Pulsating Air Flow

By NEIL P. BAILEY,[1] AMES, IOWA

Mechanically induced air flow is pulsating even when it may seem steady to the physical senses. This pulsation causes errors in velocity measurement that are often as great as twenty per cent when the conventional pitot tube or orifice is used with a liquid manometer, and it causes an increase in the velocity-energy and fluid-friction loss that can easily reach fifty per cent.

A simple portable instrument has been developed by the author which gives the true average air velocity for any amount of pulsation. In this instrument, the air velocity creates a water velocity through a submerged orifice, and this water velocity is always proportional to the air velocity at that instant, and can therefore be used to determine the true average air velocity, regardless of the amount of pulsation.

The instrument was first verified by checking it on velocity-wave forms of known characteristics. Following that a blower was tested for several conditions of operation and the air velocity was determined with the instrument and compared with the values given by the conventional instruments. In a similar manner the intake air velocity was measured for single-, four-, and six-cylinder internal-combustion engines, and the effectiveness of a receiver tank for damping pulsations was studied.

The last section of the paper is devoted to similar tests on the slip-stream velocity of an airplane propeller where the effect of pulsation on the efficiency of the propeller was worked out.

WHENEVER air is caused to move by mechanical means, the resulting air velocity is pulsating in nature. It has long been recognized that the motion of the intake air of internal-combustion engines and the discharge of reciprocating compressors is definitely cyclic. Recently H. F. Hagen[2] demonstrated that the discharge of air blowers pulsates much more than was previously realized. This same condition is also present in air flow actuated by propellers and ventilating fans. It is quite commonly appreciated that pulsation introduces serious experimental errors, but not so universally recognized that it is a source of considerable energy loss.

At present very little quantitative information is available on this subject, chiefly because there has existed no adequate experimental method for studying it. Most of the effort to date has been directed toward devising receivers, ducts, and nozzles to damp out the pulsation sufficiently to obtain reliable test data, rather than on attempts to study the pulsating flow as it actually exists under operating conditions. The direct data[2] that have been obtained required such elaborate testing technique as to make any extensive investigations almost out of the question. It is the object here to present a very simple and effective method for studying pulsating air flow, and to offer some experimental information so obtained in the hope of directing attention to some of the important facts connected with pulsating air flow.

Physical Effects of Pulsation

The usual method of determining the velocity of air is to measure the velocity head obtained from a pitot tube, nozzle, or orifice by means of a manometer or other pressure-sensitive instrument. The velocity calculated from this pressure reading is the true average velocity only when the flow is not pulsating. Since the velocity head or pressure is proportional to the square of the air velocity, and since the manometer indicates the average value of this pressure, it follows that the velocity calculated from this reading is the square root of the average value of the velocity squared, or the effective velocity.

An idea of the possible magnitude of this error may be had by considering an air velocity having a harmonic pulsation, $v_0 \sin \omega t$, superimposed on a steady average value v_{av}.

The effective value of the velocity v_{eff} is given by

$$v_{eff}^2 = \frac{\int_0^{2\pi} (v_{av} + v_0 \sin \omega t)^2\, \omega dt}{2\pi} = v_{av}^2 + \frac{v_0^2}{2} \ldots\ldots [1]$$

Or, the ratio of average velocity to effective velocity becomes

$$\frac{v_{av}}{v_{eff}} = \frac{1}{\sqrt{1 + \frac{1}{2}\left(\frac{v_0}{v_{av}}\right)^2}} \ldots\ldots\ldots\ldots\ldots\ldots [2]$$

If $\left(\frac{v_0}{v_{av}}\right)$ is defined as the pulsation, the condition of $\frac{v_0}{v_{av}} = 1$, or unit pulsation, corresponds to a flow where the velocity varies from zero to a maximum sinusoidally. For this case

$$\frac{v_{av}}{v_{eff}} = \frac{1}{\sqrt{1 + \frac{1}{2}}} = 0.816,$$

which represents considerable error for a velocity determination.

