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MECHANO-ACOUSTIC FEEDBACK IN THE CASE OF AN INTERACTION BETWEEN A SOUND SOURCE AND A RESONANCE SYSTEM

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This paper presents an analysis of the mechano-acoustic feedback between a sound source and a resonance system. In the theoretical part, the change in the mechanical impedance of the sound source which occurs when the source is affected by the external acoustic field is determined; and subsequently, using the image source method, the distribution of the standing pressure wave between the source and the resonator is given. The combination of the relations thus derived permits the distribution of the standing pressure wave between the source and the resonator to be determined, with consideration given to changes in the radiation impedance of the source and the mechanical parameters of the resonator. The experimental part gives the results of measurements of the dependence of the mean value of the modulus of the pressure amplitude of the standing wave on frequency for different resonance frequencies of the resonator and a comparison of the experimental and theoretically determined results in the case of an interaction between a sound source and a rigid baffle.

1. Introduction

In some aerodynamic problems, such as gas flow over a resonance cavity [1] or a mutual interaction between a resonance system and a sound source which occurs when gas flows on to a sharp edge [2], there is the necessity of using a physical model of the phenomenon which accounts for the interaction of mechanical, aeroacoustic and acoustic factors [2]. The process of sound generation due to the existence of the mechano-aerodynamic feedback is so complex that it has not been given an exact mathematical description; theory, in turn, is restricted to experimental formulae and relationships [3]. There is, however, the possibility of analyzing individually all the kinds of feedbacks which occur in flow phenomena.

The present paper gives a theoretical analysis of the mechano-acoustic interaction between a sound source, i.e. a loudspeaker and a resonance system with uniformly distributed surface impedance. The considerations are concerned with the frequency range over which the loudspeaker generates a plane wave.

2. Theoretical analysis

2.1. *Change in the radiation impedance of a dynamic loudspeaker caused by the introduction of reflecting surfaces or sound sources in its environment*

A dynamic loudspeaker as an electromechanical transducer of the magnetic type can be represented by an equivalent circuit where a gyrator with the impedance Z_s is the element which couples the electric and mechanical parts.

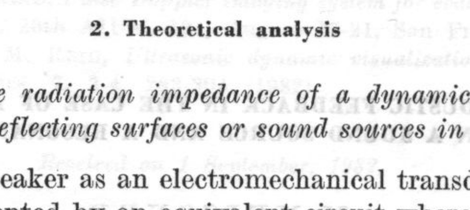

Fig. 1. A mechano-electrical equivalent circuit of an excited loudspeaker. U_0 – the rms value of the voltage supply to the loudspeaker, U_p – the rms value of the voltage at the gyrator, I – the rms value of the current intensity, F_p – the rms value of the force at the gyrator, V – the rms value of the mechanical velocity, Z_e – the impedance of the electrical part of the loudspeaker, $Z_{mg}+Z_{mp}$ – the impedance of the mechanical part of the loudspeaker, Z_{mp} – the radiation impedance

The properties of an ideal gyrator as part of the transducing part of the transducer can be defined from the matrix [1]

$$\begin{bmatrix} U_p \\ F_p \end{bmatrix} = \begin{bmatrix} 0 & -Z_s \\ -Z_s & 0 \end{bmatrix} \begin{bmatrix} I \\ V \end{bmatrix}, \tag{1}$$

where U_p is the rms value of the electric voltage at the gyrator, I is the rms value of the current intensity, F_p is the rms value of the mechanical force at the gyrator, V is the rms value of the mechanical velocity, $Z_s = Bl$; where B is the magnetic field induction in the slit and l is the winding length of the loudspeaker coil.

Using relation (1) the mechano-electric equivalent circuit of the transducer can be replaced with one which contains only mechanical or electric quantities. When on the electrical side the loudspeaker is supplied from a source with the voltage U_0, in its mechanical equivalent circuit the loading of the force source F_z with the internal impedance $Z_{mw} = Z_s^2/Z_e + Z_{mg}$ is the mechanical radiation impedance Z_{mp}, where Z_{mg} is the impedance of the mechanical system of the loudspeaker without the radiation impedance, whereas Z_s^2/Z_e is an equivalent to the electric impedance of the loudspeaker in the mechanical circuit (Fig. 2).

