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O R I G I N A L P A P E R S

INFRASOUND IN THE OCCUPATIONAL AND GENERAL ENVIRONMENT: A THREE-ELEMENT MICROPHONE MEASURING METHOD FOR LOCATING DISTANT SOURCES OF INFRASOUND

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Abstract. A short review of infrasound sources and effects on humans is presented. Polish and international standards concerning the measuring techniques of infrasound in the occupational environment are described. A practical application of a three-element microphone measuring method for locating distant sources of infrasound is presented.

INTRODUCTION

Infrasound is a subacoustic vibration in the frequency range from 0.1 to 20 Hz. Owing to its long wavelength and low attenuation by classical acoustic absorbents and the atmosphere, infrasound can propagate over very long distances. Moreover, there are two acoustic channels in the stratosphere, one at altitudes between 40 and 50 km and the other – between 100 and 110 km. Their placement is connected with the temperature gradient in the atmosphere. If infrasound wave reaches the acoustic channel it can propagate over a long distance (12).

Infrasound which occurs in the environment may be of a natural or artificial origin, especially an industrial one. The examples of natural sources are winds, storms, waterfalls, earthquakes and other natural phenomena. The most famous ones include the explosion of the Krakataoa volcano (1883), the fall of the Siberian meteorite (1904), the earthquake in Alaska (1964) and the explosion of the St. Helens volcano (1980) (21).

The most essential artificial sources of infrasonic waves are associated with the atmospheric nuclear explosions which occurred frequently in the 1950s and 1960s (21). On the other hand, the most common sources are the means of transport e.g. passenger cars, lorries, ships, trains, helicopters and jet planes (11,16).

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Infrasound is also generated by industrial machinery: jet pumps, piston compressors, ventillators, blast furnace blowers, boilers, stationary Diesel engines, slow-moving equipment etc. (11,12).

It has been commonly assumed that infrasound is inaudible. However, this is not true any more. Perception of infrasound is contingent on hearing and vibrations. The vibrations capable of inducing perception will occur only at relatively high pressure levels, 20 to 40 dB above the thresholds of auditory perception.

The threshold of hearing rises rapidly as the frequency drops, i.e. from approx. 65 dB at 32 Hz to 95 dB at 16 Hz, 100 dB at 3 Hz, and 140 dB at 1 Hz (12). Moreover, when infrasound becomes loud, it can be annoying. The annoyance associated with exposure to an audible infrasound has been the subject of a number of laboratory experiments. For example, contours of equal annoyance were determined for pure tones in the frequency range from 4.0 to 31.5 Hz. The curves show a narrowing of the dynamic range of the ear at low frequencies. The same pattern is seen for equal loudness curves, so the annoyance of infrasound is closely related to the loudness sensation (14,19).

Moreover, infrasound affects the human organism, especially the hormonal and the central nervous sytems. The high acoustic pressure levels of infrasound may damage the semicircular canals (organ of balance) and the hearing organ and can excite resonant oscillations of a frequency ranging from 0.1 to 25.0 Hz in particular parts and organs of the human body (e.g. abdomen, chest and throat) (3,11).

An American space research project has indicated that the maximum permissible short-term exposure to infrasound should approximate 140÷150 dB (11).

This paper presents:

– Polish and international standards concerning the measuring techniques of infrasound in the occupational environment (7,8,18);

– a practical application of a three-element microphone method for locating distant sources of infrasound described in the literature (13,20).

INFRASOUND MEASURING METHODS

Generally, in order to determine the acoustic field, the acoustic pressure or acoustic intensity levels can be measured using:

– the Fast Fourier Transformation (FFT) analyzer or real-time frequency analyzer with band-pass fractile (1/1, 1/3 or 1/2) octave filters[1];

– frequency-weighting networks (e.g. A, C, G) (4,7,8).

The acoustic pressure is measured with the use of a microphone. Since pressure is a scalar quantity, a pressure transducer should have an omnidirectional characteristic. The acoustic pressure is the most extensively measured acoustic parameter, especially, when trying to quantify human response to noise.