Also, for air flowing in this pulsating manner, the kinetic energy that must be given to it compared with the energy that would be necessary if the flow were free from pulsation, is given by the ratio, $\left(\frac{v_{eff}}{v_{av}}\right)^2 = 1.5$. The friction loss in ducts and

[1] Head of Mechanical Engineering, Iowa State College. Assoc-Mem. A.S.M.E. Professor Bailey received his B.S. in mechanical engineering at the University of Colorado in 1924, and his M.S. at the University of Idaho in 1927. He took the General Electric Company's test course and advanced engineering course in 1924–1925. He then taught in the mechanical engineering department of the University of Idaho four years, and spent three summers in the engineering department of the Washington Water Power Company of Spokane, Washington. After five years teaching in mechanical engineering at the University of North Carolina, he was appointed in 1934 to his present position. Among his published papers are: "Heat Flow From Underground Power Cables," in the 1929 A.I.E.E. Transactions, "The Response of Thermocouples," in the November, 1931, and "The Measurement of Surface Temperatures," in the August, 1932, issues of *Mechanical Engineering*.

[2] "Pulsation of Air Flow From Fans and Its Effect on Test Procedure," by H. F. Hagen, A.S.M.E. Trans., vol. 55, paper FSP-55-7, 1933.

Contributed by Power Test Code Committee No. 10 on Centrifugal and Turbo-Compressors and Blowers for presentation at the Annual Meeting, New York, N. Y., December 3 to 7, 1934, of The American Society of Mechanical Engineers.

Discussion of this paper should be addressed to the Secretary, A.S.M.E., 29 West 39th Street, New York, N. Y., and will be accepted for publication until January 10, 1935, in a later issue of Transactions.

Note: Statements and opinions advanced in papers are to be understood as individual expressions of their authors, and not those of the Society.

pipes is increased in this same ratio. Since this much pulsation is not at all uncommon in practise, and lesser amounts very common, it is highly desirable to be able to determine the average velocity accurately when testing, and to be able to determine the ratio v_{av}/v_{eff} to be able to compare the effectiveness of different blower, fan, and propeller designs in eliminating pulsation.

Method of Testing

Obviously, any instrument that is to measure the true average velocity when the flow is pulsating must be actuated by some

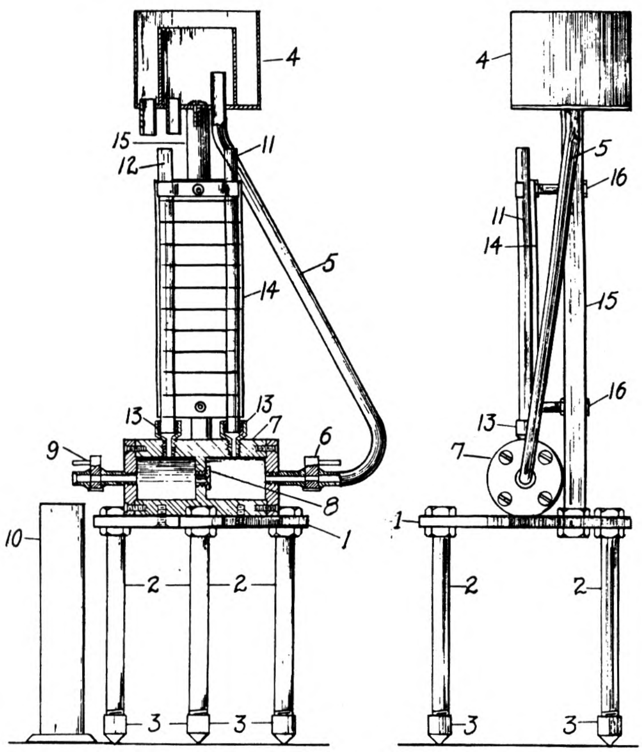

Fig. 1 Fluid-Velocity Meter

physical manifestation that is lineally related to the air velocity at any instant. The instrument[3] shown in Fig. 1 is one that meets this requirement. The velocity head or pressure of the air varies as the square of the air velocity, and the rate of flow of water through an orifice varies as the square root of the applied head, provided the coefficient of discharge is constant. In this instrument the velocity head of the air is used to cause water to flow through an orifice. The result is that at any instant the rate of flow of water through the orifice is directly proportional to the air velocity at that instant. If the water flowing through the orifice is collected for a time and the average rate of flow determined, the true average air velocity can be found, regardless of the amount of pulsation.

