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LOCATION OF THE SOURCES OF VIBROACOUSTIC DISTURBANCES IN CONTINUOUS MECHANICAL OBJECTS IN THE CASE OF A BOTTLING LINE

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This paper presents methods of locating sources of vibroacoustic disturbances in continuous mechanical objects. This problem is discussed in the case of the bottling line in a food industry enterprise. As a result of the investigations, the methods of investigation presented were found to be valuable. Their application in minimizing the acoustic activity of individual partial sources is also indicated.

1. Introduction

Location of the noise sources in industrial interiors where individual machines can be regarded as point sources, is not very difficult methodologically, e.g. using the method whereby successive sources are eliminated, or that of coherence analysis [1, 3]. An advantage of the latter method is that it permits assessment of the energy contribution of the individual partial sources to the total noise in the interior, without eliminating them from the technological process. One should also mention a new method of directional location using a detector of noise sources which is based on the directional properties of appropriate microphone transducers.

Location of noise sources becomes more complex when the object under investigation does not satisfy the basic requirements of a point source of sound. Thus the question arises as to when and under what conditions a noise source can be considered to be a point source.

A machine radiating sound into space is recognized as a point source when the following assumptions are met: that the distance r of the observation point is several times longer than the greatest linear dimension, a, of the source ($r \gg a$) and that the radiated wave length λ is also short compared to the observation distance ($r \gg \lambda$). When for any reason these two conditions are not satisfied, the noise source will be called continuous and the machine a continuous mechano-acoustical object.

There is a whole group of technological units, e.g. production lines in rolling mills, bottling lines in the food industry etc., whose linear dimensions are comparable to the dimensions of the industrial interior. Under such conditions of sound radiation it is difficult to find in the interior such a position for the observation point r that the requirements of a point source of sound can be met. In these cases the noise source should be recognized as continuous. It can be assumed in advance that the methods of location and identification of noise sources in industrial interiors applied to those machines that can be regarded as point sources (lathes, milling machines, compressors and fans etc.) require suitable modification for application to the case of the analysis of a continuous source. This results, among other things, from the fact that elimination of one component element of a discrete source (e.g. in a production line in a rolling mill or a bottling line) automatically causes the others to be eliminated. This makes it impossible to eliminate successive units of such a plant. This is the basic difficulty in the vibroacoustic analysis of continuous mechanical objects.

This paper is devoted to the location of the basic noise sources in continuous mechanical systems in the case of a Pepsi-Cola bottling line [2].

2. Formulation of the problem

Fig. 1 shows a block diagram of the bottling line discussed. It can be seen from Fig. 1 that the basic units of the line are interconnected, forming production line of a number of container conveyors of different design. The question arises as to which elements of the line radiate noise into the environment and what their share is in the total noise. The second aspect of this paper is the definition of the contribution to the total noise in the interior of the conveyors, whether empty or carrying bottles. This is a result of the fact that the admissible noise level is exceeded by 3 to 5 dB(A) along the production line. It should be noted that the noise radiated by the bottling line presented has a random character. It is a combination of continuous and pulsed noise of different origins (mechanical and aerodynamic).

3. Method of investigation and measuring apparatus

In order to carry out the task set the following investigations were performed:

— the development of a simplified acoustic map of the noise hazard zones in the interior housing the line in order to locate the most dangerous

