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NOISE SOURCES IDENTIFICATION IN MACHINES AND MECHANICAL DEVICES

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This paper presents a method for the determination of noise sources locations in machines and mechanical devices. It also describes a method for the determination of the nature of these noise sources and their effect on the overall noise. The former is based on the properties of the frequency band correlation function, the latter on the properties of the coherence function. It is shown that these two methods can be used in attempts to minimize machine noise.

1. Introduction

Most modern machines in use and manufactured today are characterized by vibro-acoustical energy of large magnitudes and by complexity. The vibro-acoustical output depends on how much of the supplied driving energy is converted into dynamic disturbances which produce vibration and noise.

These dynamic disturbances are harmful to man and the environment as well as to the machine itself since they cause material fatigue which decreases durability and reliability. The best method of reducing these undesired effects is to decrease the disturbances at their sources. However, the construction and performance of modern machines is often so complicated that, in many cases, it is difficult to determine the exact location of the disturbance sources and their physical nature without special measurements. The present work offers one method for determining the location of noise sources in machines and mechanical devices and another method for the determination of their characteristics. In other words, the method described here should make it possible to determine where the noise is produced and what its nature is, with respect to the classification of noises as either mechanical or aerodynamical.

2. The relations between vibro-acoustical processes in machines

By *vibro-acoustical processes*, we mean the noise or vibration produced by machines. These processes can be measured using suitable transducers at the following locations: in the surroundings of the machine, at the machine parts or inside the working space of the machine (e.g. in a combustion chamber).

It is obvious that most vibro-acoustical processes in machines as measured at these points will have something in common. This similarity can be divided into two classes: the general one — when the processes occur in the same machine, and the particular one — when the processes have the same source in the machine. The theory of stationary ergodic random processes, including vibro-acoustical ones, distinguishes two measures of similarity between them, namely the correlation function and the coherence function [1]. With regard to the manner in which the correlation function is calculated it can be recognized as a measure of the general similarity of the processes in the time domain and determines the similarity of two processes within a definite time interval. On the other hand, the coherence function determines the maximum similarity of processes in terms of the frequency spectrum. It does not contain any phase information (for the following procedures, phase information is not necessary). For multi-resonant systems in machines and their elements, coherence functions are much easier to interprete than correlation functions [2]. Hence, the coherence function is a measure of the detailed similarity between the processes and makes it possible to distinguish between the separate disturbance sources in the machine.

These two measures of similarity between the processes are interrelated by the normalized correlation measured over the frequency band. Therefore, we begin with determining the correlation function.

Let the two vibro-acoustical processes have the forms $x_1(t)$ and $y_1(t)$, measured either in the machine or in its surroundings. The correlation function of these processes $\psi_{x_1y_1}(\tau)$ can be expressed by means of the cross-power spectral density $W_{x_1y_1}(f)$ through the Wiener-Khinchin [1] relation

$$\psi_{x_1y_1}(\tau) = \int_{-\infty}^{\infty} W_{x_1y_1}(f)e^{j2\pi f\tau}df, \tag{1}$$

where f is frequency, τ – the time delay between the two processes and j – the imaginary unit.

The cross-spectral density $W_{x_1y_1}(f)$ is a complex quantity and, thus it can be expressed in the form $W_{x_1y_1}(f) = |W_{x_1y_1}(f)|e^{-j\varphi}$. The phase shift $\varphi = \varphi(f)$ depends on the frequency and shows the relationship between the real and imaginary components of the spectral density.

Since the correlation function is a real quantity, it follows from (1) that

$$\psi_{x_1y_1}(\tau) = \int_{-\infty}^{\infty} |W_{x_1y_1}(f)|e^{j(2\pi f\tau-\varphi)}df = 2\int_{0}^{\infty} |W_{x_1y_1}(f)|\cos(2\pi f\tau-\varphi)df. \tag{2}$$

It is well known that it is possible to derive from (2) a normalized correlation function making use of the expressions

$$\varrho_{x_1y_1}(\tau) = \frac{\psi_{x_1y_1}(\tau)}{\sqrt{\sigma_{x_1}^2\sigma_{y_1}^2}},$$

$$\sigma_{x_1}^2 = 2\int_0^\infty W_{x_1x_1}(f)\,df, \qquad \sigma_{y_1}^2 = 2\int_0^\infty W_{y_1y_1}(f)\,df, \tag{3}$$

where $\sigma_{x_1}^2$ and $\sigma_{y_1}^2$ denote the variances of the processes $x_1(t)$ and $y_1(t)$.