Acoustic intensity is a vector quantity which describes the amount and direction of net flow of acoustic energy at a given position. It can be shown that in a medium without flow, the intensity vector equals the time-averaged product of the instant-

[1] The FFT analyzer is useful for detecting narrow band, tonal and harmonic componets of noise, but the frequency display does not provide as good direct correlation with subjective impressions as the second type of frequency analyzer. This is because human frequency resolution tends to be logarithmically spaced across the frequency range, whereas the frequency resolution of the FFT analyzer is linearly spaced, across the frequency range (4).

aneous pressure (p(t)) and the corresponding instantaneous particle velocity (u(t)) at the same position (1):

$$I = \overline{p(t)\,u(t)} \quad (1)$$

Thus in order to measure the sound intensity it is necessary to measure both the instanteneous pressure and velocity. In practice the sound pressure can be obtained very easily, using a condensor microphone. On the other hand, a direct measurement of the particle velocity is extremely difficult. In order to attain it, a directional hot-wire anemometer or ultrasonic transducer ought to be used. However, it can be shown, that a sufficiently accurate estimate of the instantaneous particle velocity can be calculated from the pressure gradient obtained from two closely-spaced sound pressure measurements (1,5,10).

Therefore, today the most popular practical sound intensity probe consists of two face-to-face, closely-spaced pressure microphones which measure both the acoustic pressure and pressure gradient between the microphones. However, with a two-microphone probe we cannot measure the vector; we measure the component in one direction only, along the probe axis. The commercial use of the two-microphone intensity probe began in 1977.

The most popular applications of acoustic intensity measurements include:

— noise source location or detection of "acoustic leaks";

— in-situ sound power determination (there are no restrictions upon the sound field, which implies that the measurements can be performed in any room);

— in-situ measurements of sound absorption coefficients (6).

Unfortunately, there are measurement limitations which make that the two--microphone intensity probe be used mainly in the audible frequency range (20 – 10000 Hz) (5). Therefore, it is the acoustic pressure that is usually measured in the infrasound field.

Polish occupational hygiene standards introduce classification of noise in relation to its frequency range. Accordingly, unpleasant and unwanted infrasound (2 – 16 Hz) and low-frequency audible noise (under 50 Hz) are called the "infrasonic noise". The Polish Standard PN-86/N-01338 specifies admissible values of acoustic pressure levels of infrasonic noise (2 – 50 Hz) at workplaces as well as recommended measuring techniques (Table 1) (18).

Table 1. Infrasonic noise: admissible acoustic pressure levels at workplaces (exposure time — 8 hours) specified in the Polish Standard PN-86/N-01338

Admissible acoustic pressure levels (dB)	Octave bands with the middle frequencies (Hz)			
	4	8[a]	16	31.5
— for health protection at all workplaces;	110	**110**	**110**	**105**
— ensuring proper conditions for performing basic functions in observational dispatcher cabins, remote control on premises for precise works;	90	90	90	85
— in premises for administration, theoretical works, data handling and in design offices.	85	85	85	80

[a] Bolt figures — a limitation introduced in the Ordinance of the Minister of Labour and Social Policy, of December 23, 1994 (15).

The International Standard ISO/DIS 7196.2 recommends the use of G frequency-weighting network in order to describe infrasound (1–20 Hz) (7). G-weighting network characteristic corresponds well with the mentioned above subjective annoyance rating (14). There is no information about permissible levels.

On the other hand, the International Standard ISO/DIS 9612.2 recommends to perform measurements using 1/3 octave band filters (in the frequency range 2–20 Hz) or the G-weighting network (9).

As yet in Poland there has been no instruction concerning the measuring techniques and permissible levels in the general environment.

PRINCIPLES OF A THREE-ELEMENT MICROPHONE METHOD

This paper presents a three-element microphone method for determining acoustic pressure, and direction of wave vector k (direction of wave's propagation) in the infrasound field (13,17,20).

