubber pad and the cup. Over this fits a large brass knurled nut, which is tightened until the copper gauze is stretched tightly over the rubber pad, and gripped firmly between the nut and the top of the cup.

The lower of these contact pads is spring loaded and is mounted on the desk top of the machine, in such a manner that, as the contact is depressed, it operates the switch controlling the contact breaker.

The upper contact is of the same " resilient pad " type and is mounted on a spring loaded shaft carried in a bracket which fits into a slide bed. (See Fig. 11.) The simple depression of a small lever moves the contact pad downwards against the spring. Any component for test will thus be gripped between the upper and lower pads, and a slight extra pressure on the lever, will drive the lower pad down against its spring, and switch on the current. As soon as the lever is released the contacts will spring apart, releasing the component.

When the component is gripped tightly between the contact pad faces, the pressure automatically causes the component to sink into the soft pads, and the copper gauze will follow the contours of the ends of the component, ensuring maximum area of electrical contact. The bracket carrying the upper contact has a lock nut, and can be moved up or down the slide bed, permitting the testing of components from approximately 1 inch to 12 inches in length.

The machine has an output of approximately 1,000 amps on 200/250 volt a.c. 50 cycle mains, dependent on the resistance of the component on test.

A three position current selector switch is fitted, and in addition there is a choke control giving an additional current selection. The usual red and green pilot light are employed to indicate " Machine live to mains" and " Magnetizing current on". An indicating ammeter is mounted on the panel of the machine, to show the operator what current is flowing through the component on test.

This machine lends itself to very high speed operation, and small components can be magnetized so quickly, that the limit appears to be the speed with which the operator can pick up components and insert them between the contact pads.

In certain cases, the types of component to be crack tested or the general layout of the crack detection department, may make it undesirable or even impracticable, to use external jigs of machines of the types described above. In such cases the needs can be met admirably by the use of one of the Universal type machines (see Fig. 12). These machines are of the floor mounting type and are entirely self-contained. They incorporate an ink tank, and on the later types, a spray gun for spraying the detector ink over the components after magnetizing. Three types of jig are mounted directly on the machine, the resilient pad type contacts being a feature of the main general purpose jig.

These pads are mounted on sliding heads which run on a slide bed, being adjustable within a range from 2 inches to 4 feet on the larger models. One resilient pad is mounted solidly on to its sliding head, while the other is so mounted that it has a short travel, and is actuated by a quick action lever. In addition to driving the pad forward, this lever also locks it in position when the component is gripped firmly between the pads, always ensuring maximum pressure contact on the component. As on other types of machine previously described, the a.c. current will flow through the component when the push button on the control panel is depressed. The usual red and green pilot lights are employed.

In addition to the resilient pad contacts, the sliding heads are fitted with a bar jig, which comprises a thick copper which drops into slots on the sliding heads, where it can be locked in position by turning two thumb screws.

As a complement to the usual " Impulse " method of magnetization by means of heavy a.c. current flow, this type of machine incorporates a " Magnetic Flux " method of test. The jig for this method of test, consists of two iron Vee blocks mounted beneath the resilient pads. These blocks are actually the poles of an electro-magnet, and the component is simply placed on the blocks (no copper gauze is used in this case) for test. The depression of an additional push button on the control panel energizes the magnet and the magnetic circuit is completed through the component lying between the two poles. Care should be taken when testing components in the resilient pad jig to see that the component does not come into contact with the magnet poles.

This additional method of test, permits a very thorough examination for cracks on a large variety of components.

Cracks or defects which are along the line of current flow, or cracks in " Crazy " pattern can be revealed by the " Impulse current flow " test, while cracks which would be substantially at right angles to the line of current flow, can be effectively dealt with by the " Magnetic Flux " test. On this latter test, the ink can be sprayed over the component whilst the flux is flowing, or after the test as desired.

To sum up, the following are the salient points to be remembered in the development of a sound magnetic crack detection system :—

(1) The vital importance of magnetic crack detection should be impressed upon all operatives.

