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VERIFICATION TESTS OF A METHOD OF DETERMINING SOUND INTENSITY WITH THE APPLICATION OF A TWO MICROPHONE TECHNIQUE

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The paper presents several verification results of experimental tests. These tests led to the development of software and instrumentation for the method of measuring the acoustical intensity with the application of a two microphone technique. Results of a quantitative evaluation of chosen method errors occuring for the accepted for investigation pair of microphones were presented, as well as results of investigations leading to the evaluation of the accuracy of intensity measurements done with the developed measuring system.

1. Introduction

In the past few years we can observe a development of methods leading to a quantitative evaluation of acoustical energy flow from the source to various zones of the acoustical field of industrial systems. Energetic and statistical methods [1,7] are of special significance, because they allow the quantitative evaluation of the source radiation and the analysis of the probable transfer paths of the acoustical energy. One of the most effective methods are two- and multiparameter methods, where the mutual correlation or power spectrum density functions are applied. The two microphone method (*acoustical intensity*) is recognized among the simplest. It is based on the acoustical intensity determination from two time functions of the acoustical pressure, measured in two near lying points of the acoustical field. Lastly the possibilities of applying these methods in determining the acoustical power of machines, locating noise sources, measuring the sound attenuation coefficient and acoustical isolation, were investigated. Parallely to the development of the universal sound intensity meters, research is conducted on the improvement of sound intensity estimation. Several research centres are engaged into its implementation in their own laboratories with the application of their computing systems. This paper presents the results of theoretical calculations and experimental research on the development of an acoustical intensity measurement method, applying two microphone probes produced in Poland. An analysis of chosen errors of the method is also presented, as well as results of research on the accuracy evaluation of the intensity measurements done with the developed measuring system.

2. Theoretical foundations of the two microphone method

In currently applied methods of measuring acoustical intensity a principle of simultaneous acoustical pressure measurements in two near lying spots, with a two microphone probe, is put into use. At the same time the two microphone probe is applied for simultaneous measurements of the acoustical pressure and acoustical velocity. The acoustical velocity can be theoretically defined from the Euler equation. For a linear medium without a considerable flow this equation will be

$$\overrightarrow{\operatorname{grad} p} = -\varrho \frac{d\vec{v}}{dt}, \tag{1}$$

where p – acoustical pressure [Pa], $\vec{v}$ – acoustical velocity [m/s], ϱ – medium density [kg/m^3].

For a chosen direction, x, equation (1) will be

$$v_x = -\frac{1}{\varrho} \int \frac{\partial p}{\partial x} dt, \tag{2}$$

where v_x – coordinate of vector $\vec{v}$ in direction x.

Assuming that the distance between the microphones is small in comparison to the wave length, we can replace the acoustical pressure gradient by a finite difference

$$\frac{\partial p}{\partial x} \approx \frac{p_2 - p_1}{\Delta x}, \tag{3}$$

where p_1, p_2 – acoustical pressures in the first and second measuring point respectively [Pa], Δx – distance between the microphone membranes [m].

Taking advantage of the acoustical intensity definition and of equation (3), we can determine the approximate value of the acoustical intensity component in direction x

$$I_x = \frac{1}{2\varrho \Delta x} \left\langle (p_1 + p_2) \int (p_2 - p_1) dt \right\rangle, \tag{4}$$

where symbol $\langle \cdot \rangle$ means a mean in time.

There are two main methods of processing time signals of acoustical pressure:

a) analogue,
b) numerical.

A. Analogue method

This method, called also the *sum-difference method,* directly applies equation (4). The practical construction of analogue meters is difficult considering the significant influence of phase shifts occuring during signal filtration, on the measurement accuracy. To avoid this problem certain method modifications are applied; such as using one filtering system and switching measuring channels.

B. Numerical method

The numerical method of determining acoustical intensity applies the Fourier transform of microphone signals. The theoretical analysis shows that the acoustical intensity can be determined from the imaginary part of the cross spectrum of microphone signals

$$I_x(f) = \frac{\operatorname{Im}\{G_{12}(f)\}}{2\pi f \varrho \Delta x}, \tag{5}$$

where $I_x(f)$ — acoustical intensity in direction x [Wm^{-2}], f — middle frequency of measuring band [Hz], ϱ — medium density [kg/m^3], Δx — distance between microphones [m], $G_{12}(f)$ — cross spectrum of microphone signals [Pa^2].

The numerical method of calculating acoustical intensity is based on the determination of the Fast Fourier Transform of the pressure time function and then the cross spectrum function. The constant coefficients in equation (5) differ in dependence of the individual frequency bands. Calculations are done numerically with the application of an analogue-to-digital converter and a computer.