Water is brought from the constant head supply tank (4), through the tube (5), and the inlet valve (6), to the high-pressure side of the working chamber (7). After passing through the orifice (8), the water reaches the low-pressure side of the working chamber, leaves through the discharge valve (9), and is collected for measurement in the graduate (10). The water rises in the glass tubes (11), and (12), that communicate with the high-pressure and low-pressure sides of the working chamber through the stuffing glands (13). The height of water in the glasses (11), and (12) can be measured by the scale (14).

When the meter is in operation, the velocity head of the air being measured is brought from the pitot tube or nozzle and connected to tubes (11) and (12) in such a manner that the higher pressure is applied to tube (11). The rate of flow of water to and from the chamber is regulated by valves (6) and (9) until the height of the water is the same in columns (11) and (12). In such a condition, the only head causing water to flow through the orifice is the velocity head of the air being studied. Since the rate of flow of water through the orifice at any instant is directly proportional to the air velocity being measured, if the average rate of flow of water through the orifice is determined by measuring the discharge, the true average velocity of the air can be determined from the calibration curve of the meter, irrespective of the amount of pulsation of this velocity.

The meter is calibrated by regulating the inlet and discharge valves until the water in column (11) is some amount higher than in (12), when both are open to the atmosphere. Since the effective and average velocities of the air are identical with no pulsation, the resulting rate of flow of water through the orifice corresponds to a steady average velocity of air that would give

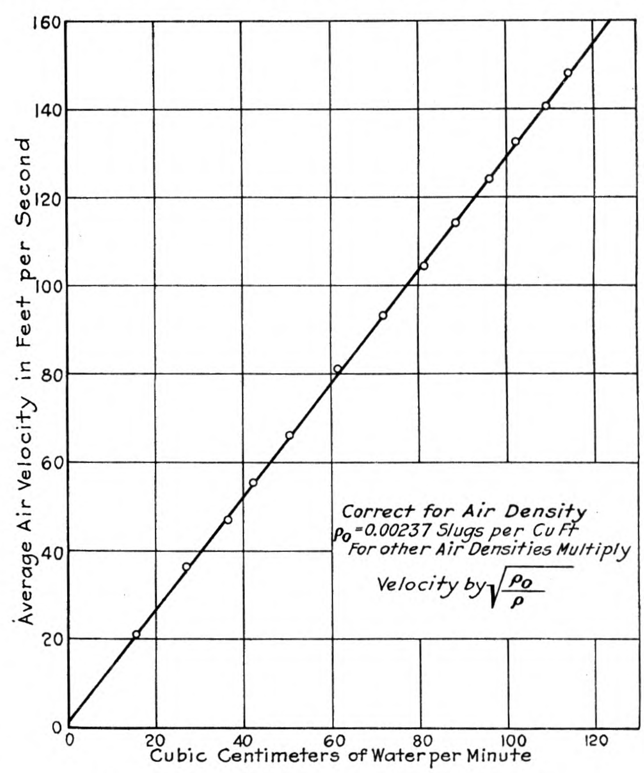

Fig. 2 Calibration of Fluid-Velocity Meter

a velocity head equal to the difference between columns (11) and (12).

Such a calibration curve for this instrument is shown in Fig. 2. The fact that this curve fails to pass exactly through the origin makes necessary a consideration of the characteristics of orifices under low heads. The usual form of the equation of discharge, $Q = CA\sqrt{2gh}$, must be modified to the form, $Q = CA\sqrt{2g(h - h')}$ for low heads, where C is the coefficient of discharge and h' is the head necessary to overcome surface tension and start the flow.

The first orifice built was really a hole in brass, 0.05 in. in diameter and 0.10 in. long with rounded entrance and discharge.

[3] A patent has been applied for by the author.

When it was first constructed, the calibration curve passed exactly through the origin. However, after a few weeks' use it was discovered that the curve had shifted and passed through the point of 9 ft per sec air velocity at zero cc of water per minute, and showed an increase in discharge at higher air velocities.

It was finally observed that freshly machined brass is not really wetted by water, and no surface-tension effect is present. After being used a while the chlorine or manganese in the water covered the surface of the brass with a black film which caused the water to wet the brass with a corresponding evidence of surface-tension effect at low heads, and a decreased jet contraction at higher heads.

After this experience, the orifice was made sharp edged to cut down the wetted surface, and was allowed to be in the water some time before calibration. The result was an orifice that holds its calibration and whose calibration curve comes sufficiently close to passing through the origin for all practical purposes.