(2) An efficient system of anti-glare lighting is highly essential.

(3) Ample working space with a neat and labour saving layout are well worth while.

(4) Operators must use the machines in the manner laid down, and not introduce any fancy ideas of their own, such as 6 or 7 depressions of the push switch "just to make sure".

(5) No ferrous trays and equipment must be used for components which have been magnetized. It is no good magnetizing your components well and then stacking them in heaps or laying them on iron benches or trays before inspection.

(6) Detector ink should always be maintained in good condition, otherwise the success of the whole test will be jeopardized.

(7) When demagnetizing, components should not be left lying in or near the coil, they should be passed slowly through once and removed from the vicinity of the coil, otherwise components may remain magnetized.

(8) Regular maintenance of all electrical equipment employed is very necessary. All contacts and joints must be tight, and sound. Copper gauze must be renewed as soon as it becomes frayed or dirty.

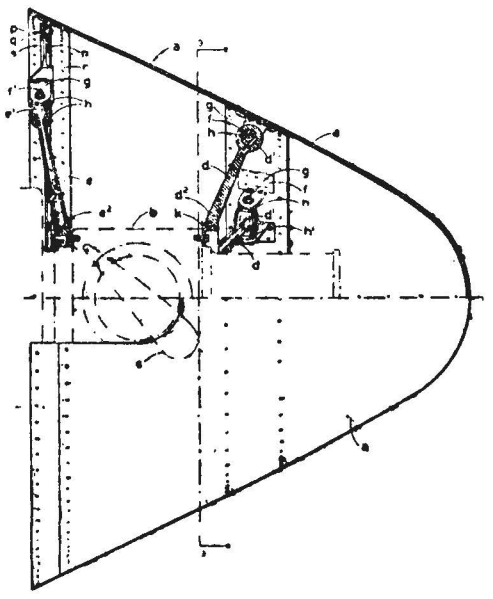
(9) Operators should use antiseptic for their hands to avoid dermatitis.

(10) Strict control should be maintained over acceptance or rejection of doubtful components.

U.S. Patent Specifications*

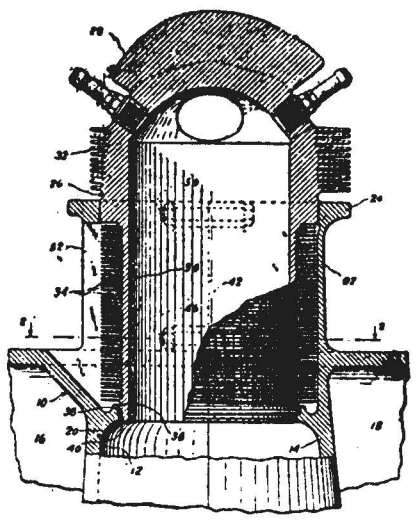
2,353,578. Spinner for Airscrews. Frederick George Marshall, Leamington Spa, England, assignor to Constant Speed Airscrews Limited, Warwick, England. Application June 9, 1941, Serial No. 397,347. In Great Britain April 5, 1940. 6 Claims. (Cl. 170—159.)

In a spinner for the hub of an airscrew, a spinner shell, spoked supports therefor adapted for attachment to said hub, an annular member adapted for detachable connexion with said spinner shell, a plurality of brackets fixed around said member, pivot pins carried by said brackets with their axes arranged tangential to a circle concentric with the rotational axis of said spinner shell, open-ended sockets at the ends of the spokes of said supports adapted for engagement with said pins and rubber bushes arranged between said pins and sockets with their ends bearing against said brackets.