3. Errors of the two microphone method

The accuracy of the acoustical intensity measurements done with the application of the two microphone method depends mainly on the following factors:

distance between the microphones (distance between the membranes or axis of the microphones),

phase shifts developed in the measuring system,

ratio of the microphone signal amplitudes,

linear dimensions of the microphones,

random errors occuring during signal processing.

Among the above mentioned factors the phase shifts have a decisive influence on the measuring accuracy in the range of low and medium frequencies. Numerical methods allow the correction of the error due to phase shifts through introducing constant corrections. The value of an error due to a finite distance between the microphones and the occurrence of the phase shifts can be calculated theoretically. As an example, an equation is given for a monopole source

$$I_t = 10\log_{10}\frac{I_p}{I_d} = 10\log_{10}\left[\frac{\sin(k\Delta x+\varphi)x^2}{k\Delta x\, x_1\, x_2}\right], \qquad (6)$$

where I_d — accurate value of the acoustical intensity [$\mathrm{Wm^{-2}}$], I_p — approximate value of the acoustical intensity [$\mathrm{Wm^{-2}}$], x_1, x_2 — distance of the microphones, 1 and 2, from the centre of the source [m], x — distance of the midpoint between the microphones from the centre of the source [m], k — wave number [rd/m], φ — phase shift angle between the microphone signals [rd].

In the case of the numerical method the influence of the phase shifts on the measuring accuracy is limited by a very careful selection of the pair of microphones.

4. Testing microphone probes

In order to avoid or eliminate the effects of errors due to phase shifts research has been undertaken on the phase characteristics of a two microphone probe. The following methods were applied:

measuring method in the far field of the loudspeaker,
measuring method in the near field of a vibrating piston,
electrostatic actuator method,
measurement of the phase shift of the microphone preamplifiers.

The measuring method in the far field of the loudspeaker was based on the measurement of the phase shift between the acoustical pressures measured by two microphones placed beside each other in an anechoic chamber at a considera-

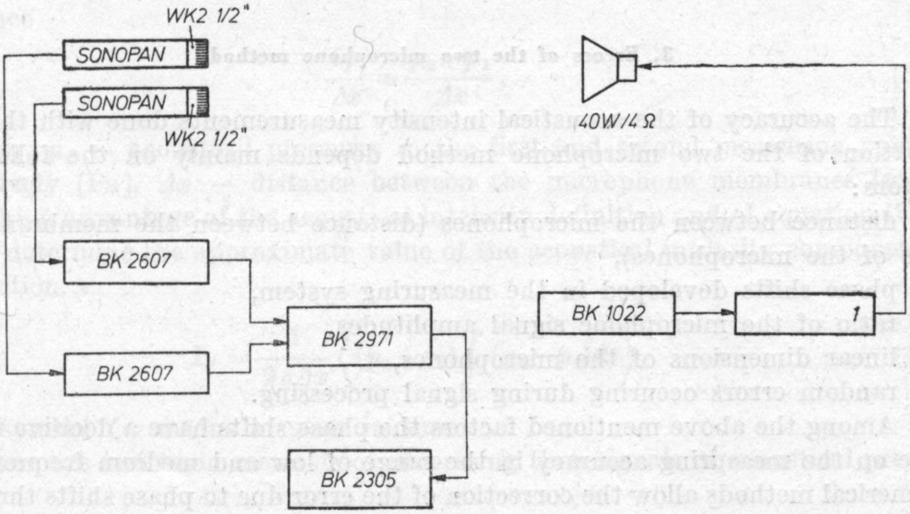

Fig. 1. Diagram of measurements of phase shifts between microphone signals. Measurements in the far field of the loudspeaker; *1* — power amplifier

ble distance from the loudspeaker (about 3 m). The microphones were located exactly in a plane perpendicular to a line connecting the microphones and the loudspeaker being turned toward the loudspeaker.

Investigations were conducted for harmonic signals of the frequency of the middle octave bands, ranging from 125 to 2000 Hz. Fig. 1 presents the measuring system diagram. The obtained phase measurement results were not stationary. The method proved itself useless for this kind of tests.