A Check on the Test Method

The logical method of verifying the theory of this method of measuring pulsating air velocity is to try it out on a velocity wave of known characteristics and compare the test results with the theoretical ones. To accomplish this a jet of air was blown through a small nozzle against the outer edge of the cut-out disk shown in Fig. 3*a* and a pitot tube was located in the path of the jet close behind the disk. When this disk was rotated, a square wave of air velocity was impressed on the pitot tube.

A complication arose, however, because the air was furnished by a blower that caused the flow of the primary air jet to be pulsating rather than steady, giving a wave form as shown in Fig. 3(*b*). During most of the test, the disk was rotated at 240 rpm, giving a primary frequency of 8 cycles per second. The blower was a high-pressure exhauster having 6 vanes on its rotor, which, when running at 2100 rpm, gave a superimposed frequency of 210 cycles per second. This gave 26.25 cycles of high-frequency pulsation for one cycle of primary frequency.

The impact tube of the pitot tube was connected to tube (11) of the instrument, and the static tube was connected to tube (12). By using Y-connections, this same velocity head was put on an inclined manometer. With the disk removed and the blower at 2100 rpm, the manometer head gave an effective velocity for the primary jet of $v_{eff} = 121.5$ ft per sec. The cc per minute of water from the instrument when converted from the calibration curve gave an average velocity $v_{av} = 118.0$ ft per sec. This gave a ratio $v_{av}/v_{eff} = 0.972$, which when used in Equation [2], gave a primary pulsation $v_0/v_{av} = 0.32$.

With the blower and pitot tube as before and the disk rotating at 240 rpm, the effective velocity V_{eff} became 82.5 ft per sec, and the average value V_{av} was 57.5 ft per sec. This corresponded for a $V_{av}/V_{eff} = 0.70$. The theoretical value of V_{av}/v_{av} should of course be 0.50 and was by test equal to $\frac{57.5}{118} = 0.495$. The theoretical value of V_{eff} for the wave of Fig. 3(*b*)

$$V_{eff} = \sqrt{\frac{\int_0^{\pi} (v_{av} + v_0 \sin n\theta)^2 d\theta}{2\pi}} \qquad [3]$$

Or, assuming n an integer which may or may not be realized

$$V_{eff} = \sqrt{\frac{v_{av}^2}{2} + \frac{v_0^2}{4}} \qquad [4]$$

but, since

$$V_{av} = \frac{v_{av}}{2}$$

$$V_{av}/V_{eff} = \frac{1}{\sqrt{2 + (v_0/v_{av})^2}} \qquad [5]$$

Substituting the value of $v_0/v_{ax} = 0.32$ previously found for the primary jet, gives $V_{av}/V_{eff} = 0.69$. Thus, the theoretical $V_{av}/v_{av} = 0.5$ as compared with a test value of 0.495, and a theoretical $V_{av}/V_{eff} = 0.69$ as against a test value of 0.70 gives a very satisfactory check for this method of testing pulsating flow. With the disk going at a speed of 1200 rpm or 40 cycles per second, a test value of $V_{av}/V_{eff} = 0.704$ was found. These are but samples of many similar checks on the instrument.

A possible source of error in this instrument is worthy of mention here. In an earlier instrument, the tubes (11) and (12) were quite large compared with the rubber tubing that came

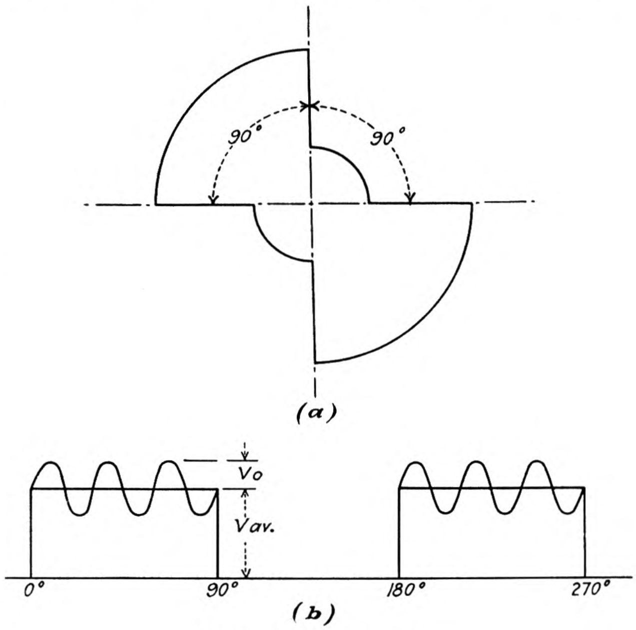

Fig. 3 Pulsating Flow
(*a*, Disk for generating pulsating flow; *b*, Velocity-wave form.)