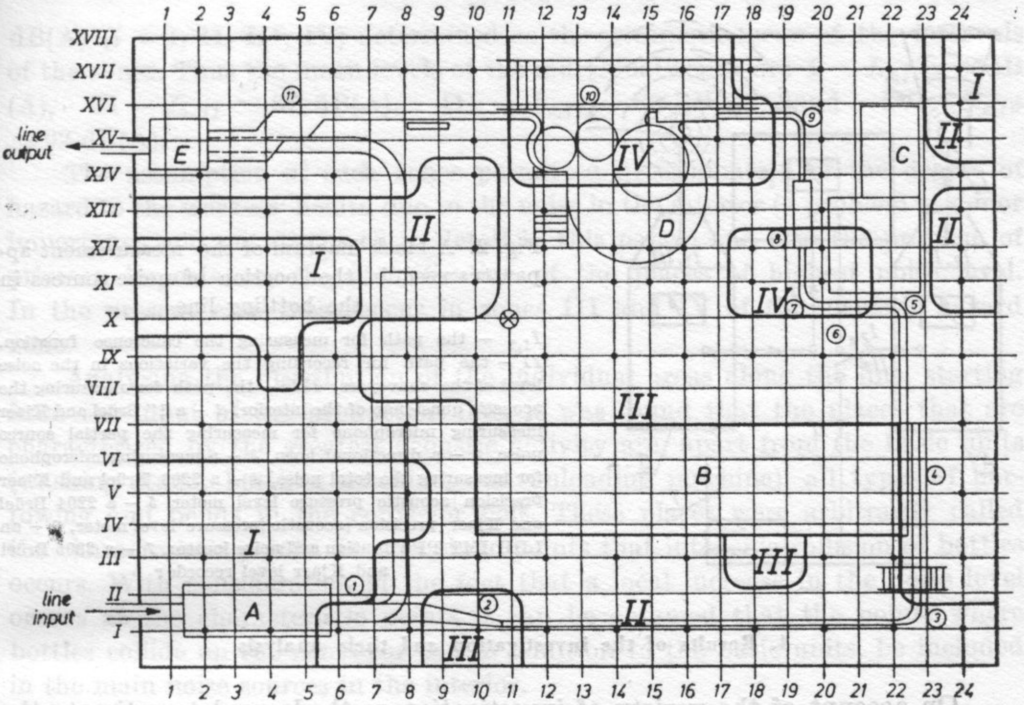


Fig. 1. The block diagram of the position in the interior of the Pepsi-Cola bottling line with the noise hazard zones and the spacing of the points for measuring the partial sources plotted

(I-IV hazard zones)

A **– unloading machine,** ***B*** **– washing stand,** ***C*** **– viewer,** ***D*** **– bottling machine,** ***E*** **– unloading machine for empty bottles; ● – a grid measurement point, ○ – a point for measuring the partial source noise, ⊗ – a point for measuring the total noise L_w = 88 dB (A) ⟨II; III⟩**

points acoustically, and the determination of the mean noise level L_w weighted with respect to the area. This is particularly significant for the selection of the position (zone) for measuring the total noise in the interior as is necessary in the coherence method for the location of noise sources;

– the use of the coherence method for the location of partial noise source in order to determine their energy share in the total noise in the interior;

– the investigation of the acoustic pressure distribution along the conveyor belts only in order to detect those points in the conveyors which are characterized by an increased acoustic activity. This is another way of locating partial noise sources along the conveyor belts.

The whole of the investigations in the present paper were performed using the set of devices shown in Fig. 2. With exception of the vibration and noise locator (a device of the authors' design, which makes it possible to determine the normalised correlation function of two vibroacoustic processes on the basis of sign correlation – a polar correlator), it satisfies the requirements of the Polish Standard PN-64/T-06460.

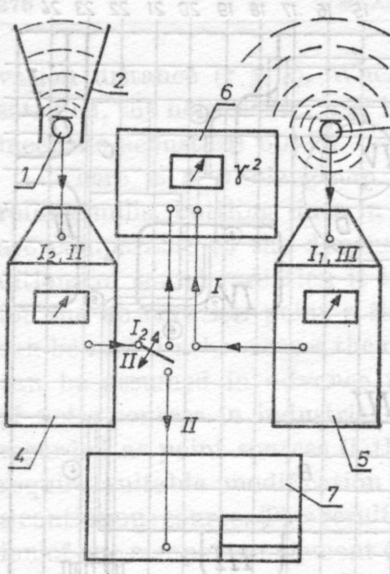


Fig. 2. A block diagram of the measurement apparatus used in the location of noise sources in the bottling line

$I_{1,2}$ – the path for measuring the coherence function, II – the path for recording the variations in the noise level of the conveyors, III – the path for measuring the acoustic quasi-map of the interior, 1 – a 1″ Brüel and Kjaer measuring microphone for measuring the partial source noise, 2 – a directional horn, 3 – a measuring microphone for measuring the total noise, 4 – a 2203 Brüel and Kjaer precision acoustic pressure level meter, 5 – a 2204 Brüel and Kjaer precision acoustic pressure level meter, 6 – an LDH IMT PP vibration and noise locator, 7 – a 2305 Brüel and Kjaer level recorder

4. Results of the investigation and their analysis

On account of the variety of investigation methods used to estimate the vibroacoustical activity of the bottling line the successive stages of the investigation are discussed individually, with an indication of their agreement as to the correct location of the partial sources in the bottling line.

In order to develop a simplified acoustical map (noise hazard zones) of the interior, a 1 m × 1 m grid was superposed on the whole surface area of the interior. The measured quantities were in this case the noise levels measured with respect to the characteristics of the device: the correction characteristic (A) and the linear characteristic (Lin). In these measurements the measuring microphone (path III, Fig. 2), was placed at a height of about 1.5m above the floor of the interior. On the basis of the results obtained the following intervals of noise levels in dB (A) were assumed as the limits of the hazard zones:

I – $L_I \in \langle 84;\ 86 \rangle$,
II – $L_{II} \in \langle 86.5;\ 88 \rangle$,
III – $L_{III} \in \langle 88.5;\ 90 \rangle$,
IV – $L_{IV} \in \langle 90.5;\ 93 \rangle$.