Thus, from (2) and (3) the normalized correlation function of the two processes is expressed by

$$\varrho_{x_1y_1}(\tau) = \frac{\int_0^\infty |W_{x_1y_1}(f)|\cos(2\pi f\tau-\varphi)\,df}{\sqrt{\int_0^\infty W_{x_1x_1}(f)\,df \int_0^\infty W_{y_1y_1}(f)\,df}}. \tag{4}$$

It is known that the normalized correlation function of Gaussian processes can most conveniently be measured by means of the polar correlator [4]. Let the processes $x_1(t)$ and $y_1(t)$ from the vibro-acoustical field of the machine be

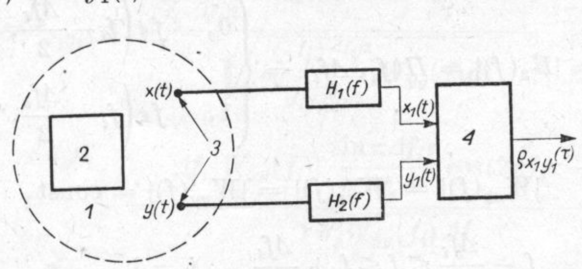

Fig. 1. General schematic representation of measurement procedure
1 – vibro-acoustical field, 2 – machine or mechanical device under test, 3 – transducers, 4 – polar correlator

fed to the input of the correlator. Let the transmittance of the measuring channels $x(t)$ and $y(t)$, be $H_1(f)$ and $H_2(f)$ respectively as shown in Fig. 1. From the diagram of signal transmission shown in Fig. 1, the spectral relations in (4) between the processes $x_1(t)$, $y_1(t)$, $x(t)$ and $y(t)$ can be expressed [5] by

$$W_{x_1x_1}(f) = |H_1(f)|^2 W_{xx}(f), \qquad W_{y_1y_1}(f) = |H_2(f)|^2 W_{yy}(f),$$
$$W_{x_1y_1}(f) = H_1(f)H_2^*(f)W_{xy}(f), \tag{5}$$

where $W_{xx}(f)$ and $W_{yy}(f)$ denote the power spectral densities of the processes $x(t)$ and $y(t)$ respectively, and $W_{xy}(f)$ the cross-spectral density of the vibro-acoustical processes $x(t)$ and $y(t)$ (the asterisk denotes a conjugate complex). Substituting the spectral relations (5) into (4) yields

$$\varrho_{x_1y_1}(\tau) = \frac{\int_0^\infty |W_{xy}(f)H_1(f)H_2^*(f)|\cos(2\pi f\tau-\varphi)\,df}{\int_0^\infty W_{xx}(f)|H_1(f)|^2\,df \int_0^\infty W_{yy}(f)|H_2(f)|^2\,df}. \tag{6}$$

Thus by introducing the spectral transmittances of the measuring channels the relations between the normalized correlation function and the spectral properties of the processes measured can be derived.

The formula (6) will now be used for the determination of the spectral-correlation method for the investigation of vibro-acoustical processes.

3. The spectral-correlation method

Let us assume initially that the transmittances of the measuring channels can be represented by identical band-pass filters with mid-frequency f_i which have a flat transmission curve over their bandwidth. Let us further assume that the spectral densities of the processes of interest here are smooth functions also flat in the transmittance band Δf_i. Hence we can write

$$|H_1(f)| = |H_2(f)| = \Pi(f_i, \Delta f_i) = \begin{cases} 0, & f \notin \left(f_i - \frac{\Delta f_i}{2}, f_i + \frac{\Delta f_i}{2}\right), \\ 1, & f \in \left(f_i - \frac{\Delta f_i}{2}, f_i + \frac{\Delta f_i}{2}\right), \end{cases} \tag{7}$$

$$|W_{xy}(f)| = |W_{xx}(f)| = |W_{yy}(f)| = \text{const},$$

$$f_i - \frac{\Delta f_i}{2} \leqslant f \leqslant f_i + \frac{\Delta f_i}{2}, \quad i = 1, \ldots, n.$$

We insert the above formulae into (6) and perform transformations to obtain

$$\varrho_{x_1 y_1}(\tau) = \frac{\int\limits_{f_i - \Delta f_i/2}^{f_i + \Delta f_i/2} |W_{xy}(f)| \cos(2\pi f \tau - \varphi)\, df}{\sqrt{\int\limits_{f_i - \Delta f_i/2}^{f_i + \Delta f_i/2} W_{xx}(f)\, df \int\limits_{f_i - \Delta f_i/2}^{f_i + \Delta f_i/2} W_{yy}(f)\, df}} = \frac{|W_{xy}(f_i)| \frac{\sin \pi \Delta f_i \tau}{\pi \Delta f_i \tau} \cos(2\pi f_i \tau - \varphi)}{\sqrt{W_{xx}(f_i) W_{yy}(f_i)}}. \tag{8}$$

It is well known [1, 2, 3] that the coherence function of two random processes is expressed as follows

$$\gamma_{xy}^2(f) = \frac{|W_{xy}(f)|^2}{W_{xx}(f) W_{yy}(f)}. \tag{9}$$

Hence, the normalized correlation function within the band Δf_i, (8) can be written in the following form:

$$\varrho_{x_1 y_1}(\tau) = \gamma_{xy}(f_i)\,\frac{\sin\pi\Delta f_i\tau}{\pi\Delta f_i\tau}\,\cos(2\pi f_i\tau-\varphi), \qquad \varphi = \varphi(f_i). \tag{10}$$

Thus we have obtained the relation between the spectral similarity measure of processes $\gamma^2_{xy}(f_i)$ and the normalized band correlation function of those processes. The question of how to use this relation in practice will be dealt with later.