from the pitot tube, and it was found that the length of rubber tubing materially affected the result obtained. When the inside bores of the glass tubes, of the rubber tubes, and of the passages of the pitot tube were made essentially the same, it was found that a variation in rubber-tube length from a few inches to several feet made no detectable difference in the results. It was also found that a pitot tube with a greater static hole area than usually used, is desirable for the same reason. Most of the static pressure damping[2] and the error due to rubber tubing seems to be effectively eliminated by keeping the air-passage area constant all the way from the pitot tube to the water surface of the instrument.

The accuracy of this method of measuring pulsating air velocities is independent of the frequency except for very high and very low frequencies. Suppose, for example, that the total length of air path from the pitot tube to the instrument is two feet. The critical frequency of such a tube length would be 280 cycles per second, which would correspond to a blower speed of 2800 rpm for a six-impeller rotor. This upper frequency limit can be raised by coupling the whole system shorter.

The lower frequency limit for accuracy seems to be about 5 cycles per second for the instrument used. Below that frequency the water surface is in such violent agitation as to make the leveling of the two water columns difficult. As the frequency is increased above this value the water quiets down, until at 10 or 12 cycles per second the very surface of the water is all that has any motion. This lower limit of frequency can doubtless be lowered by the correct proportioning of the tubes and working chamber together with the sizes of valve openings and of the orifice.

Pulsation of Air Blowers

The work of H. F. Hagen[2] established the fact that the pulsation in the discharge of air blowers assumes serious proportions. It not only complicates the test procedure, but also may cause entirely erroneous ideas of performance. To illustrate the foregoing method of testing with pulsating flow, a high-

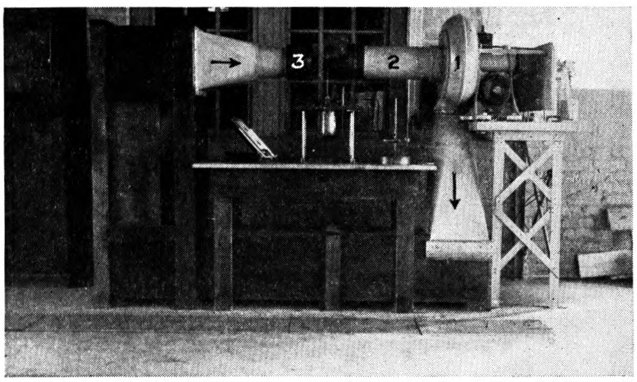

Fig. 4 Blower and Wind Tunnel

pressure blower with a 6-vane rotor was tested for pulsation under various conditions of operation. This blower is normally part of a 6-inch, open-throat wind tunnel shown in Fig. 4.

The blower was first tested when removed from the tunnel and discharging directly into the atmosphere. With a pitot tube placed in the discharge, the average velocity, v_{av}, and the effective velocity, v_{eff}, were determined as previously explained at speeds ranging from 800 to 2700 rpm.

The blower was next placed back in the tunnel and the air was blown around the tunnel and through the discharge nozzle (3) with the intake pipe (2) removed. The average and effective velocities at the discharge nozzle were obtained for the same range of speeds. Following this, the 6-inch discharge nozzle was replaced by a 2-inch nozzle and the tests repeated.

The resulting curves of (v_{av}/v_{eff}) are shown plotted against blower speed in Fig. 5(*a*), and values of (v_0/v_{av}) calculated from Equation [2] are shown in Fig. 5(*b*). It is worthy of note that at 800 rpm the pulsation (v_0/v_{av}) of the blower with a free discharge is almost unity, which represents a flow that practically ceases between impulses. For such a condition of flow a pitot-tube traverse would credit the blower with 21 per cent too much air delivered, and the kinetic energy contained by the air is 47 per cent greater than would be the case with steady flow.