The main part of the measuring system is a probe which consists of three microphones placed at corners of a right-angled isosceles triangle ABC (A = AC = a). Such a system is at its optimum when a = 1/2 λ (λ-wavelength).

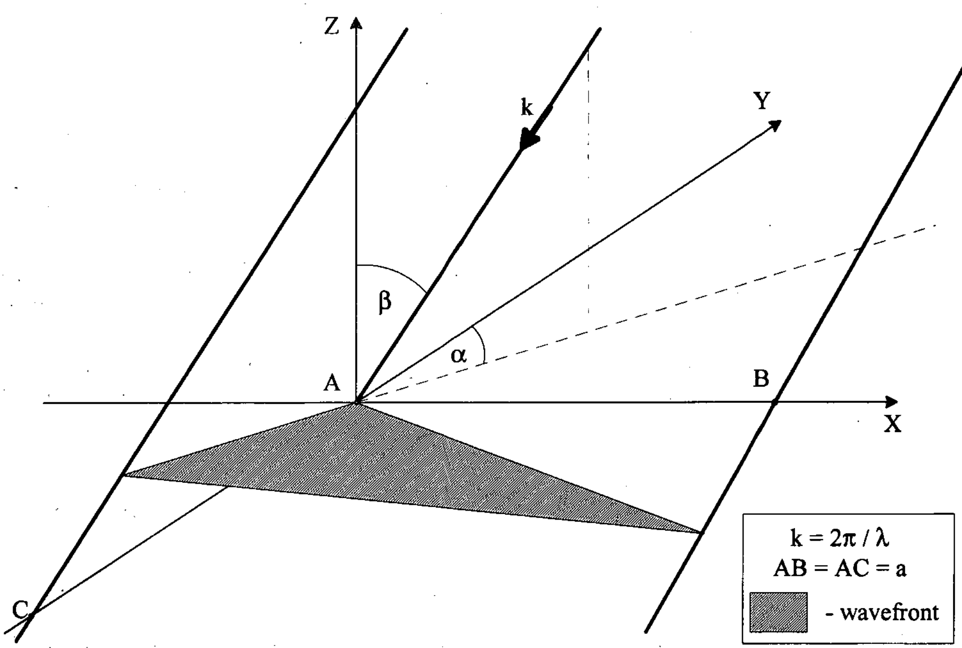

Fig. 1. A plane wave in the cartesian coordinate system XYZ.

If a plane wave arrives at angles α and β, as seen in Fig. 1, the phase differences between microphone pairs A-B ($\Delta\phi_{A-B}$) and A-C ($\Delta\phi_{A-C}$) can be expressed as (2), (3) (Fig. 2):