On the basis of these intervals, the hazard areas corresponding to the individual zones were plotted and the limits of the areas were set using algebraic interpolation (the arithmetic mean) between the noise levels of the neighbouring measurement points. The boundaries of the individual areas and their size are shown in Fig. 1. On account of the large number of measurement points it was assumed that each zone could be represented by the mean level L_{mi} in dB(A) (i = I, II, III, IV) determined as the arithmetic mean of the intervals of the zones. Thus the mean levels of the individual zones are I – $L_{mI} \cong$ 85dB (A), II – $L_{mII} \simeq$ 87 dB(A), III – L_{mIII} 89 dB(A) and IV – L_{mIV} $\simeq$ 92 dB(A).

The assumption of such zones permitted determination of the degree of hazard to the workers' health due to the noise in the interior (a problem of minor importance and not discussed in detail in this paper) and also the problem of primary importance, the identification of the places of highest noise level. In the present case these occur in zones III and IV of the acoustic hazard zone.

Analyzing the distribution of the individual areas along the line, starting from the input of the production line, it was found that the places that are characterized by the greatest acoustic activity are, apart from the basic units (washing stand, bottling machine, and unloading machine), all types of narrowing and bends in the conveyor belt. These places were arbitrarily called the characteristic points. It is at these points that intensive collision of bottles occurs. With consideration of the fact that a local increase in the noise level occurs at the characteristic points it can be assumed that the points where bottles collide on the conveyor can in addition to the basic units, be included in the main noise sources in the interior.

Although the simplified acoustic map (Fig. 1) permitted separation of the basic noise sources in the bottling line, it gave no information on the energy share of the individual partial sources (the units and characteristic points of the conveyor line) in the total noise in the interior. This is significant, since apart from the significance in terms of the energy of the individual sources, it also gives the ranking of potential measures for minimizing the noise.

The latter end is served by the coherence method of location, which consists in the measurement of the band function of the normal coherence. It is a measure of the similarity of two vibroacoustical processes: the first being the total noise in the interior – path I in Fig. 2, the second being the noise radiated by an elementary source – path II in Fig. 2. It can be used to determine the maximum statistical similarity between the total noise in the interior and the sound disturbances of the individual partial sources in the spectral domain. The present investigation used for this purpose octave bands of the following central frequencies: 100, 250, 500, 1000, 2000, 4000 and 8000 Hz.

Knowing the coherence function of the processes investigated, x and y, in the ith frequency band, similarity or identity can be determined, since:

$\gamma_{xy}^2(f_i) = 1$ if the processes are statistically identical in the band Δf_i;

$0 < \gamma_{xy}^2(f_i) < 1$ if the processes are statistically similar in the band Δf_i;

$\gamma_{xy}^2(f_i) = 0$ if the processes are statistically different in the band Δf_i.

In order to determine the share of the elementary source in the total noise, it is necessary to set a limit, from which the partial source will to a greater or lesser extent affect the overall noise level (total level) in the interior.

From acoustics it is known that when the difference in the noise levels of two sources exceeds 10 dB [2], then the influence on the total noise of the source with a lower sound level can be neglected. Taking this into account, a boundary value (in terms of the sound pressure) can be established, below which the noise from an elementary source will not affect the total noise level 10 dB $\Rightarrow$ 0.316.

Thus the power radiated by a partial source can be neglected if

$$|\gamma_{xy}(f_i)| \leqslant 0.316 \Leftrightarrow \gamma_{xy}^2(f_i) \leqslant 0.1,$$

i.e. 0.1 is the boundary value of the coherence function.

It can be seen from the above remarks that the coherence method for the location of noise sources requires a measurement of the total noise (measurement in a diffuse acoustic field) and a measurement of the sound disturbances from the source itself. The set of necessary apparatus for the task to be carried out is shown in Fig. 2.

The position of the microphone for measuring the total noise level (path I_1 in Fig. 2) was chosen on the basis of the noise hazard zones established. The mean noise level L_w dB(A), weighted with respect to area, was determined for the whole of the interior using the relation

$$L_w = 10\log\frac{\sum_{i=I}^{IV} S_i I_{mi}}{S_c} \quad [\text{dB(A)}],$$

where S_i is the area corresponding to the ith zone [m²], I_{mi} is the sound intensity [W/m²] corresponding to L_{mi} (the mean level of the ith zone),

$$L_{mi} = 10\log\frac{I_{mi}}{I_0} \quad [\text{dB(A)}],$$

S_c is the total area of the interior [m²], I_0 is the intensity of reference sound, $I_0 = 10^{-12}\ \text{W}\cdot\text{m}^{-2}$.

In the case under investigation, the L_w level was 80 dB(A). Considering further the intervals of noise level for the individual hazard zones, it was found that $L_w \in \langle \text{II-III} \rangle$ zones.