A comparison of the curves for the blower alone and for the blower with the tunnel and nozzle illustrates the effect of a receiver and nozzle on damping out pulsation. It is possible to predict accurately[4] the curve with the tunnel and nozzle from the curve of the blower alone. The amount of damping produced by a receiver and nozzle increases with frequency, receiver volume, and quantity of discharge and increases as the discharge nozzle area is decreased.

While the foregoing tests are for only one machine, they seem to illustrate the need, not only of considering pulsation when testing, but also of emphasizing the desirability of studying the performance of existing designs in order to determine the types that are free from excessive pulsation.

Pulsation of Engine Intakes

Some very ingenious methods exist for damping out the pulsation in the intake air of internal-combustion engines sufficiently to obtain reliable air determinations, but here again, very little is known about the actual amount of pulsation present under different conditions.

The first engine tested was a single-cylinder, four-stroke-cycle, gasoline engine with a displacement of 24.9 cu in. and a rated speed of 1000 rpm. A rounded entrance nozzle, 0.383 in. in throat diameter was placed in the air inlet to the carburetor. The velocity-head draw-down given by a static tube in the nozzle throat was connected to tube (12) of the instrument, Fig. 1, and also to an inclined manometer. The average and effective air velocities through the nozzle were determined for several operating conditions.

For the next set of tests, the air was drawn by the engine through the same nozzle and through an intermediate tank

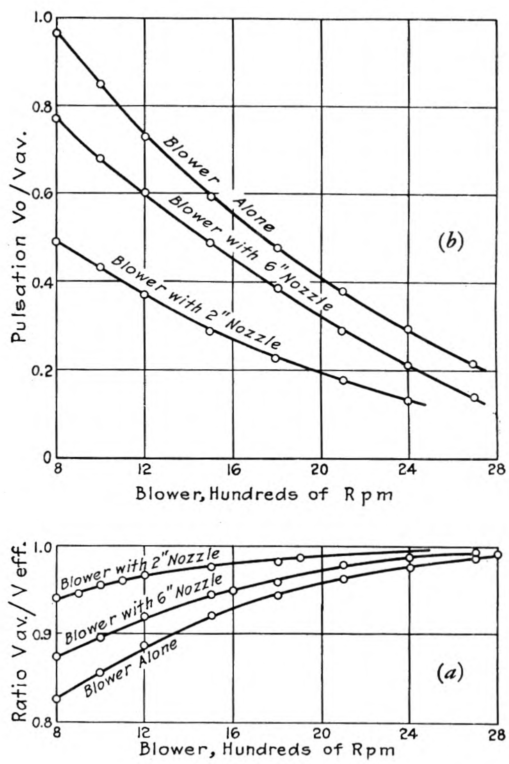

Fig. 5 Blower Pulsation
(a, V_{av}/V_{eff} vs. rpm; b V_0/V_{av} vs. rpm.)

having a volume 278 times the engine displacement. The pulsation of the air flowing into the tank was determined as before.

The results are shown in Fig. 6, along with the theoretical pulsation. The theoretical value of $v_{av}/v_{eff} = 0.45$ was calculated by assuming the air entering the cylinder to be a true loop of a sine curve during the suction stroke, and the air flow then remaining zero until the next suction stroke.

The difference between the theoretical value and the (v_{av}/v_{eff}) for the air with a direct intake shows how much pulsation was damped out in the intake or induction system of the engine. The amount of damping produced by the receiver tank and nozzle is also considerable, but even then the air measurement

[4] Not included here because the mathematics are somewhat tedious and involved.

to the engine, if made in the usual manner, would be about 10 per cent in error.

A standard four-cylinder automobile engine was tested next by placing a nozzle in the carburetor intake and measuring the average and effective velocities. Over a wide range of operating conditions, the results stayed quite close to an average value of v_{av}/v_{eff} = 0.927. The theoretical value found by assuming sine loops for the intake strokes of such a four-cylinder, four-stroke cycle engine is v_{av}/v_{eff} = 0.90. This represents much less damping in the induction system than in the case of the single-cylinder engine, which is typical of all attempts to damp pulsation. When large amounts of pulsation are present, it is relatively easy to damp out a greater part of it, but as the pulsation decreases, it becomes correspondingly more difficult to decrease the amount of variation in the flow.