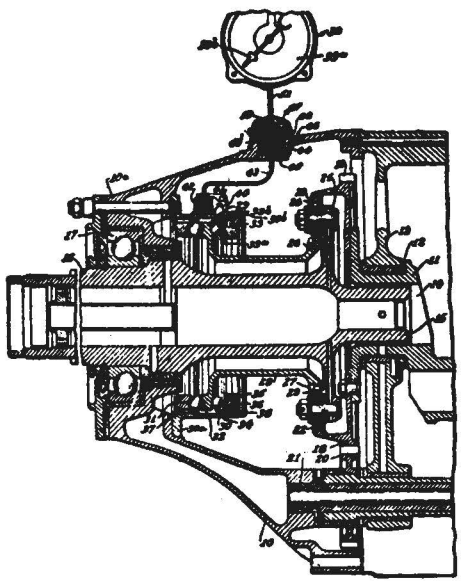


2,353,779. Cylinder Attaching Means. Veon I. Moncrieff, West Hartford, Conn., assignor to United Aircraft Corporation, East Hartford, Conn., a corporation of Delaware. Application October 9, 1941, Serial No. 414,319. 10 Claims. (Cl. 123—171.)

In an engine having a crankcase and a cylinder comprising a finned head portion and a finned barrel portion secured to said head portion, means for securing said cylinder in operative position on to said crankcase, comprising, an integral boss extending outwardly from said crankcase surrounding a depression in said crankcase, a guide seat surrounding an aperture in the bottom of said depression and engaging the inner end of said barrel portion, and means on said head portion engaging said boss at its outer end, said barrel fins extending over substantially the entire length of said barrel.



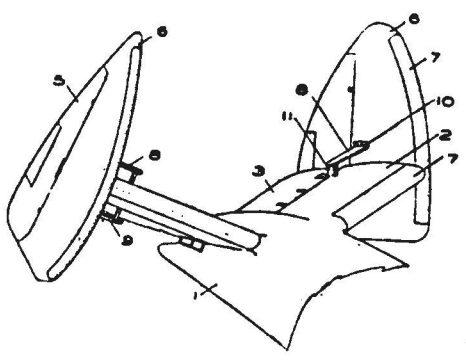
2,353,814. Torque Indicator. Chester C. De Pew, Farmingdale, N.Y., assignor to Fairchild Engine and Airplane Corporation, Farmingdale, N.Y., a corporation of Maryland. Application March 14, 1942, Serial No. 434,720. 12 Claims. (Cl. 265—25.)



In a device for measuring torque, the combination of a driving member and a driven member, a planetary gear system coupling said driving and driven members, said system having a sun gear axially movable and rotatable relatively to said driving and driven members, cam means including a fixed member and a ring member having opposed cam faces, said ring member being connected to and coaxial with said sun gear for shifting said sun gear axially in response to rotation thereof and spring means resiliently opposing axial movement of said sun gear to render axial movement of said sun gear proportional to the torque exerted on said driving and driven members.

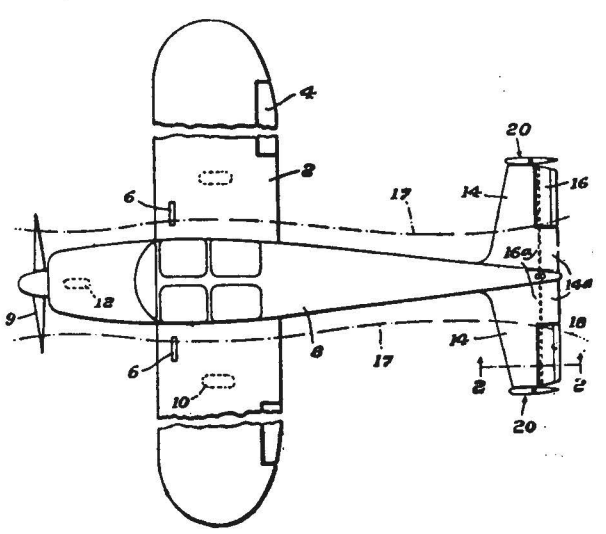
2,353,856. Auxiliary Airfoil. Ellis D. Shannon, Baltimore, Md., assignor to The Glenn L. Martin Company, Middle River, Md., a corporation of Maryland. Application November 21, 1942, Serial No. 466,445. 2 Claims. (Cl. 244—87.)