Accordingly, the microphone for measuring the total noise in the coherence method, was placed at the boundary of zones II and III (Fig. 1). The partial sources in the present method were the basic units of the line and the so called characteristic points (points of narrowing and bends in the conveyor belts etc). Their situation is also shown in Fig. 1.

The values of the function $\gamma_{xy}^2(f_i)$ as a function of the central frequencies of the octave bands are listed in Table 1 and also shown graphically in Fig. 3.

Curves *4* (washing stand) and *10* (bottling machine) show the share of the noise from these units in the total noise. The boundary value assumed for

Table 1. The values of the coherence function $\gamma_{xy}^2(f_i)$ for noise processes in an interior housing the Pepsi-Cola bottling line

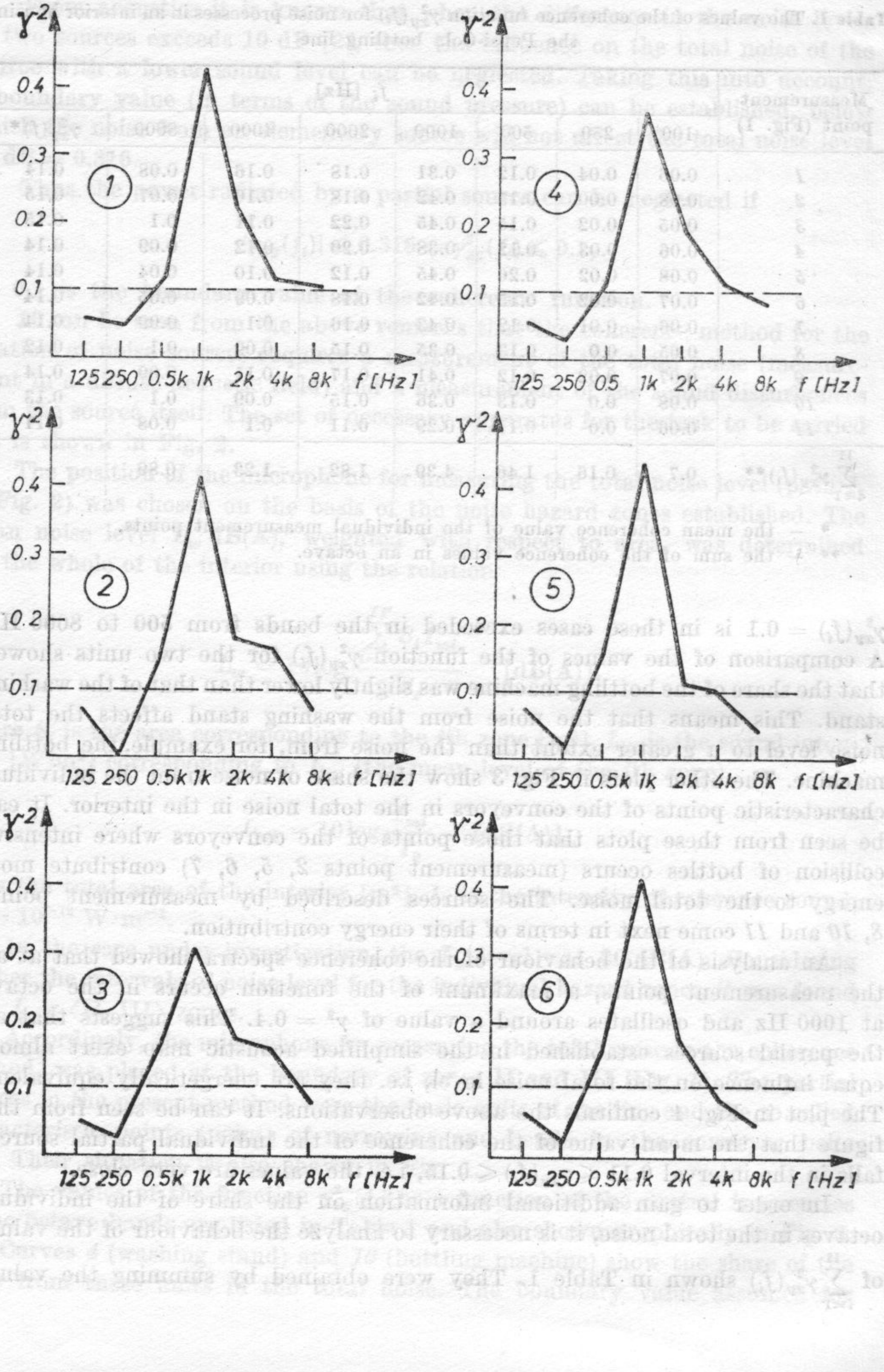
Measurement point (Fig. 1)	f_i [Hz]							
	100	250	500	1000	2000	4000	8000	$\gamma_{xy}^2(f)$*
1	0.06	0.04	0.12	0.31	0.18	0.16	0.08	0.14
2	0.08	0.00	0.15	0.42	0.18	0.16	0.07	0.15
3	0.05	0.02	0.15	0.45	0.22	0.11	0.1	0.15
4	0.06	0.03	0.12	0.38	0.20	0.12	0.09	0.14
5	0.08	0.02	0.26	0.45	0.12	0.10	0.04	0.14
6	0.07	0.02	0.15	0.42	0.18	0.09	0.05	0.14
7	0.06	0.01	0.12	0.43	0.16	0.1	0.09	0.14
8	0.05	0.0	0.13	0.35	0.15	0.09	0.1	0.12
9	0.07	0.02	0.12	0.41	0.17	0.11	0.09	0.14
10	0.08	0.0	0.13	0.36	0.15	0.09	0.1	0.13
11	0.06	0.0	0.11	0.29	0.11	0.1	0.08	0.11
$\sum_{i=1}^{11} \gamma_{xy}^2(f_i)$**	0.7	0.16	1.46	4.39	1.82	1.23	0.89	–