We shall now consider another possible form of the transmittance of measuring channels (Fig. 1).

Let us now assume that the transmittance of a measuring channel of the process $x(t)$ has unit gain (i.e. $|H_1(f)| = 1$), while the transmittance of the second channel $H_2(f)$ and the spectral densities satisfy equation (7). On the basis of these assumptions and (6) we can write

$$\varrho_{x_1 y_1}(\tau) = r_{x_1 y_1}(\tau) = \frac{\int\limits_{f_i-\Delta f_i/2}^{f_i+\Delta f_i/2} |W_{xy}(f)|\cos(2\pi f\tau-\varphi)\,df}{\sqrt{\sigma_x^2 \int\limits_{f_i-\Delta f_i/2}^{f_i+\Delta f_i/2} W_{yy}(f)\,df}}$$

$$= \frac{\Delta f_i\,|W_{xy}(f_i)|\,\dfrac{\sin\pi\Delta f_i\tau}{\pi\Delta f_i\tau}\,\cos(2\pi f_i\tau-\varphi)}{\sqrt{\sigma_x^2 W_{yy}(f_i)\,\Delta f_i}}. \tag{11}$$

To make expressions (10) and (11) similar, let us transform the factor linked with the trigonometric expressions

$$\frac{\Delta f_i\,|W_{xy}(f_i)|}{\sqrt{\sigma_x^2 W_{yy}(f_i)\,\Delta f_i}} = \sqrt{\frac{(\Delta f_i)^2\,|W_{xy}(f_i)|^2}{\sigma_x^2 W_{yy}(f_i)\,\Delta f_i}}$$

$$= \sqrt{\frac{\Delta f_i W_{xx}(f_i)\,|W_{xy}(f_i)|^2}{\sigma_x^2 W_{xx}(f_i)\,W_{yy}(f_i)}} = \sqrt{E_x^2(f_i)\,\gamma^2_{xy}(f_i)}, \tag{12}$$

where $E_x^2(f_i) = \Delta f_i W_{xx}(f_i)/\sigma_x^2$.

Apart from the coherence of processes (9) we have introduced here a new quantity $E_x^2(f_i)$ which can be termed the energy contribution of the band Δf_i of the process $x(t)$ to the total energy of the whole process, because

$$E_x^2(f_i) = \frac{\text{variance in band } \Delta f_i}{\text{total variance}} = \frac{\Delta f_i W_{xx}(f_i)}{\sigma_x^2}. \tag{13}$$

Hence it follows that the normalized band correlation function of the processes $x(t)$ and $y(t)$, as measured using one filter, takes the final form

$$r_{x_1 y_1}(\tau) = E_x(f_i)\,\gamma_{xy}(f_i)\,\frac{\sin\pi\Delta f_i\tau}{\pi\Delta f_i\tau}\,\cos(2\pi f_i\tau-\varphi). \tag{14}$$

Comparing the final expressions (10) and (14), we can easily find that they are similar in character, i.e. the terms depending on the time delay τ between the processes are identical while terms depending on the spectral pattern of the processes under discussion are analogous.

Let us notice now that, on the basis of properties of the function $(\sin x)/x$ and the experimental results [6], it is possible to simplify these expressions because

$$\frac{\sin \pi \Delta f_i \tau}{\pi \Delta f_i \tau} \approx 1, \qquad \Delta f_i \tau \leqslant 0.2. \tag{15}$$

Then, with equation (15) satisfied, we have

$$\varrho_{x_1 y_1}(\tau) = \gamma_{xy}(f_i)\cos(2\pi f_i \tau - \varphi) \tag{16}$$

and

$$r_{x_1 y_1}(\tau) = E_x(f_i)\gamma_{xy}(f_i)\cos(2\pi f_i \tau - \varphi). \tag{17}$$

If we now find the values of the two functions for such time instants τ_0, τ_1 that $\tau_1 = \tau_0 + 1/4f_i$ (for which there is a corresponding phase shift $\pi/2$ at the frequency f_i, easily obtained by electrical means) and that according to (15)

$$\Delta f_i\left(\tau_0 + \frac{1}{4f_i}\right) < 0.2,$$

then the sum of squares of these functions yields

$$\gamma_{xy}^2(f_i) = [\varrho_{x_1 y_1}(\tau_0)]^2 + [\varrho_{x_1 y_1}(\tau_1)]^2, \tag{18}$$

$$E_x^2(f_i)\gamma_{xy}^2(f_i) = [r_{x_1 y_1}(\tau_0)]^2 + [r_{x_1 y_1}(\tau_1)]^2. \tag{19}$$

It follows that by the measurement of the polar correlation function using two identical filters, it is possible to determine the coherence function of processes, whereas using only one filter the product of a coherence function and the energy contribution of unfiltered process can be determined. The energy contribution of the process $x(t)$ can be easily determined by means of the same filter, so if $E_x^2(f_i) \neq 0$, the two methods can be recognized as equivalent.

It is obvious that the use of a single filter is simpler from the point of view of the measuring equipment, whereas the method of two filters is faster.