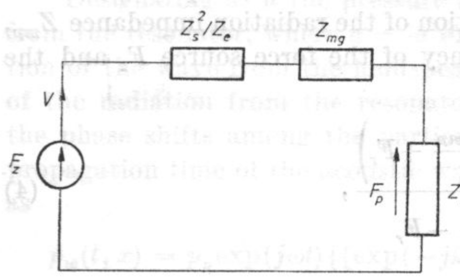

Fig. 2. A mechanical equivalent circuit of a loudspeaker radiating into unbounded space. F_z – the rms value of the force at the force source, equivalent to the voltage source U_0 in the mechanical circuit, F_p – the rms value of the mechanical force corresponding to the loading of the loudspeaker by an unbounded medium, Z_s^2/Z_e – the equivalent of the electric impedance of the loudspeaker in the mechanical equivalent circuit, Z_s – the coupling impedance of the gyrator, $Z_{mg}+Z_{mp}$ – the impedance of the mechanical part of the loudspeaker, Z_{mp} – the radiation impedance, V – the rms value of the mechanical velocity

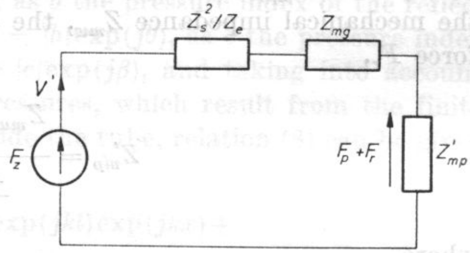

Fig. 3. A mechanical equivalent circuit of a loudspeaker acted upon by a reflexive acoustic wave. F_z – the rms value of the force of the force source which is the equivalent of the voltage source U_0 in the mechanical circuit, F_p – the rms value of the mechanical force corresponding to the loading of the loudspeaker by an unbounded medium, F_r – the rms value of the mechanical force which describes the additional loading of the loudspeaker by the reflexive acoustic field, V' – the rms value of the mechanical velocity, Z_s^2/Z_e – the equivalent of the electric impedance of the loudspeaker in the mechanical equivalent circuit, Z_s – the coupling impedance of the gyrator, $Z_{mg}+Z'_{mp}$ – the impedance of the mechanical part of the loudspeaker, Z'_{mp} – the radiation impedance

When only the wave radiated by the loudspeaker occurs in the medium, it follows from the third principle of dynamics that the medium acts on the loudspeaker with the force $-F_p = -Z_{mp}V$. When in the space surrounding the loudspeaker fed there are reflecting surfaces or sound sources, the additional force $-F_r$, which results from the existence of the reflexive or external acoustic field, acts on the loudspeaker. At a constant value of the supply voltage U_0 the additional force acting on the loudspeaker causes a change in its radiation impedance (Fig. 3). Considering the relationship resulting from the circuit in Fig. 3,

$$V' = \frac{F_p + F_r}{Z'_{mp}} = \frac{F_z}{Z'_{mp} + Z_{mw}}, \tag{2}$$

and the expression of the magnitude of the force F_p from Fig. 2,

$$F_p = Z_{mp}\frac{F_z}{Z_{mp}+Z_{mw}}, \tag{3}$$

after some transformations, the value of the new radiation impedance of the loudspeaker, Z'_{mp}, can be obtained as a function of the radiation impedance Z_{mp}, the mechanical impedance Z_{mw}, the efficiency of the force source F_z and the force F_r,

$$Z'_{mp} = \frac{Z_{mw}\left(\dfrac{F_z Z_{mp}}{Z_m}+F_r\right)}{\dfrac{F_z Z_{mw}}{Z_m}-F_r}, \tag{4}$$

where

$$Z_m = Z_{mp}+Z_{mw}; \tag{5}$$

$$Z_{mp} = R_{mp}+jX_{mp}; \tag{6}$$

$$Z'_{mp} = R'_{mp}+jX'_{mp}. \tag{7}$$

2.2. *The value of the acoustic pressure inside the Kundt tube*

Over the frequency range at which the acoustic wave length is at least twice as large as the diameter of the Kundt tube, the wave radiated by the loudspeaker can be replaced with a plane wave [4], whereas the membrane of the loudspeaker can be regarded as a plane, circular vibrating piston [5]. The origin of the axis of the coordinate x, which defines the propagation of acoustic perturbations in space, lies on the surface of this piston. Inside the tube, at the distance l from the source, there is a resonance system with uniformly distributed surface impedance and dimensions corresponding to the

ed by it and the wave radiated by the system have the form of plane waves with the same propagation directions as that of the incident wave.