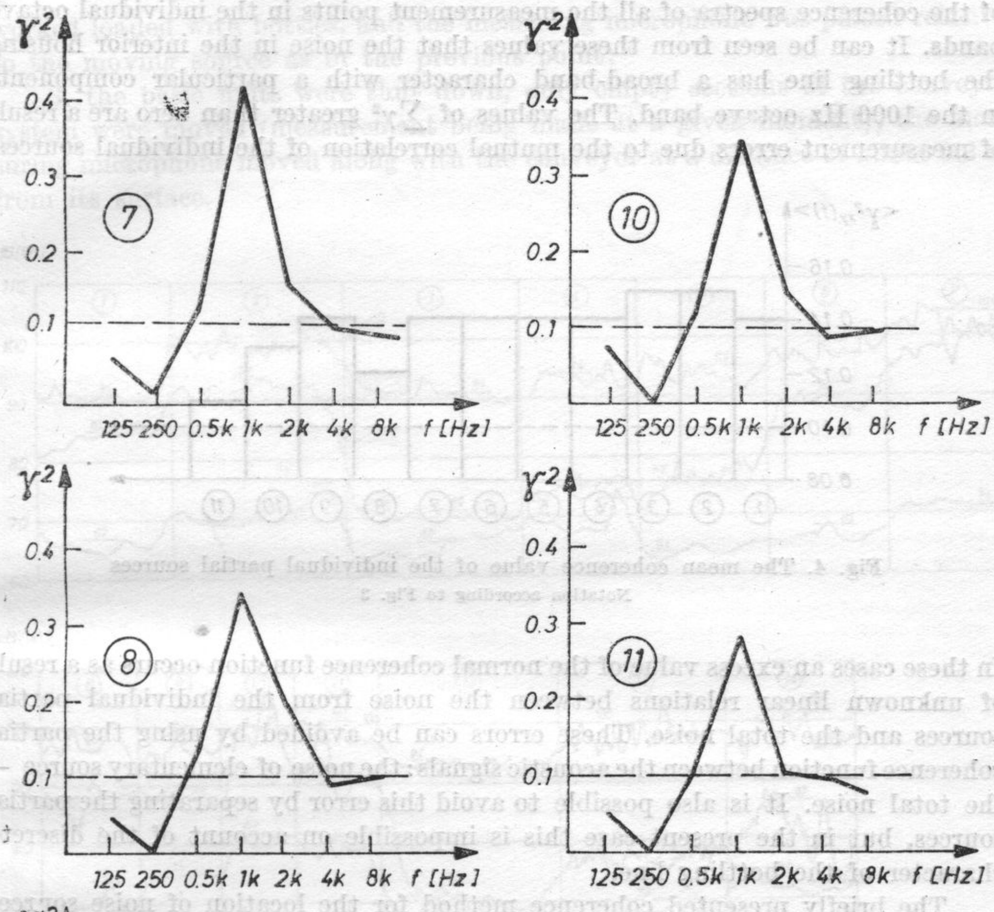
* – the mean coherence value of the individual measurement points,
** – the sum of the coherence values in an octave.

$\gamma_{xy}^2(f_i) = 0.1$ is in these cases exceeded in the bands from 500 to 8000 Hz. A comparison of the values of the function $\gamma_{xy}^2(f_i)$ for the two units showed that the share of the bottling machine was slightly lower than that of the washing stand. This means that the noise from the washing stand affects the total noise level to a greater extent than the noise from, for example, the bottling machine. The other plots in Fig. 3 show the share of noise from the individual characteristic points of the conveyors in the total noise in the interior. It can be seen from these plots that those points of the conveyors where intensive collision of bottles occurs (measurement points *2*, *5*, *6*, *7*) contribute most energy to the total noise. The sources described by measurement points *8*, *10* and *11* come next in terms of their energy contribution.