$$\Delta\phi_{A-B} = ka \sin\alpha \cos\beta; \tag{2}$$

$$\Delta\phi_{A-C} = -ka \cos\alpha \sin\beta \tag{3}$$

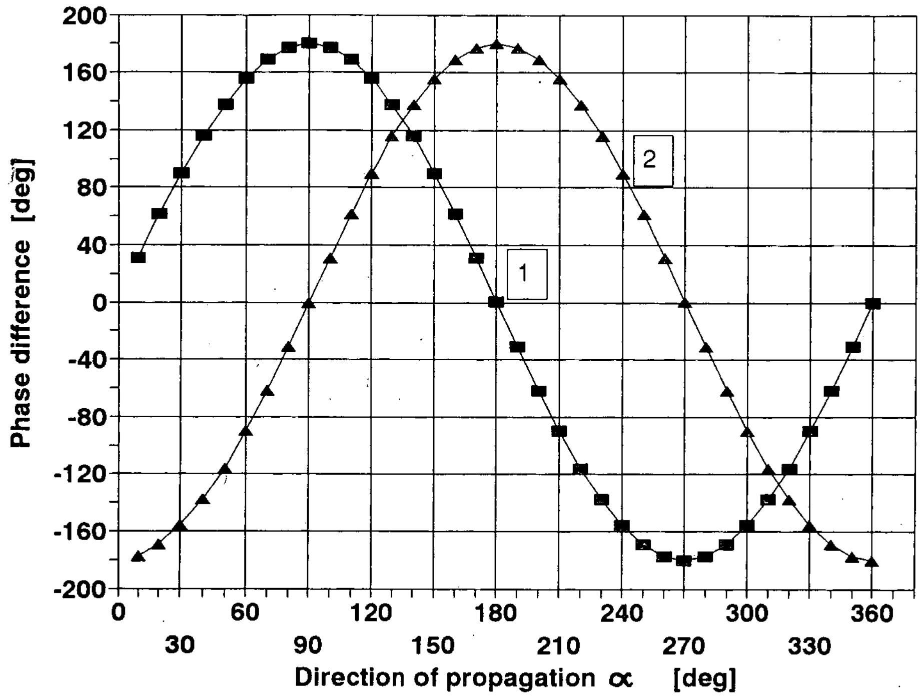

Fig. 2. Calculated phase variations with α ($\beta = 90°$, a 1/2 λ); 1 — $\Delta\phi_{A-B}$, 2 — $\Delta\phi_{A-C}$.

Combining equations (2) and (3) we obtain the following formulas for α and β (4), (5):

$$\operatorname{tg}\alpha = -\frac{\Delta\phi_{A-B}}{\Delta\phi_{A-C}}; \tag{4}$$

$$\sin^2\beta = \frac{(\Delta\phi^2{}_{A-B} + \Delta\phi^2{}_{A-C})}{(ka)^2}. \tag{5}$$

They allow only an accurate determination of the angle α, which is sufficient for locating the source of infrasound. In order to attain this, the measurements ought to be performed at two different positions of the probe.

It is worth noting that when the pair of microphones A-B is oriented in the north to south direction and the pair A-C east to west, than the angle α is an azimuth of the direction of the wave's arrival.

When a three-microphone probe is to be used for determining the infrasonic noise (2—50 Hz) the optimum distance required between the microphones ranges from 3.4—85.0 m. Using the tape measure and flagpoles this distance can be measured with accuracy of 0.01—0.10 m; the right angle can be set with accuracy of $\pm 6'$, using square while by applying a levelling instrument one can position the microphones with accuracy of ± 0.001 m. The placement of microphones with the accuracies specified above makes the uncertainity of the angle α approximate the value of $\pm 3.0°$.

MEASURING SYSTEM

A block diagram of the arranged measuring system of a three-element microphone method is presented in Fig. 3.