For plane waves propagating in a direction parallel to the walls of the tube the instantaneous value of the sound pressure at all points of the cross-section of the tube is the same and the image source method can be used to analyze the resultant pressure inside the tube. In a steady state the resultant sound pressure is the sum of four kinds of pressure, i.e.

1. the pressure radiated by the loudspeaker, $p_0\exp[j(\omega t-kx)]$,
2. the pressure radiated by the resonator, $p_1\exp[j(\omega t+kx)]$,
3. the pressure being the sum of an infinite number of reflections from the resonator and the loudspeaker of the wave radiated by the loudspeaker, $p_2(t, x)$,

4. the pressure being the sum of an infinite number of reflections from the resonator and the loudspeaker of the wave radiated by the resonator, $p_3(t_x)$, i.e.

$$p_w(t, x) = p_0 \exp[j(\omega t - kx)] + p_1 \exp[j(\omega t + kx)] + p_2(t, x) + p_3(t, x). \quad (8)$$

Designating as a the pressure index of the reflection of the acoustic wave from the resonator, where $a = |a| \exp(j\phi)$, as b the pressure index of the reflection of the wave from the loudspeaker, $b = |b| \exp(j\theta)$, as c the pressure index of the radiation from the resonator, $c = |c| \exp(j\beta)$, and taking into account the phase shifts among the particular pressures, which result from the finite propagation time of the acoustic wave inside the tube, relation (8) can be given as

$$\begin{aligned} p_w(t, x) = p_0 \exp(j\omega t)\{[&\exp(-jkx) + c\exp(jkl)\exp(jkx) + \\ &+ a\exp(jkl)\exp(jkx) + ab\exp(j2kl)\exp(-jkx) + \\ &+ a^2b\exp(j3kl)\exp(jkx) + a^2b^2\exp(j4kl)\exp(-jkx) + \ldots] + \\ &+ [cb\exp(j2kl)\exp(-jkx) + cab\exp(j3kl)\exp(jkx) + \\ &+ cab^2\exp(j4kl)\exp(-jkx) + ca^2b^2\exp(j5kl)\exp(jkx) + \ldots]\}; \end{aligned} \quad (9)$$

which after transformations becomes

$$\begin{aligned} p_w(t, x) = p_0 \exp(j\omega t)\{&\exp(-jkx)[1 + bc\exp(j2kl)] + \\ &+ \exp(jkx)[a\exp(jkl) + c\exp(jkl)]\}\Big\{1 + \sum_{n=1} [ab\exp(j2kl)]^n\Big\}. \end{aligned} \quad (10)$$

Since $|b| < 1$ and $|a| \leqslant 1$, the infinite series which occurs in formula (10) is convergent and the use of the formulae

$$1/2 + \sum_{n=1}^{\infty} D^n \cos nz = 1/2 \frac{1 - D^2}{1 - 2D\cos z + D^2}; \; |D| < 1; \quad (11)$$

$$\sum_{n=1}^{\infty} D^n \sin nz = \frac{D \sin z}{1 - 2D\cos z + D^2};$$

and some simple transformations give the relation

$$1 + \sum_{n=1}^{\infty} [ab\exp(j2kl)]^n = \frac{1}{1 - ab\exp(j2kl)}; \quad (12)$$

thus the final expression of the resultant pressure inside the tube becomes

$$\begin{aligned} p_w(t, x) = \frac{p_0 \exp(j\omega t)}{1 - ab\exp(j2kl)}\{&\exp(-jkx)[1 + bc\exp(j2kl)] + \\ &+ \exp(jkx)[a\exp(jkl) + c\exp(jkl)]\}. \end{aligned} \quad (13)$$

From relation (12), the maximum and minimum values of the modulus of the pressure $p_w(t, x)$,

$$|p_w(t, x)|_{\min}^{\max} = |p_0| \frac{1 \pm |a| \pm |c| \pm |bc|}{[1-2\,|ab|\cos(2kl+\phi+\theta)+|ab|^2]^{1/2}}; \tag{14}$$

and, from equations (14), the mean value of the pressure modulus

$$\frac{|p_w(t, x)|\max + |p_w(t, x)|\min}{2} = \frac{p_0}{[1-2|ab|\cos(2kl+\phi+\theta)+|ab|^2]^{1/2}}. \tag{15}$$

can thus be obtained.