This is again illustrated by the pulsation of a standard six-cylinder automobile engine with a nozzle in the carburetor intake. Theoretical calculations from intake loops that overlap 60 degrees give v_{av}/v_{eff} = 0.994. Careful tests over a wide range of conditions gave experimental values ranging from 0.995 to 0.997 for v_{av}/v_{eff}.

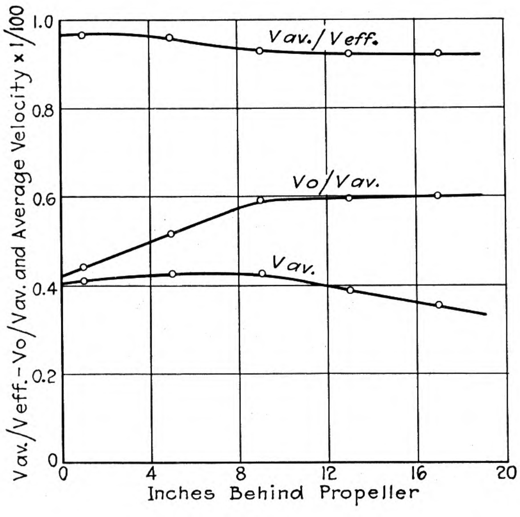

FIG. 7 PULSATION BEHIND A PROPELLER
(Pitot tube at 9-in. radius with a 30-in. diameter propeller.)

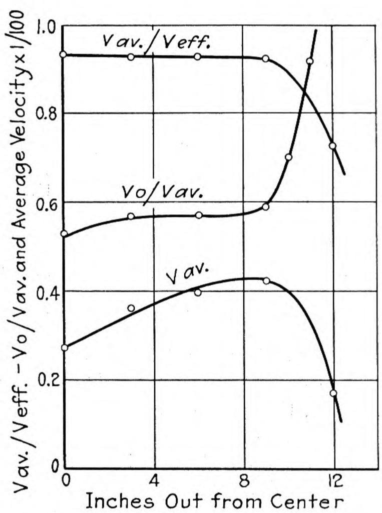

FIG. 8 PULSATION ACROSS A PROPELLER
(Pitot tube 9 in. behind 30-in. diameter propeller.)

PULSATION OF PROPELLERS

An airplane propeller creates a thrust by increasing the momentum of the air that it handles. This increase in velocity represents kinetic energy that is given to the air by the propeller to obtain a thrust. The thrust depends on the average velocity, but the kinetic energy given to the air stream depends on the effective velocity. Any pulsation that the propeller creates represents an increase in propeller power over and above that necessary if the flow were steady.

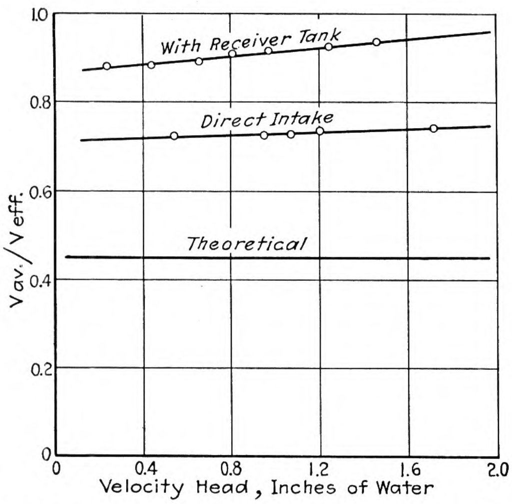

FIG. 6 INTAKE PULSATION FOR SINGLE-CYLINDER ENGINE

All propeller theory tacitly assumes no pulsation, but it is rather improbable that anything as intermittent as the passage of a narrow propeller blade can possibly produce steady flow.

The test propeller used was a 30-in. diameter, Navy Type, wooden propeller, with a pitch ratio of 0.7, the specifications for which are given under propeller L, p. 161 of the 1926 Report of the National Advisory Committee for Aeronautics. This propeller was turned at its rated speed of 1700 rpm by a $^1/_2$-hp, d-c motor. No wind tunnel large enough to mount the propeller was available, so only static tests could be run.

According to the momentum theory, part of the increase in velocity is accomplished by inflow in front of the propeller, the propeller then builds up the pressure of the air, and this pressure energy is converted into velocity behind the propeller. In the light of this, a change in the amount of pulsation would be expected as the pitot tube is moved further back from the plane of the propeller.