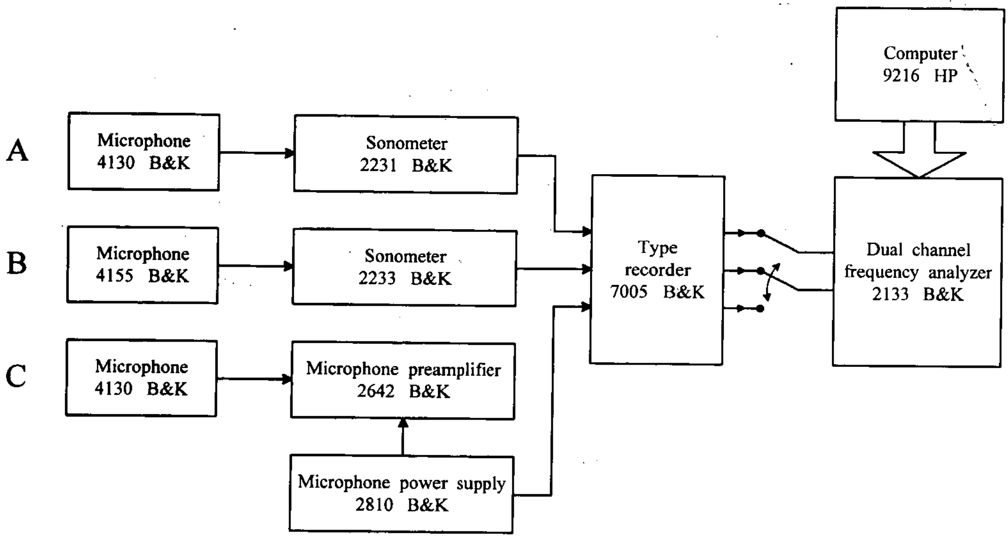

Fig. 3. A block diagram of measuring system; (B&K-Bruel and Kjaer-Denmark, HP-Hewlett-Packard--USA).

The acoustic pressure levels in 1/12 octave-bands are measured as autospectra of microphone A(S_{AA}), B(S_{BB}) and C(S_{CC}). Furthermore, the phase differences $\Delta\phi_{A-B}$ and $\Delta\phi_{A-C}$ are determined on the ground of cross spectra of the pairs of microphones A-B (S_A) and A-C (S_{AC}), respectively (9).

The optimum measuring system should consist of 3 microphones, preamplifiers, amplifiers, channels of tape recorder with identical phase response, and have a flat amplitude response as a function of the frequency in the range considered (2 – 50 Hz). Thus, in order to perform the correction of phase-mismatching of the chains A, B, C of the measuring system, the ratios of transfer functions H_A/H_B and H_A/H_C were determined using special calibration procedure in the plane wave field (in a standing-wave tube) (6).

LABORATORY EXPERIMENTS USING A THREE-ELEMENT MICROPHONE METHOD

In the natural environment infrasound propagates usually as spheric waves; however, the formulas for calculating the angle α have been developed for plane waves. Generally, an error of measurement for the angle α which results from the measuring principle for a spheric wave of 0 order within the distance of $r \geqslant 10\lambda$ is not higher than $\pm 10.0^0$ (Fig. 4).[1]

[1] For β from the range $10-170^0$.

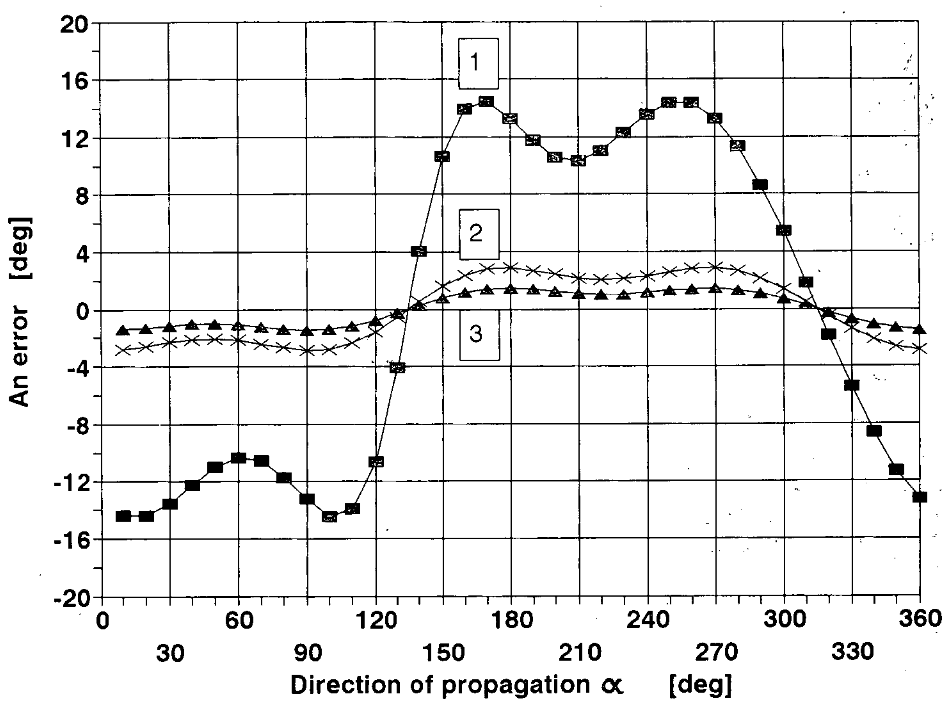

Fig. 4. Calculated error of the measurement of the angle α — a spheric wave of 0 order (a point source of the acoustic wave is placed in the plane XY); 1 — r/λ = 1. 2 — r/λ = 5. 3 — r/λ = 10 (r — a distance from the source).