An analysis of the behaviour of the coherence spectra showed that at all the measurement points, a maximum of the function occurs in the octave at 1000 Hz and oscillates around a value of $\gamma^2 = 0.4$. This suggests that all the partial sources established in the simplified acoustic map exert almost equal influence on the total noise level, i.e. they are energetically equivalent. The plot in Fig. 4 confirms the above observations. It can be seen from this figure that the mean value of the coherence of the individual partial sources falls in the interval $0.11 \leqslant \gamma_{xy}(f_i) \leqslant 0.15$, i.e. the values are very close.

In order to gain additional information on the share of the individual octaves in the total noise, it is necessary to analyze the behaviour of the values of $\sum_{i=1}^{11} \gamma_{xy}^2(f_i)$ shown in Table 1. They were obtained by summing the values


γ²
0.4
0.3
0.2
0.1
1
2
3
4
5
6
125 250 0.5k 1k 2k 4k 8k f [Hz]
125 250 0.5 1k 2k 4k 8k f [Hz]



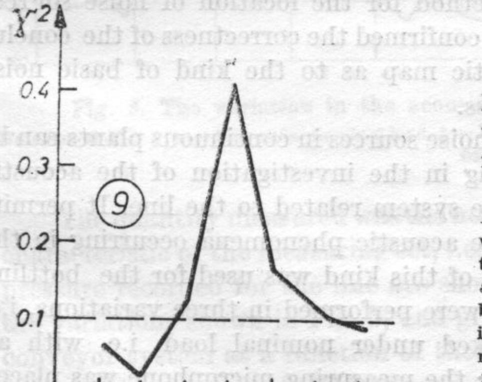


Fig. 3. The coherence noise spectra in an interior housing a Pepsi-Cola bottling line (coherence: total noise – a specific area of the line)

1 – the input to the unloading machine, *2* – the narrowing behind the unloading machine, *3* – the bend before the washing stand, *4* – the work post before the viewer, *5* – the bend after the washing stand, *6* – the narrowing before the viewer, *7* – the bend before the viewer, *8* – the input to the viewer, *9* – the bend before the bottling machine, *10* – the work post at the bottling machine, *11* – the change of direction before the unloading machine for empty bottles (the discontinuous line denotes the boundary value γ_{xy})

of the coherence spectra of all the measurement points in the individual octave bands. It can be seen from these values that the noise in the interior housing the bottling line has a broad-band character with a particular components in the 1000 Hz octave band. The values of $\sum\gamma^2$ greater than zero are a result of measurement errors due to the mutual correlation of the individual sources.

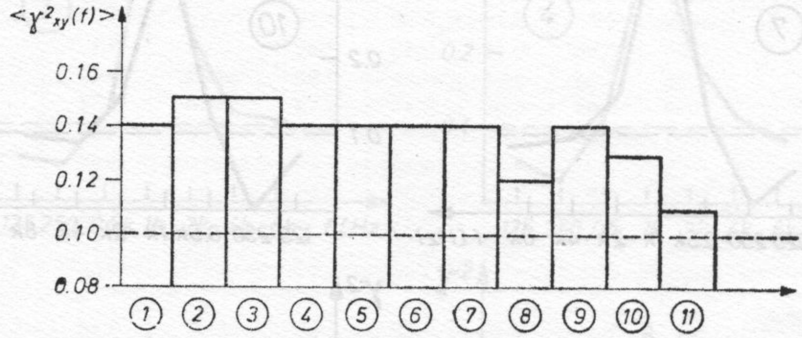


Fig. 4. The mean coherence value of the individual partial sources
Notation according to Fig. 3

In these cases an excess value of the normal coherence function occurs as a result of unknown linear relations between the noise from the individual partial sources and the total noise. These errors can be avoided by using the partial coherence function between the acoustic signals: the noise of elementary source – the total noise. It is also possible to avoid this error by separating the partial sources, but in the present case this is impossible on account of the discrete character of the bottling line.

The briefly presented coherence method for the location of noise sources in a mechanical continuous system fully confirmed the correctness of the conclusions arising from the simplified acoustic map as to the kind of basic noise sources occurring in systems of this class.

These two methods of locating the noise sources in continuous plants can be complemented with a method consisting in the investigation of the acoustic pressure of a production line in a mobile system related to the line. It permits a precise and continuous analysis of the acoustic phenomena occurring in the work of a plant investigated. A method of this kind was used for the bottling line described, where the investigations were performed in three variations, i.e.