An aircraft empennage comprising a pair of intersecting stabilizers arranged substantially normal to one another, movable control airfoils secured to said stabilizers, one of said movable control air-



foils having a cut-out portion extending from a point adjacent the intersection of the trailing edges of said stabilizers, to the trailing edge of said control airfoil to permit the movement of the other control airfoil, an auxiliary airfoil mounted on the stabilizer adjacent, and substantially parallel to, the leading edge of the cut-out movable airfoil, having a lateral extent substantially equal to and spanning the cut-out portion of said airfoil, to effect a smooth flow of air thereover.

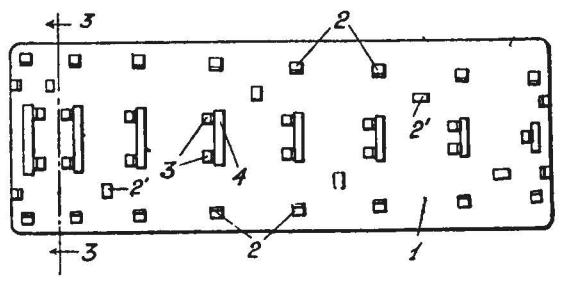
2,353,907. Aeroplane. Otto C. Koppen, Newton, Mass., assignor to General Aircraft Corporation, Dover, Del., a corporation of Delaware. Application August 9, 1943. Serial No. 497,907. 2 Claims. (Cl. 244—87.)



An aeroplane having in combination, a supporting wing, a fuselage having nose, body and tail portions, a single tractor propeller at the nose having its axis substantially in the vertical plane of the longitudinal axis of said fuselage, a horizontal stabilizer laterally extending on each side of the tail portion of said fuselage in general L form and extending across the propeller slipstream in normal level flight attitude, said stabilizer in normal flight presenting to the propeller slipstream only normally fixed surfaces, a single pair of elevators mounted on the stabilizer with each elevator laterally spaced a substantial distance from said fuselage, each hingedly mounted in the angle of an L of said stabilizer thereby minimizing elevator tip losses at the in-board end of each said elevator and having its major portion located laterally outside the zone of the propeller slipstream, and vertical tail surface means symmetrically disposed with reference to said propeller axis.

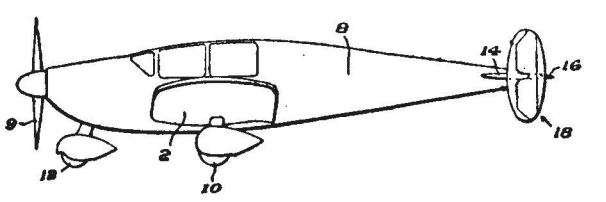
2,353,954. Jig for Assembling Components of Substructures. David H. Duffy, James W. Wiley, and Milburn M. Ross, Wichita, Kans., assignors to Beech Aircraft Corporation, Wichita, Kans., a corporation of Delaware. Application June 25, 1942. Serial No. 448,450. 2 Claims. (Cl. 144—288)

In a jig of the class described, a plate of a suitable thickness, length and width, a plurality of abutment elements secured to one side of the plate and outwardly extending therefrom, said abutment elements being arranged in two pair of arcuate rows, the pairs being oppositely disposed on the plate so that the concavity of the pairs will confront each other and a plurality of members arranged in pairs, said pairs of members being spaced apart longitudinally of the plate and arranged between the pairs of rows of the abutment elements substantially as shown.



2,353,962. Aeroplane. Otto C. Koppen, Newton, Mass., assignor to General Aircraft Corporation, Dover, Del., a corporation of Delaware. Application July 28, 1943. Serial No. 496,425. 15 Claims. (Cl. 244—82.)