Knowing the coherence function of a process within a frequency band f_i, it is possible to determine directly a measure of the statistical similarity or identity of these processes, since $\gamma_{xy}^2(f_i) = 1$ denotes the processes statistically identical over the frequency band under consideration, $0 < \gamma_{xy}^2(f_i) < 1$ denotes the processes only statistically similar over the frequency band under consideration, and $\gamma_{xy}^2(f_i) = 0$ denotes the processes statistically different over the frequency band under consideration. Thus the coherence function indicates the degree of dependence between vibro-acoustic processes, their origin, and the relative significance of a given partial process in complex processes etc.

4. The identification of noise sources

The spectral correlation method presented here can, in general, be employed for determining the source location of both vibration and noise in machines. However for vibration it is required that additional assumptions concerning the resonance and dissipation properties of the machine investigated are satisfied. Therefore, the discussion here is limited to the determination of the location of noise source and its nature in machines and devices.

An analysis of formulae (16) and (17) shows that to determine the location of a partial noise source in a machine two procedures can be used. In the first procedure the measure of similarity between the partial noise source and the resultant noise in the machine is used. This can be done if the coherence function is known. Let us assume that the process $x(t)$ represents the resultant overall

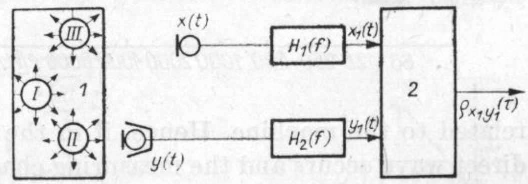

Fig. 2. Schematic representation of coherence measurement procedure
1 – machine or mechanical device, *2* – polar correlator

noise of the machine measured sufficiently far from it, while the process $y(t)$ is the partial noise measured at a very close range from its source. The measurement set-up is shown in Fig. 2 where Roman numerals denote the presupposed locations of the noise sources.

By performing the measurements according to formulae (16) and (17) we shall find the value of coherence within each frequency band of the process analyzed. Plotting these values as a function of frequency for each of the sources, we can find the two extreme forms of the coherence function.

A flat form and a low value of coherence indicates that the partial noise sources are equally significant with respect to the chosen measuring point for the channel $y(t)$.

A coherence function with one or several maxima indicates that a significant partial noise source in a given band (the corresponding curves *1* and *2* in Fig. 3) is close to the measuring point.

Thus, a method of trial and error, in which many microphone locations for the partial noise sources are employed, will determine the location of the important noise sources and their relative significance.

The second procedure used for the determination of noise source locations follows from the directional properties of (16) and (17) and is based on the change of time delay from changes of positions of the transducers. This procedure is similar to that proposed by Goff [7] but, in this case, the object of measurement is the frequency band correlation function.

Let us assume that two microphones are mounted on a rotary arm at a distance d as shown in Fig. 4. Assuming plane waves and rotation of the arm by an angle α, the difference in distance between the microphones is $l = d\sin\alpha$. The time delay related to this difference is $\tau = (d\sin\alpha)/c$, where c is the sound velocity in air. Fig. 4 shows that the processes $x(t)$ and $y(t)$ are identical as

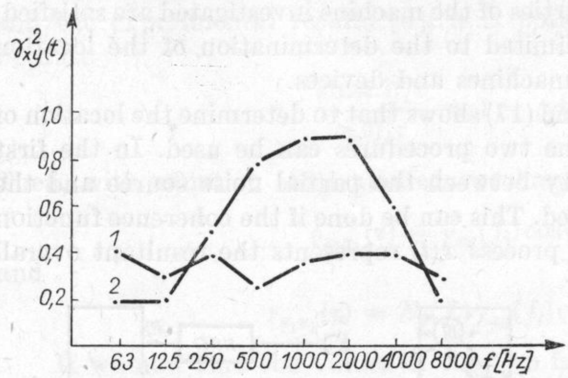

Fig. 3. Coherence of different sources
1 – no-determining of sound source location, 2 – determining of sound source location

related to the machine. Hence, if in the measuring room only the field of the direct wave occurs and the measuring channels are identical, we can assume that

$$\gamma_{xy}(f_i) \simeq 1, \quad \varphi(f_i) \simeq 0.$$

Thus formulae (16) and (17) are simplified to the form

$$\begin{aligned} \varrho_{x_1y_1}(\tau) &\cong \cos\left(\frac{2\pi f_i d\sin\alpha}{c}\right), \\ r_{x_1y_1}(\tau) &\cong E_x(f_i)\cos\left(\frac{2\pi f_i d\sin\alpha}{c}\right). \end{aligned} \tag{20}$$

It is clear that by looking for the maxima of functions (20) through the change of angle α, the direction of an arbitrary noise source in a given frequency band Δf_i can be found.

Let us return now to the relation which restricts the time change τ (15). By substituting the time resulting from the change of the distance l into (15) we obtain

$$\Delta f_i \tau = \Delta f_i \frac{|d\sin\alpha|}{c} \leqslant 0.2. \tag{21}$$

Most investigations of vibro-acoustical processes, particularly noise, are carried out by means of filters with a constant relative bandwidth β, $\beta = \Delta f_i/f_i$ = const, where for octave filters $\beta = 0.7071$, for $\frac{1}{3}$ octave filters $\beta = 0.2310$.