The measuring method in the near field of a vibrating piston applied a rigid piston as a plane wave source. Microphones were placed on a rigid support in such a mannerr so their membranes were in a plane parallel to the piston surface. A constant value of the acoustical pressure in the surroundings of the microphones was maintained, owing to the application of a feedback with a vibration exciter. The measuring diagram is shown in Fig. 2. Measurements were conducted in a frequency range from 20 to 5000 Hz. Obtained frequency characteristics can be recognized as consistent with reality only in the range from 20 Hz to about 2000 Hz. In higher frequency ranges significant phase changes, amounting to 360°, were observed. They were due to the non-homogenity of the acoustical field of the piston and the vibrations of the console supporting the microphones. The vibrations of the console were registered by a BK 4332 type accelerometer placed between the microphones. Significant phase changes occurred a ta frequency of about 2000 Hz. This corresponds to a frequency at which resonance vibrations of the support have been observed.

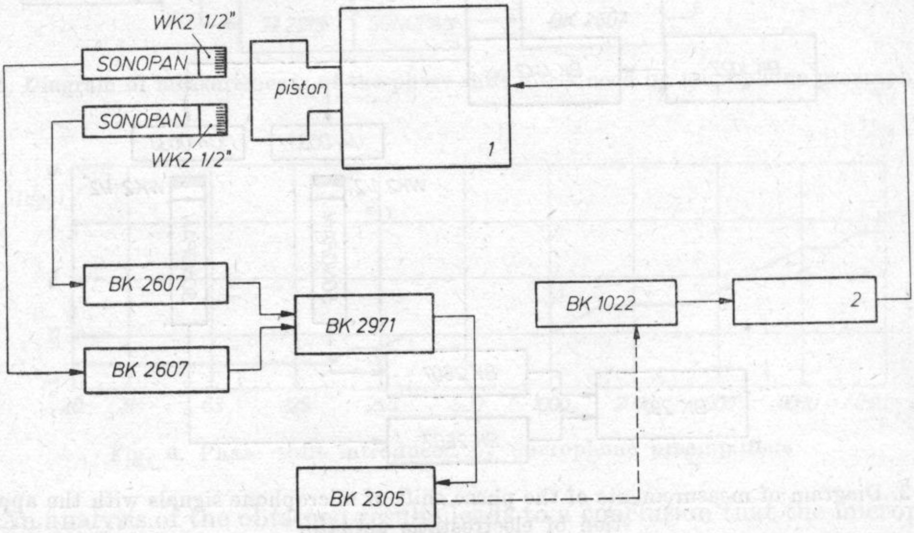

Fig. 2. Diagram of measurements of the phase shift between microphone signals. Measurement in the near field of a vibrating piston; *1* — exciter of vibrations RFT; *2* — power amplifier

The electrostatic actuator method made use of a BK 4142 standard reciprocity calibration apparatus. The electrostatic actuator was used in the measurement of the amplitude characteristic of the microphone. After putting it on a microphone a condenser is formed, where the microphone membrane and the electrostatic actuator are the plates. The actuator is supplied with a current with an altering voltage, which is a sum of a constant voltage (800 V) and a variable voltage of an amplitude of 30÷40 V. This causes the formation of an electrostatic force acting on the microphone membrane in a similar manner as the acoustical pressure which achieves accordingly a level of 88–100 dB. Thanks to supply voltage retuning and microphone signal registration an amplitude characteristic can be obtained. After placing two actuators supplied from one power source on two microphones, the measurement of a phase shift between the microphone signals is possible. Because the acoustical field surrounding the microphone may have an influence on the accuracy of the measurement, it is advised to make sure that the background pressure level does not exceed 30 dB.

The measuring diagram is shown in Fig. 3. The obtained phase characte-

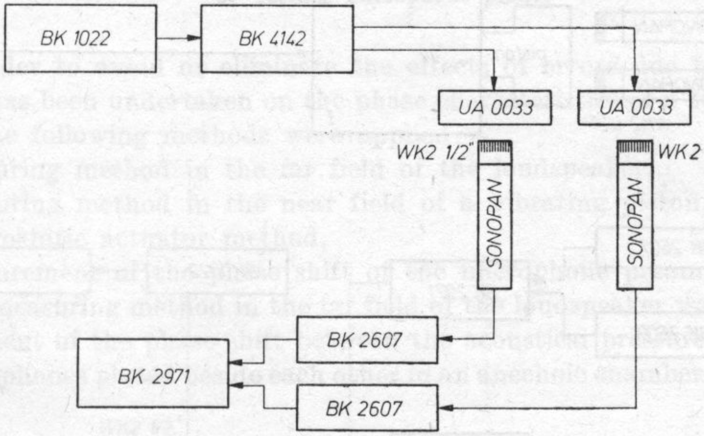

Fig. 3. Diagram of measurements of the phase shift of microphone signals with the application of electrostatic actuator