In a two-control aeroplane constructed and arranged to be flown by direct manual operation of ailerons and elevators only, a supporting wing, ailerons on the wing, a fuselage having a nose, body, tail portions, a stabilizer and elevator mounted on the rear end of the fuselage, and laterally spaced vertical rudders each movable about a vertical axis sufficiently rearward of the leading edge of said rudders as to render them aerodynamically unstable, each of said rudders having hingedly attached thereto at the rearward portion thereof a movable tab linked to a fixed portion of the aeroplane so that in flight when each rudder is displaced by an in-



creased angle of attack and the rear edge thereof departs angularly to one side of a neutral trailing position, the trimming tab thereof is angularly displaced outwardly with respect to said rudder and progressively towards the same side to an extent sufficient to maintain its rudder in equilibrium at the existing angle of attack and to restore its rudder to a neutral trailing position when the angle of attack becomes zero, the length of said tail portion and the aggregate lift of said movable rudders and tabs being such as with the aforesaid related elements of the aeroplane to provide a stable yawing moment curve.

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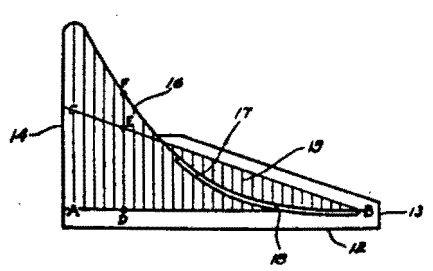
Except where otherwise stated, the specification is unaccompanied by drawings if none is reproduced.

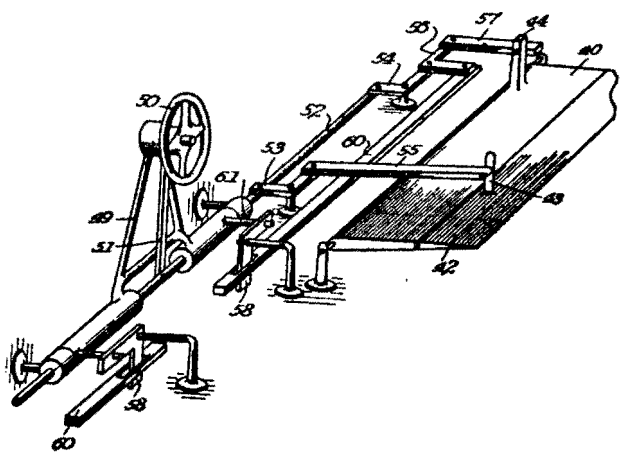
2,353,974. Scale. Walter Norman Stone, Glastonbury, Conn., assignor to United Aircraft Corporation, East Hartford, Conn., a corporation of Delaware. Application March 18, 1943. Serial No. 479,613. 7 Claims. (Cl. 33—75.)

An instrument for determining functional areas for any plane figure about a base line comprising, a form having a base line scribed thereon, a line scribed thereon at an oblique angle thereto, and a curved boundary edge on said form having perpendicular heights from said base line at any point proportional to a power of the distance between said base and oblique lines in a line normal to said base line through said point.



2,354,042. Longitudinally Controllable Airfoil. Max M. Munk, Cottage City, Md. Application May 1, 1937. Serial No. 140,238. 2 Claims. (Cl. 244—13.)

In a tailless aeroplane, in combination, an inherently longitudinally stable wing a ,longitudinal control surface mounted for vertical angular displacement relative to said wing for developing pitching moments acting in the desired direction to longitudinally control the aeroplane an adverse lift neutralizing surface mounted for vertical angular displacement relative to said wing to adjusted positions relative to the control positions of said longitudinal control surface, respectively, for neutralizing adverse lift developed by said control surface, pilot operated control mechanism connected to said longitudinal control surface and to said adverse lift neutralizing surface, said pilot operated control mechanism being effective for angularly vertically displacing said longitudinal control surface to control positions and constructed and arranged whereby simultaneous displacement of said neutralizing surface in a direction opposite the direction of displacement of said longitudinal control surface is effected to thereby substantially reduce the adverse lift developed by said longitudinal control surface in any control position thereof throughout the operating range of said longitudinal control surface.



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