Equation (15) indicates that, depending on the frequency and the mechanical parameters of the loudspeaker and the resonator, the mean value of the modulus of the pressure in the tube varies greatly. This is related to the resonance of the Kundt tube itself, whose frequencies can shift as the reflection properties of the loudspeaker and the resonator change. The denominator of expression (15) reaches its minimum value of $1-|ab|$ at frequencies for which the relation

$$2kl+\phi+\theta = 2n\pi, \quad n \in N; \tag{16}$$

is satisfied, and its maximum value $1+|ab|$ when

$$2kl+\phi+\theta = (2n+1)\pi, \quad n \in N. \tag{17}$$

Since, however, because of the mutual interaction between the loudspeaker and the resonator, the value of the modulus of the pressure radiated by the loudspeaker, $|p_0|$, varies depending on the frequency, the maximum and minimum mean values of the modulus of the pressure in the tube can occur for frequencies different from those for which relations (16) and (17) are satisfied.

2.3. *Mutual interaction between the dynamic loudspeaker as a sound source and the resonance system in the Kundt tube*

As a result of the presence of a resonance system in the effective range of the loudspeaker, part of the energy radiated by the loudspeaker in the form of acoustic waves returns to the source and, depending on the phase shifts, the conditions of sound radiation improve or worsen. The value of the amplitude of the sound pressure acting on the membrane of the loudspeaker can be obtained from formula (13), by the substitution $x = 0$, i.e.

$$p_{wa}(x=0) = \frac{p_0}{1-ab\exp(j2kl)}[1+bc\exp(j2kl)+a\exp(jkl)+c\exp(jkl)]. \tag{18}$$

The amplitude of the pressure which occurs at the loudspeaker as a result of multiple reflections of the acoustic wave from the resonator and loudspeaker and as a result of the radiation from the resonator is thus defined by the relation

$$p_{ra} = p_{wa}(x=0) - p_0. \tag{19}$$

Substitution of mechanical forces for the pressures gives the expression of the force F_r acting on the loudspeaker (point 2.1.),

$$F_r = F_w(x=0) - F_0 = F_0(A_0 - 1), \tag{20}$$

where

$$A_0 = \frac{1 + bc\exp(j2kl) + a\exp(jkl) + c\exp(jkl)}{1 - ab\exp(j2kl)}. \tag{21}$$

It should be noted that the force F_0, which corresponds to the pressure of the acoustic wave emitted by the loudspeaker, occurs in the condition of the bounded radiation field of the loudspeaker, and therefore

$$F_r = 1/2 R'_{mp} V'(A_0 - 1) = 1/2 \frac{R'_{mp} F_z}{Z_{mw} + Z'_{mp}} (A_0 - 1). \tag{22}$$

The introduction of the factor 1/2 accounts for the fact that only one side of the membrane of the loudspeaker emits acoustic waves into the tube. Substitution of relation (22) into formula (4) and some transformations give the relationship

$$Z_{mw}(Z'_{mp} - Z_{mp}) = 1/2\, R'_{mp}(A_0 - 1)(Z_{mw} + Z_{mp}), \tag{23}$$

and accordingly the expressions of the values of the radiation impedance and the impedance of the mechanical system of the loudspeaker, Z'_m,

$$R'_{mp} = \frac{R_{mp}}{1 - 1/2\, Re\left[(A_0 - 1)\left(1 + \dfrac{Z_{mp}}{Z_{mw}}\right)\right]}; \tag{24}$$

$$Z'_m = Z_m + \frac{1/2\, R_{mp}(A_0 - 1)\left(1 + \dfrac{Z_{mp}}{Z_{mw}}\right)}{1 - 1/2\, \mathrm{Re}\left[(A_0 - 1)\left(1 + \dfrac{Z_{mp}}{Z_{mw}}\right)\right]}. \tag{25}$$