Taking it into consideration in (21), we get

$$\frac{\Delta f_i |d\sin\alpha|}{c} = \frac{\beta f_i |d\sin\alpha|}{c} = \frac{\beta\, |d\sin\alpha|}{\lambda_i} \leqslant 0.2, \tag{22}$$

where $\lambda_i = c/f_i$ is an acoustical wave length corresponding to a frequency f_i. Restricting α to the desired scanning angle $\alpha = \pm 15°$ we obtain

$$\frac{d}{4\lambda_i} \leqslant \frac{0.2}{\beta}. \tag{23}$$

Hence, the distances between microphones and the wavelengths for particular filters should satisfy the relations:

$$\begin{aligned} d/\lambda_i &\leqslant 1 \quad \text{for octave filters,} \\ d/\lambda_i &\leqslant 4 \quad \text{for } \tfrac{1}{3}\text{-octave filters.} \end{aligned} \tag{24}$$

Now, by positioning the machine in such a way that its angular width does not exceed 30° and restrictions (24) are satisfied, it is possible to find the location of the main noise sources for each band Δf_i. Similar restrictions are imposed

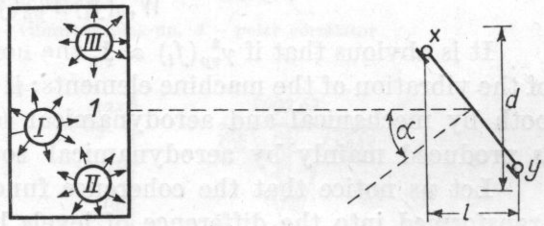

Fig. 4. Schematic representation of measurement procedure for the determination of locations of the noise sources

1 – machine or mechanical device

on the method of coherence using formulae (18) and (19). The required time delay $\Delta\tau = \tau_0 - \tau_1 = 1/(4f_i)$ must satisfy the same relation, that is $\Delta f_i \Delta\tau \leqslant 0.2$. By expressing Δf_i in terms of the relative bandwidth $\Delta f_i = \beta f_i$, we obtain the condition

$$\frac{\beta}{4} \leqslant 0.2, \quad \text{i.e.} \quad \beta \leqslant 0.8. \tag{24a}$$

It follows that inequality (24a) for octave filters $\beta = 0.7071$ is still satisfied. Therefore with all the remaining conditions being satisfied, these filters may be utilized for determining the coherence function as well.

When the locations of the sources of noise have been found, it may be possible to determine where the noise is generated, and to what degree and in which frequency bands the noise is produced by vibration of machine parts or by turbulent flow of the medium. Thus it becomes necessary to use, once more, the properties of the coherence function by placing the microphone $x(t)$ at the point $y(t)$ as shown in Fig. 2. Let the process $y(t)$ be the velocity of vibration of a machine element in the neighbourhood of the source under investigation. The noise received by the microphone is denoted by $p(t)$, $[x(t) \to p(t)]$ and the velocity of vibration of the machine element by $v(t)$, $[y(t) \to v(t)]$.

The noise $p(t)$ is the non-correlated sum of the mechanical noise $m(t)$ and the aerodynamic noise $n(t)$, so that

$$x(t) = p(t) = m(t)+n(t), \qquad W_{pp}(f) = W_{mm}(f)+W_{nn}(f). \tag{25}$$

Assume also that the transmittance of vibration velocity into mechanical noise is denoted by the transfer function $H(f)$. Then, $W_{mm}(f) = |H(f)|^2 W_{vv}(f)$. It can be shown that with no correlation between the vibration velocity and aerodynamic noise, the following relationship is valid:

$$|W_{vp}(f)|^2 = W_{vv}^2(f)\,|H(f)|^2 = W_{vv}(f)W_{mm}(f). \tag{26}$$

Thus the value of coherence between the vibration velocity and noise at the point considered for the Δf_i band can be expressed in the following form:

$$\gamma_{vp}^2(f_i) = \frac{|W_{vp}(f_i)|^2}{W_{vv}(f_i)W_{pp}(f_i)} \cong \frac{W_{mm}(f_i)}{W_{pp}(f_i)}. \tag{27}$$

It is obvious that if $\gamma_{vp}^2(f_i) \approx 1$, the noise is mainly the result of conversion of the vibration of the machine elements; if $0 < \gamma_{vp}^2(f_i) < 1$ the noise is produced both by mechanical and aerodynamical sources and if $\gamma_{vp}^2(f_i) \approx 0$, the noise is produced mainly by aerodynamical sources.

Let us notice that the coherence function (27) can, in a simple way, be transformed into the difference of levels between the resultant noise L_p and the noise produced by mechanical sources L_m. By expressing (27) in terms of the noise levels, we get

$$\Delta L_{pm_i} = L_{p_i} - L_{mi} = 10\log\frac{1}{|\gamma_{vp}(f_i)|^2}, \qquad |\gamma_{vp}(f_i)| < 1. \tag{28}$$

A similar transformation can be applied to the energy contribution $E_p^2(f_i)$ in formula (17).