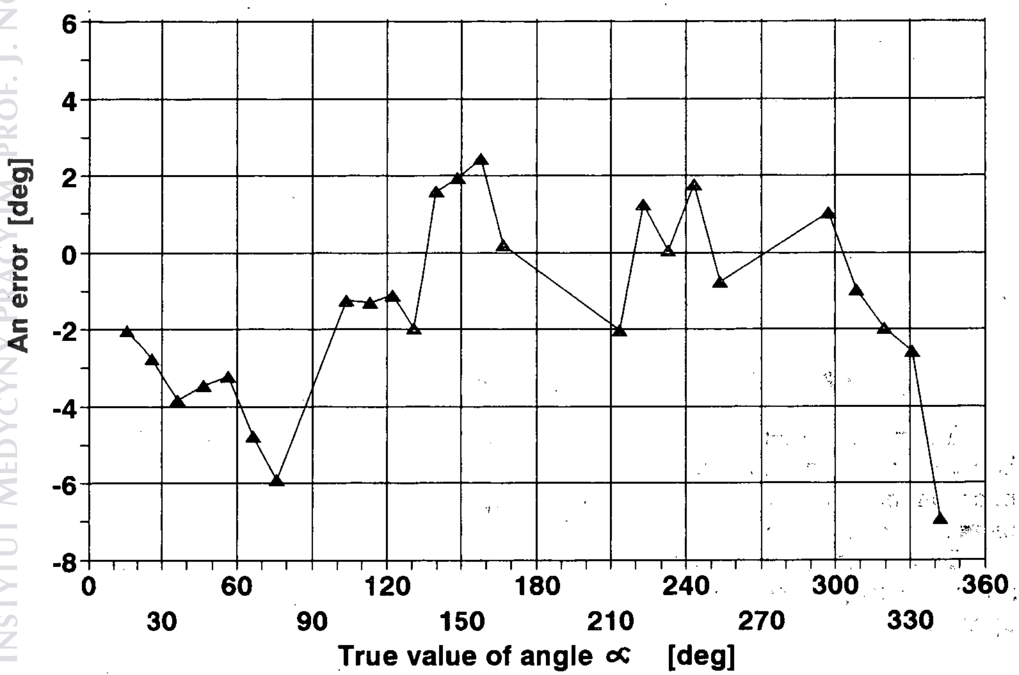

Fig. 5. An anechoic chamber — an error of the measurement of the angle α.

To check the usefulness of this method for determining the direction of wave vector, laboratory experiments in an anechoic chamber were made with a model of the probe adjusted to a frequency of 170 Hz[2]. The microphones and preamplifiers were mounted on triangular support, the centre of which was fixed horizontally on a tripod. This arrangement was stable and enabled controlled rotation of the array.

The results obtained using a loudspeaker generating pure tone, revealed that the directional resolution of the probe approximated $\pm 2.2^0$ (mean value) (Fig. 5). These findings confirm the usefulness of this method for determining the direction of wave vector of acoustic wave in the far field ($r \geqslant 2.5\ \lambda$).

PRACTICAL APPLICATION OF A THREE-ELEMENT MICROPHONE METHOD

An example of the practical application of the described method are the measurements made around a power plant. The plant is located about 10 km from a small town and is surrounded by woodland. In the wide-band noise spectrum measured around the plant, the tone components in the frequency range of $16.3 \div 30.7$ Hz were found (Fig. 6).