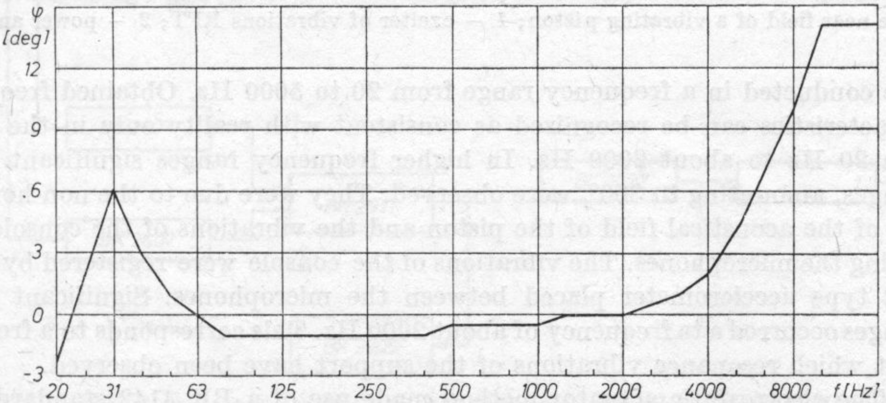

Fig. 4. Phase shift between microphone signals

ristic for a chosen pair of microphones, presented in Fig. 4, is a total phase characteristic of microphones with microphone preamplifiers.

Investigations of the phase shift introduced by the microphone preamplifiers were conducted for a pair of preamplifiers applied in the two microphone probe. In order to supply identical signals to the preamplifiers, JJ 2615 adaptors were applied in place of microphone cartridges. Frequencies of signals supplied to the adaptors were changed in a continuous way in a range from 20 to 20 000 Hz. Phase shifts were read for frequencies of the middle octave bands. The measurement diagram and the test results are shown in Fig. 5 and 6, respectively.

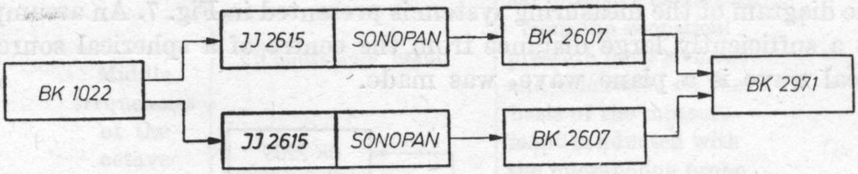

Fig. 5. Diagram of measurements of the phase shift introduced by microphone preamplifiers

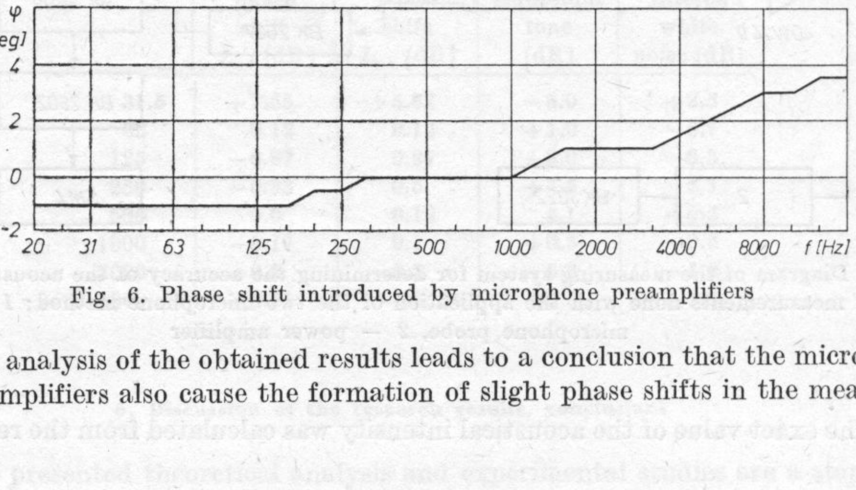

Fig. 6. Phase shift introduced by microphone preamplifiers

An analysis of the obtained results leads to a conclusion that the microphone preamplifiers also cause the formation of slight phase shifts in the measurements.

5. Verification tests of the two microphone method

A. *Measuring system*

A system consisting of the elements mentioned below was applied for the measurements done according to the two microphone method:

two microphone probe, made from microphones and preamplifiers produced by "SONOPAN" in Białystok,

microphone amplifiers, type BK 2607,

digital recorder BK 7502,

multiplexer BK 5699,
digital computer SM 4.

According to equation (5) a program was worked out in order to calculate numerically acoustical intensity.