It is known that, if the level difference from two sources exceeds 10 dB, the effect of the source with a lower level on the resultant noise is negligible. This fact taken into account in formula (28) shows that for $|\gamma_{vp}(f_i)| < 0{,}3$ the effect of vibration on the noise level of the source is insignificant. It follows from this reasoning that the measured coherences of vibration, velocity and noise of a given source can show how this noise is generated and what is the significance of the mechanical component with regard to the resultant noise level.

Summarizing the discussion so far it can be stated that with the use of instruments functioning as defined by the formulae (16) to (19), it is possible to determine the locations of noise sources in the machine and the means by which the noise is generated. Moreover, this informations is obtainable for each separate frequency band.

5. Experimental investigations

To estimate the usefulness of the method described for the vibro-acoustical investigation of machines and mechanical devices, we prepared a laboratory experiment. A block diagram of the measuring apparatus is shown in Fig. 5.

It consisted of two equivalent channels, each containing the MPDA-10 noise level meter with an analyzer to measure the noise and vibration in the octave bands from 63 Hz to 8 kHz.

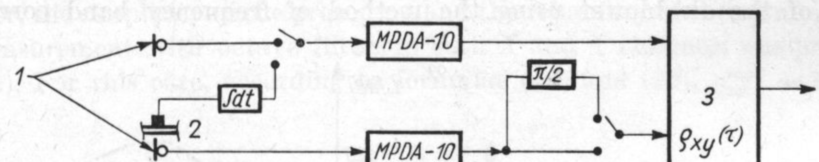

Fig. 5. Experimental set-up for the identification of noise and vibration sources in machines

1 – condenser microphones, *2* – vibration pick-up, *3* – polar correlator

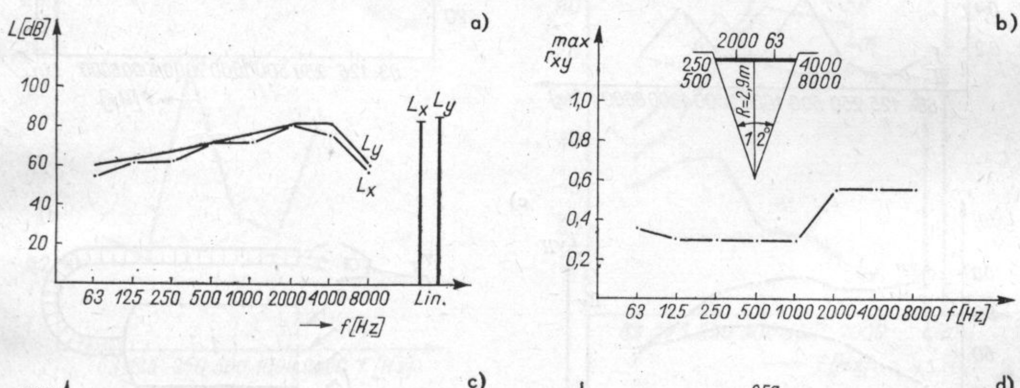

Fig. 6. *a*) Octave spectrum of noise measured at the points X and Y, *b*) results of the determination of the noise source locations in the blower «PYE-LING» – using $r_{xy}^{\max}$, *c*) results of the determination of the noise source locations in the blower «PYE-LING» – using $\varrho_{xy}^{\max}$, *d*) results of the determination of the noise source locations in the blower «PYE-LING» – using $r_{xy}^{\max}$

Output voltages from the two channels were fed to a polar correlator (designed by the authors of this report) directly or through a phase shifter $\varphi = 90°$ in one of the channels. This set-up was used for investigating two noise sources, namely a «PYE-LING» blower designed for air cooling of vibration exciter units and also a one-cylinder portable compressor. The experiments were performed in a laboratory room about $11 \times 5 \times 3\ m^3$, in which it was impossible to measure only the direct waves generated by the source.

Firstly, we performed experiments to determine the location of the noise sources of the air blower using the method of frequency band correlation.