1. the entire bottling system worked under nominal load, i.e. with an output of about 90 000 bottles per shift; the measuring microphone was placed at a distance of about 0.15 m above a given bottle and moved at the velocity of the conveyor along the entire line from the unloading machine to the loading machine;

2. the basic units of the line (the unloading machine, the washing stand etc.) were shut down, only individual sections of the conveyor system being

worked loaded with bottles, and the measuring microphone was placed relative to the moving source as in the previous point;

3. the basic units were shut down, only empty sections of the conveyor system were moved (measurement being made at a given moment); the measuring microphone moved along with the conveyor at a distance of about 0.2 m from its surface.

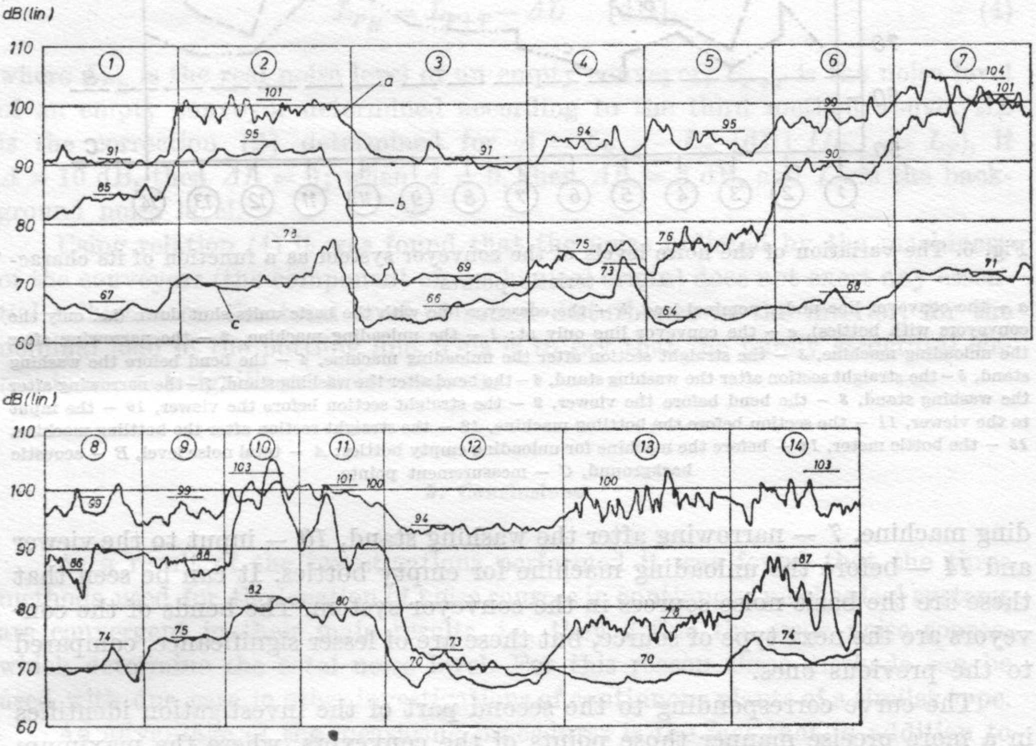


Fig. 5. The variation in the acoustic pressure level along the conveyor line

Notation as Fig. 3; *a* — line under nominal load, *b* — line under nominal load but without basic units, *c* — empty conveyors

The quantity measured was the noise level measured with respect to the linear characteristic of the measuring set, i.e. in dB(Lin). The variations of the acoustic pressure recorded for the line are shown in Fig. 5. Fig. 6 was constructed from the variations shown in Fig. 5, and gives the variations in the noise level of the conveyor system as a function of their characteristic points (narrowings, bends, straight sections etc.). This figure also shows the linear values of the total noise level and of the background noise, which determine the validity of the results obtained.

It can be seen from the behaviour of the curve corresponding to the nominal line load that the highest noise levels occur where intensive collision of bottles takes place. These are the points designated as *2* — narrowing after the unloa-

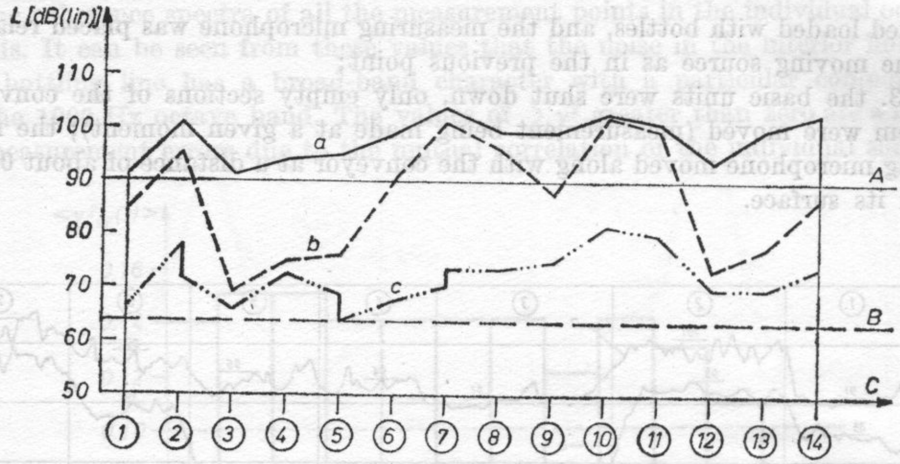


Fig. 6. The variation of the noise levels of the conveyor system as a function of its characteristic points