The first run was made with the pitot tube out at a radius of 9 in. and at varying distances behind the propeller. Curves of v_{av}, v_{av}/v_{eff}, and v_0/v_{av} are shown in Fig. 7 for a propeller speed of 1700 rpm. This curve shows a slight increase in average velocity, v_{av}, up to a point 9 in. behind the propeller, where it begins to decrease uniformly. It should be remembered, however, that in the first 9 inches, the viscous drag about the jet is also tending to decrease v_{av} just as it does after the 9-in. point is reached. It follows, then, that the actual tests only show a part of the increase in v_{av} that would take place under idealized conditions.

The pulsation v_0/v_{av} increases up to this same point and then remains constant after the pulsating pressure energy has all been converted to velocity. Values of v_{av}/v_{eff} = 0.92 and v_0/v_{av} = 0.60 show that a very appreciable amount of pulsation is present and should be considered in the theory.

Fig. 8 shows the same tests with the pitot tube 9 in. back of the propeller and at different radii. It shows that the amount of pulsation is fairly constant until the edge of the jet is reached, where the flow becomes violently pulsating in nature. In this connection, it was observed that when an air disturbance in the test room caused the propeller tips to set up a violent flutter and noise, with the pitot tube near the tip of the propeller, the average velocity practically disappeared even though the manometer continued to indicate a fair value of effective velocity. There appeared to be more than an incidental connection between the amount of pulsation and the amount of noise.

As previously pointed out, this pulsation in the air flow represents an increased propeller loss above that necessary with steady flow. For example, with an airplane traveling with a velocity V, suppose the propeller gives an increase in air velocity of $v_{av} + v_0 \sin \omega t$. The average velocity in the slip stream is given by $V + v_{av}$, and the effective velocity turns out to be

$$V_{eff} = \sqrt{(V + v_{av})^2 + \frac{1}{2} v_0^2} \qquad [6]$$

By modifying the classical momentum theory of propellers to include pulsation, it can be shown that the ratio of the ideal efficiency with pulsation to the ideal efficiency with steady flow is given by,

$$\frac{E_p}{E} = \frac{V + \frac{1}{2} v_{av}}{V + v_{av}\left(\frac{1}{2} + \frac{1}{4}\frac{v_0^2}{v_{av}^2}\right)} \qquad [7]$$

When the velocity of the airplane is very large compared with the slip-stream increase, this efficiency ratio, of course, approaches unity. In the intermediate range where the ratio of $\frac{v_{av}}{V}$ is, say 0.2, this ratio is 0.985, if the previously determined test value of $v_0/v_{av} = 0.60$ is used. At very low velocities, such as at take-off, the velocity V approaches zero and the efficiency ratio becomes 0.85.

Thus, the effect of pulsation on a propeller is a decrease in efficiency of about one per cent at high velocities up to a decrease of 15 per cent at take-off. Stated another way, for a given power input to a propeller, the presence of unavoidable pulsation decreases the static thrust 15 per cent below the value that could be attained with steady flow.

Conclusions

With a simple portable instrument available for studying pulsating flow, it is possible to find out much more about fluid flow than has previously been possible, and there is a wide field that needs investigation.

Considerable work seems desirable on the determination of the rate of decay of pulsation along ducts and pipes. As mentioned before, pulsation causes a serious increase in friction loss in pipes above that which is necessary with steady flow. Plans are under way to adapt the present instrument to the study of the pulsation of flowing water and other fluids. It seems reasonable to believe that liquid pumps are just as liable to create pulsating flow as are air blowers.

The decrease in pulsation between a four-cylinder engine and a six-cylinder one seems to suggest a logical method for decreasing pulsation. In a six-cylinder engine, the suctions overlap, and a great reduction in pulsation results. An air blower with two independent rotors drawing air from separate intakes, but having the rotors staggered and delivering air to a common discharge seems to be a logical method of obtaining overlapping discharges free from pulsation.

It is rather difficult to realize that air flow, that is usually considered steady, is actually badly pulsating. The physical sense of feel can detect pulsation up to a frequency of as high as 60 cycles a second. Above this frequency, air flow that is actually discontinuous seems perfectly steady. In any case, however, the determination of the true average and effective velocities as previously described, not only detects the presence of pulsation, but also tells quantitatively how much pulsation is present.