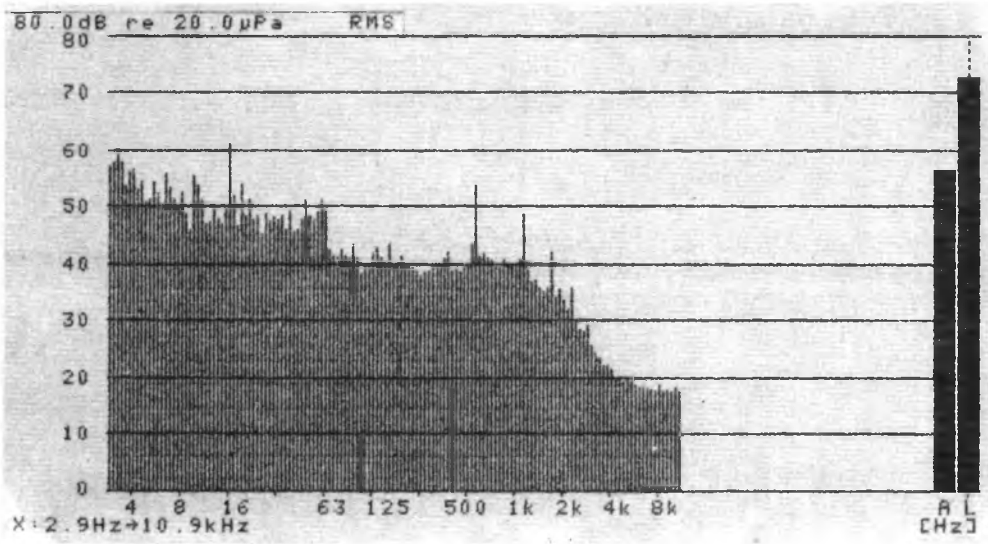

Fig. 6. 1/12 octave-band spectrum measured around a power plant.

The measurement were made using different locations of the probe. The distance between microphones was adjusted to the frequency of 16.3 and 30.7 Hz. Each microphone was mounted on its own tripod. They were arranged using a tape measure, flagpoles, square and leveller.

The results obtained are presented in Fig. 7. They confirmed the usefulness of a three-microphone method for locating distant sources of infrasonic noise in the open space.

[2] The choice of the frequency depended on dimensions of the anechoic chamber.