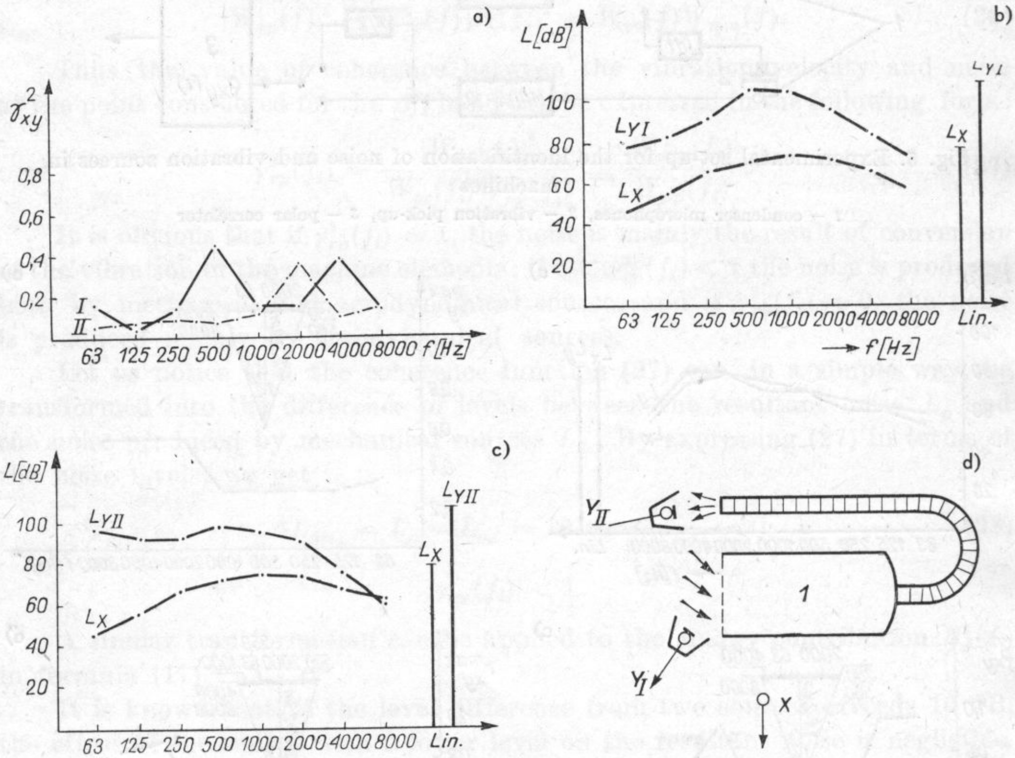

Fig. 7. *a*) Coherence of partial sources in the blower «PYE-LING», *I* – inlet, *II* – outlet, *b*) octave spectrum of noise measured at the points X and Y_I, *c*) octave spectrum of noise measured at the points X and Y_{II}, *d*) situation of microphones in the measurement according to Fig. 7: *1* – blower «PYE-LING»

Results of these experiments are shown in Figs 6a to d. Fig. 6a presents the octave-band noise spectrum measured in the channels X and Y with the microphones located on a moving base as shown in Fig. 4. It can be seen that the unweighted linear noise levels differ only slightly frome ach other. The octave levels differ to some extent although they are identical in character. Fig. 6b presents the experimental results for the determination of the locations of the noise sources in the blower by means of the quantity $r_{xy}^{\max}$. Channel X had a unit gain flat transmittance, whereas channel Y had a band-pass transmittance for each octave filter. The opposite situation is shown in Fig. 6d, and results in which both X and Y channels had octave filters are shown in Fig. 6c. It followed from the octave band measurements that in all cases the sources were measured within the scanning angle ($\alpha = 12°$) with respect to the noise source. It is possible to observe only octave displacements related to the kind of quantity measured. However, the simplicity of the procedure and the reliability of the results showed that measurement with octave filters in both X and Y channels was preferable (Fig. 6c). For this case, according to formulae (16) and (20), $\varrho_{xy}^{\max} \approx 1$ should

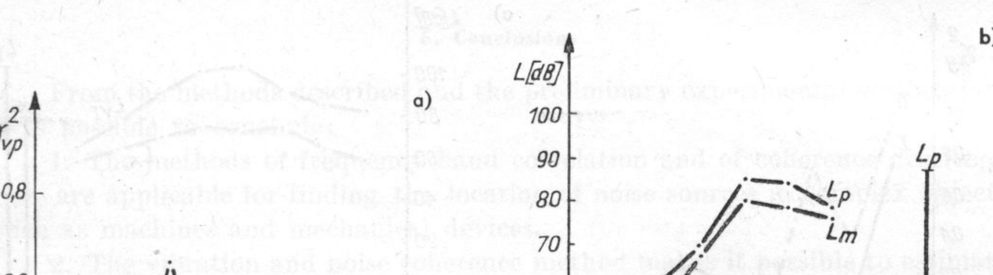

Fig. 8. a) Coherence of vibration-noise at the blower «PYE-LING», b) octave spectrum of the total noise L_p, the mechanical noise L_m and the vibration velocity L_v

be obtained. However, disturbances in the acoustic field due to the room properties make this quantity in some octave bands much less than unity. In an open space or an anechoic chamber the condition $\varrho_{xy}^{\max} \approx 1$ will be more fully realized.

Secondly, we attempted to determine the location of the same sources by means of the coherence function which was measured for two arbitary partial sources: the air inlet I and the air outlet from hose II. Figs 7a-d show the results of these experiments and the corresponding arrangement of microphones.

It follows from the diagram of the coherence function, Fig. 7a, that the blower outlet can be treated as a noise source only within the 2 kHz octave while the blower inlet produces significant components of the resultant noise level within the 500 Hz and 4 kHz octaves.

The attempts to determine the character of the blower noise on the basis of the measured coherence between the casing vibration velocity $[v(t)]$ and the resultant noise $[p(t)]$ are illustrated in Figs 8a and 8b.