a – the conveyor line under nominal load, *b* – the conveyor line with the basic units shut down (i.e. only the conveyors with bottles), *c* – the conveyor line only at: *1* – the unloading machine, *2* – the narrowing after the unloading machine, *3* – the straight section after the unloading machine, *4* – the bend before the washing stand, *5* – the straight section after the washing stand, *6* – the bend after the washing stand, *7* – the narrowing after the washing stand, *8* – the bend before the viewer, *9* – the straight section before the viewer, *10* – the input to the viewer, *11* – the section before the bottling machine, *12* – the straight section after the bottling machine, *13* – the bottle meter, *14* – before the machine for unloading empty bottles; *A* – total noise level, *B* – acoustic background, *C* – measurement points

ding machine, *7* – narrowing after the washing stand, *10* – input to the viewer and *14* – before the unloading machine for empty bottles. It can be seen that these are the basic noise sources in the conveyor system. The bends of the conveyors are the next type of source, but these are of lesser significance, compared to the previous ones.

The curve corresponding to the second part of the investigation identifies in a more precise manner those points of the conveyors, where the maximum noise levels occur. These are narrowings (points *2* and *7*), the points where the containers enter the viewer (point *10*), and the section of the curved line together with the bend before the bottling machine. Slight differences in the noise levels at these points were determined for the first and second working variations and they suggest that these points of the conveyors are among the basic noise sources in the interior. The values of these differences show, however, the magnitude of the influence of the basic units on the noise levels at the points of the conveyors under discussion.

The last curve, plotted from the third part of the investigation, shows the variation of the acoustic pressure level along the conveyors when they run idle. An analysis of the behaviour of this curve as a function of the position of the characteristic point of the conveyors, showed that on straight sections the noise level corresponds approximately to the noise level of the acoustic background. An increase in the level of sound disturbances was observed only at those points of the conveyors where the straining and driving elements are situated. The questions arise as to whether the mechanical noise from an empty conveyor affects the total noise level in the interior and whether an empty conveyor can be regarded as a partial source. In order to answer these questions it is above all necessary to determine the real noise of the empty conveyor. This can be done using relation [2]

$$L_{P_R} = L_{P+T} - \Delta L \quad [\mathrm{dB}], \tag{4}$$

where L_{P_R} is the real noise level of an empty conveyor, L_{P+T} is the noise level of an empty conveyor determined according to the third method above, ΔL is the correction [2] determined for $\Delta = L_{P+T} - L_T$ [dB] ($L_{P+T} > L_T$), if $\Delta > 10$ dB, then $\Delta L = 0$; when $\Delta = 0$, then $\Delta L = 3$ dB, and L_T is the background noise level.

Using relation (4) it was found that the noise radiated by the machinery of the conveyors (the component of mechanical origin) does not exert any essential influence on the total level of sound disturbance in the interior, for the nominal load of the bottling line. This is to say that the purely structural elements are not significant noise sources.

5. Conclusions

As a result of the investigations performed it was found that the three methods used for the location of noise sources in continuous mechanical systems are convergent in their main results, i.e. they define the same noise source, which determine the total noise level. For this reason these methods can be used with due care in other investigations of continuous plants of a similar type.

An advantage of the measuring procedures is the fact that in addition to source location they make it possible to estimate the noise hazard (in terms of a simplified acoustic map of the interior) to the health of the employees, and to determine the energy share (using the coherence method) of the individual partial sources in the total noise. The latter method also makes it possible to choose the optimum way of reducing excess noise.

This investigation also happened to show that the coherence method sometimes gives erroneous results in the energetic quantification of partial noise sources for continuous sources (see Table 1). Despite this, it permits some tentative qualitative and quantitative conclusions to be drawn. Its modification must, however, be proposed or otherwise another method must be developed, which is designed to be applied to a continuous noise source. The acoustic map used in the investigation once more showed its usefulness for noise hazard estimation. Moreover, the investigation of the noise level in a moving line system, which has been used here for the first time, is worth recommending as a method of locating the areas of high noise level within the continuous source itself. The reliability of this method and also its possible mutations will doubtless be investigated in the future.

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