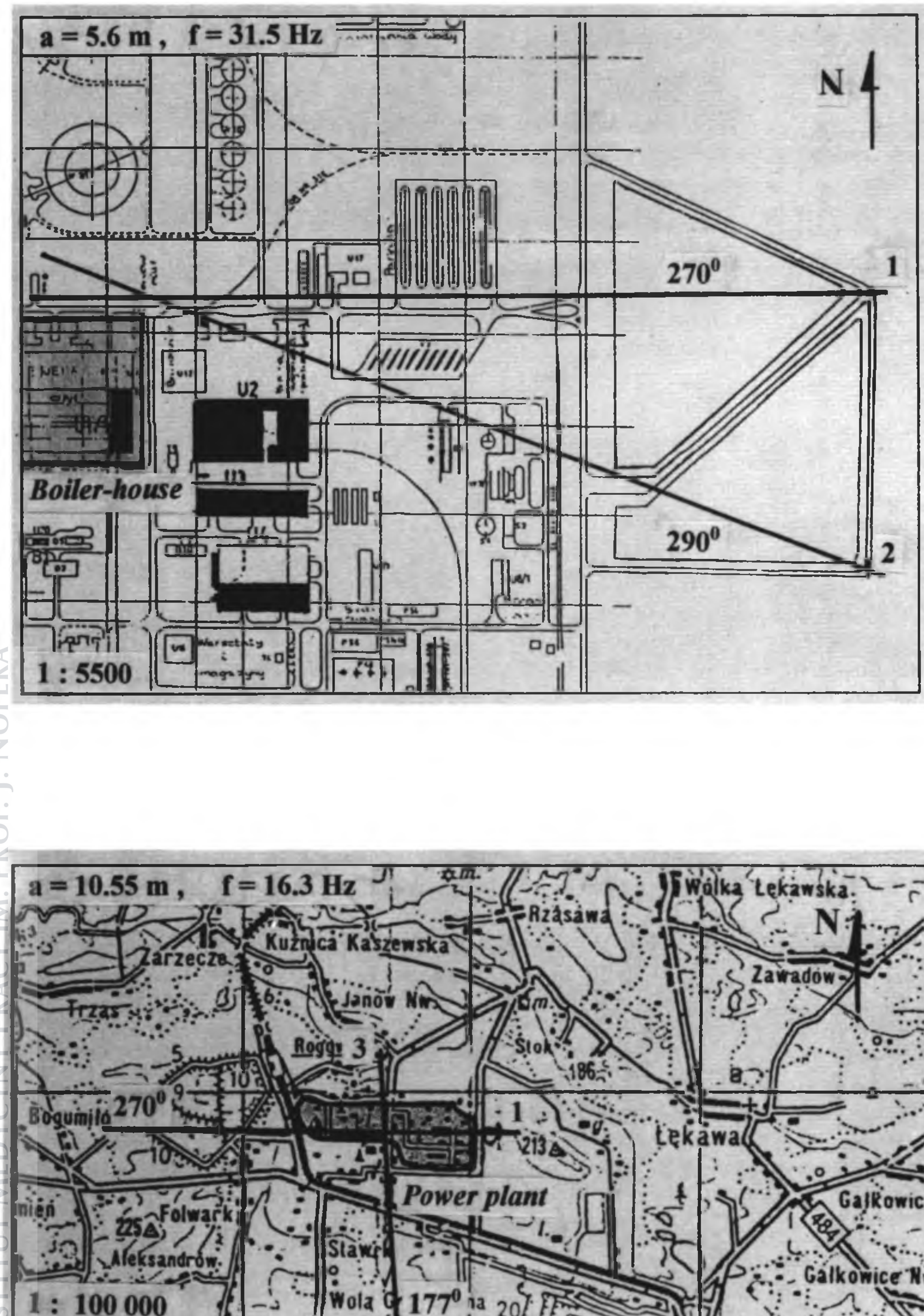

Fig. 7. Directions of wave's propagation, determined at different probe locations, around a power plant; a) at locations 1 and 2; b) at locations 1 and 3.

CONCLUSIONS

1. Exposure to infrasound at levels normally experienced by man does not tend to produce any dramatic health effects, but it causes considerable disturbance and annoyance. Because of its long wavelength infrasound can propagate over very long distances and can have an impact on the human organism even when far from its source.

2. The Polish Standard PN-86/N-01338 specifies admissible values of the acoustic pressure levels of infrasonic noise (2–50 Hz) at work places as well as recommended measuring techniques. As yet in Poland there has been no instruction concerning measuring techniques and permissible levels in the general environment.

3. A three-element microphone method enables to determine the time-spatial distribution of acoustic pressure and the direction of wave vector (direction of wave's propagation) in the infrasound field.

4. Industrial sources of infrasonic noise usually generate spheric waves; hence application of a three-microphone method is justifiable only in the far field i.e. within the distance from the source $r \geqslant 10\lambda$.

5. A three-element microphone method can be used for the open-space monitoring or locating distant sources of infrasonic noise. The measurements ought to be performed at two different positions of the probe.

6. The distance between microphones in the probe ought to be adjusted to the wavelength ($a \leqslant 1/2\ \lambda$).

7. The measuring system should consist of 3 microphones, preamplifiers, amplifiers, channels of tape recorder with identical phase response, and have a flat amplitude response as a function of frequency in the frequency range of 2–50 Hz. Alternatively, the correction of phase-mismatching of all the measuring chains A, B, C should be performd.

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