It can be seen in Fig. 8a that the radiation of mechanical noise by the vibrating casing can be recognized as significant in the 250 Hz and 2 kHz octave bands ($\gamma_{vp}^2 > 0.5$) in spite of the fact that the level of vibration velocity for 2 kHz octave is low (Fig. 8b). This indicates that the vibration to noise conversion is highly efficient in this band. Fig. 8b demonstrates the spectrum of the mecha-

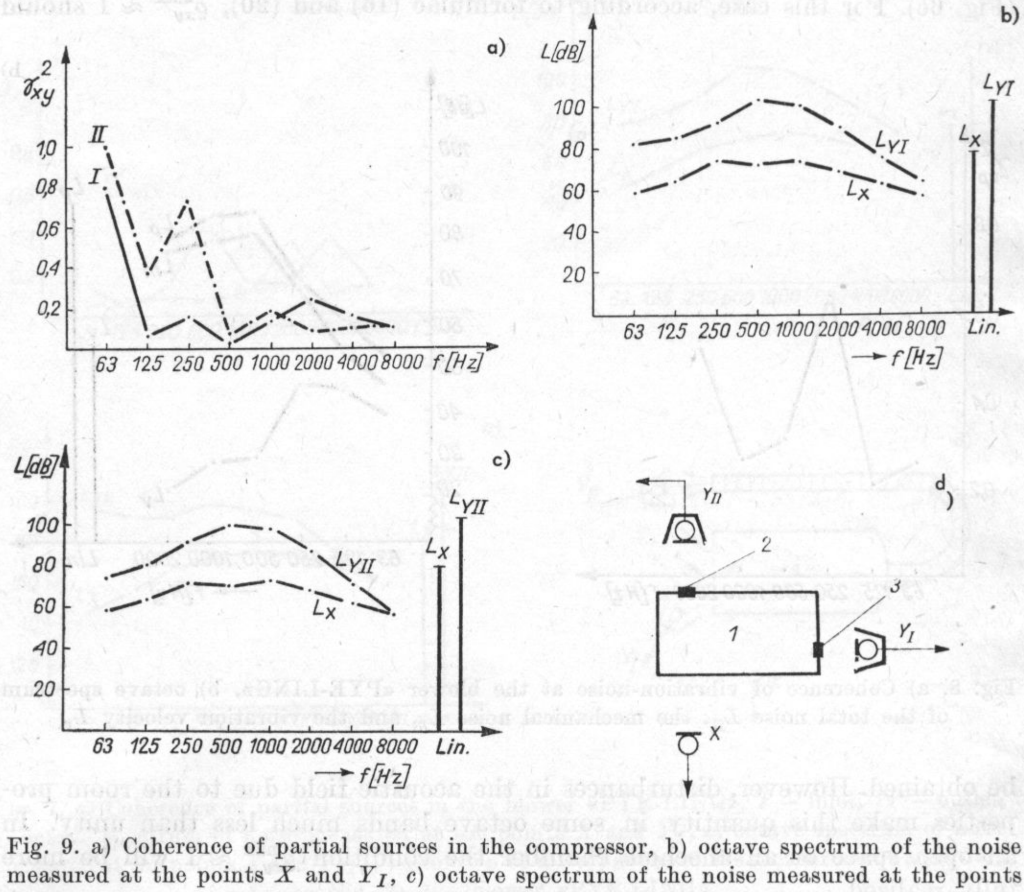

Fig. 9. a) Coherence of partial sources in the compressor, b) octave spectrum of the noise measured at the points X and Y_I, c) octave spectrum of the noise measured at the points X and Y_{II}, d) situation of microphones in the measurements according to Fig. 9
1 – single stroke compressor, 2 – air filter, 3 – electric motor

nical noise obtained by subtracting ΔL_{pm_i} (28) from the spectrum for L_{p_i}. It can be seen that the difference of levels L_{p_i} and L_{m_i} fluctuates within 5 to 7 dB outside the bands of high coherence. This fact indicates that these components are of distinct aerodynamic origin.

Attempts were also made to use the coherence method to determine locations of noise sources in the compressor, treating the filter inlet (*II*) and the electric motor ventilator (*I*) as the arbitrary noise sources. The results of these experiments and the experimental arrangement are shown in Fig. 9a to 9d. It can be seen from Fig. 9a that the inlet filter (*II*) is the main sound source for the low and medium frequencies, 63 to 250 Hz, while the motor ventilator (*I*) produces only the high frequency components, 2 to 4 kHz. The high value of coherence for 63 Hz should presumably be ascribed to the unfavourable location of the microphone Y_I which received not only the noise from the source of interest but also the low frequency components of the resultant noise in the room where the experiments were performed.

6. Conclusions

From the methods described and the preliminary experimental verification, it is possible to conclude:

1. The methods of frequency band correlation and of coherence described here are applicable for finding the location of noise sources in complex objects such as machines and mechanical devices.

2. The vibration and noise coherence method makes it possible to estimate the nature of these noise sources and their effect on the overall noise.

The information obtained in items 1 and 2 can be utilized to reduce noise and vibration in machines and mechanical devices. It should, however, be emphasized that to get more detailed data, it is necessary to improve both the method and measuring set-up for application under industrial conditions. Also a more precise investigation of the distribution of vibrational and acoustical fields around the machine is necessary.

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