B. Acoustical intensity measurements

The verification of the accuracy of the acoustical intensity measurements with the application of the developed measuring system, was done by measuring acoustical intensity in the far field of a loudspeaker placed in an anechoic chamber. The diagram of the measuring system is presented in Fig. 7. An assumption, that at a sufficiently large distance from the centre of a spherical source the acoustical wave is a plane wave, was made.

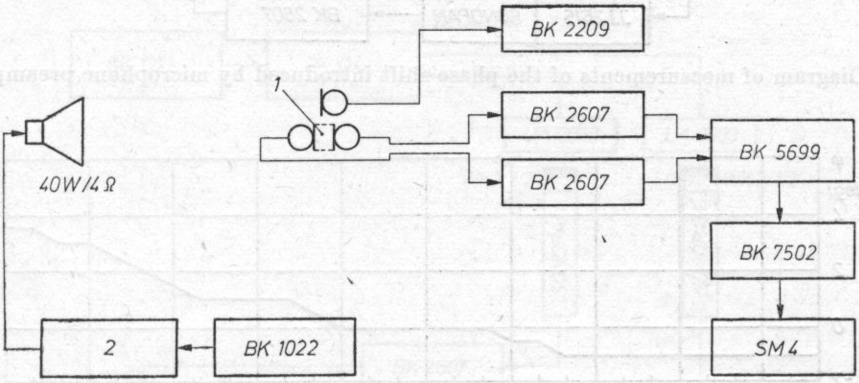

Fig. 7. Diagram of the measuring system for determining the accuracy of the acoustical intensity measurements done with the application of the two microphone method; *1* – two microphone probe, *2* – power amplifier

The exact value of the acoustical intensity was calculated from the relationship

$$I_x = \frac{p_{su}^2}{\varrho c} \quad [\mathrm{Wm^{-2}}], \tag{7}$$

where p_{su} – rms value of the acoustical pressure [Pa], ϱ – air density [kgm^{-3}], c – sound velocity in air [m/s].

The measurement was conducted through placing an additional microphone near the probe. A loudspeaker and a system of loudspeakers with a circular directional characteristic in the investigated frequency range were the sound source. Acoustical signals generated by the source had the character of white noise filtered in third-octave bands and sinusoidal tones with frequencies of middle octave bands.

Results achieved by the discussed methods are presented in Tab. 1.

Table 1 gives also the results of numerical calculations of the theoretical error of the method for a monopole source, taking into account real phase shifts occuring in the applied two microphone probe.

Table 1. Comparison of the results of the acoustical intensity measurements done with the application of different methods, and list of method errors determined theoretically

Middle frequencies of the octave bands	Theoretical error		Level difference between the acoustical intensity calculated from the acoustical pressure measurement and calculated on the basis of the measurement conducted with the microphone probe	
	for a positive phase shift $L_{\varepsilon+}$ [dB]	for a negative phase shift $L_{\varepsilon-}$ [dB]	forcing with sinusoidal tone [dB]	forcing with filtered white noise [dB]
31.5	+7.55	+5.62	−8.0	+3.5
63	0.12	0.12	+1.0	−6.7
125	−0.87	0.87	+3.0	−3.5
250	−0.33	0.5	+4.5	−2.7
500	0.0	0.12	4.1	−0.5
1000	−0.17	0.1	+0.3	−0.5
2000	−0.2	−0.2	+5.3	−1.0
4000	−0.81	−1.0	+2.0	−2.3

6. Discussion of the research results, conclusions

The presented theoretical analysis and experimental studies are a stage of a work of implementing the two microphone method of determining acoustical intensity.

The theoretical analysis of the method errors and measurements of the phase shifts between microphone signals enable the theoretical evaluation of the corrections introduced into the calculating program, in order to obtain the exact value of the measured acoustical intensity.

On the basis of literature studies, theoretical analysis and conducted tests the following conclusions can be reached:

a good conformity between the acoustical intensity measured with the two microphone probe and the results obtained from the measurements of the acoustical pressure in the far field, has been reached in the frequency range from

125 Hz to 2000 Hz. This concerns noise signals;

investigations on phase shifts between microphone signals for a chosen pair of microphones have proved that their values vary in a range of ±1° in the frequency range from 63 to 2000 Hz;

there is a possibility of implementing the two microphone method of determining acoustical intensity with the application of the imaginary part of the cross spectrum function, on the basis of possesed measuring and calculating instrumentation (system SM 4);

the accuracy of the acoustical intensity evaluation depends upon the source radiating character (e.g. order of source power) and the distance of the microphones;

further verification studies should include other types of signals and the cases of signals generated by industrial sources.

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