Like the loudspeaker with changing working conditions, the resonator, when excited to vibration, changes the mechanical parameters. Analogously to the case of the loudspeaker, the mechanical force F_{rR} acting on the resonator can be determined with respect to the work of the resonator in a reflectionless environment,

$$F_{rR} = F_w(x = l) - F_{0R}, \tag{26}$$

where the force F_{0R} corresponds to the pressure radiated by the resonator. Thus, from Fig. 4,

$$F_{0R} = R'_{mpR} V_R = F_0 \frac{R'_{mpR}(1 - a)}{Z_{mwR} + Z'_{mpR}}. \tag{27}$$

and finally

$$F_{rR} = F_0\left[B_0 - \frac{R'_{mpR}(1-a)}{Z_{mwR}+Z'_{mpR}}\right]; \tag{28}$$

where

$$B_0 = \frac{\exp(-jkl)+bc\exp(jkl)+a\exp(j2kl)+c\exp(j2kl)}{1-ab\exp(j2kl)}. \tag{29}$$

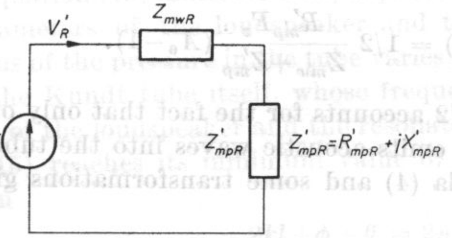

Fig. 4. The equivalent circuit of an excited resonator. F_{0zR} – the rms value of the mechanical force exciting the resonator system, F_0 – the rms value of the force corresponding to the acoustic pressure generated by the loudspeaker, a – the index of acoustic wave reflection from the resonator, V'_R – the mechanical velocity of vibrations in the resonator system, $Z_{mwR}+Z'_{mpR}$ – the mechanical impedance of the resonator system, Z'_{mpR} – the radiation impedance of the resonator

The use of formula (4), but in relation to the parameters of the resonator, and of relation (28) give the relationships

$$Z'_{mR} = \frac{Z_{mR}}{Z_{mwR}-Z_{mR}C_0}(Z_{mwR}-R'_{mpR}); \tag{30}$$

$$R'_{mpR} = \frac{\mathrm{Re}\left(\dfrac{Z_{mwR}Z_{mR}}{Z_{mwR}-Z_{mR}C_0}-R_s\right)}{\mathrm{Re}\left(1+\dfrac{Z_{mR}}{Z_{mwR}-Z_{mR}C_0}\right)}, \tag{31}$$

where $C_0 = B_0/(1-a)$ and R_s is the loss resistance of the resonator.

Since the quantities A_0 and C_0 are related to the mechanical parameters Z_m, Z_{mR}, R_{mp} and R_{mpR} by a system of implicit functions (see **Appendix**), Z'_m, Z'_{mR}, R'_{mp} and R'_{mpR} can be determined by solving numerically equations (24), (25), (30) and (31). This method is efficient, i.e. there is a solution and only one solution when the functions of the variables Z'_m and Z'_{mR} which occur on the right side of equations (25) and (30) satisfy the Banach principle, being converging functions [6]. According to this principle, irrespective of the selection of the initial data, the iteration series converges to one and only one solution.

From formula (13) and Fig. 3,

$$p_{wa}(x) = Ap_0 = A\frac{R'_{mp}F_z}{Z'_m} = A\frac{R'_{mp}}{Z'_m}\frac{R_{mp}F_z/Z_m}{R_{mp}/Z_m}, \tag{32}$$

where

$$A = \frac{\exp(-jkx)[1+bc\exp(j2kl)]+\exp(jkx)[a\exp(jkl)+c\exp(jkl)]}{1-ab\exp(j2kl)}. \tag{33}$$

Since, however, $p_1 = R_{mp}F_z/Z_m$ is the pressure radiated by the loudspeaker into unbounded space, the ratio p_{wa}/p_1 represents the pressure transmittance of the mechanical system loudspeaker-tube-resonator. Thus,

$$p_{wa}/p_1 = G_p = A\,\frac{R'_{mp}/R_{mp}}{Z'_m/Z_m} = A\left(1+\frac{\Delta R_{mp}}{R_{mp}}\right)\left(1+\frac{\Delta V}{V}\right) = A\,\frac{1+(\Delta R_{mp}/R_{mp})}{1+(\Delta Z_m/Z_m)}; \tag{34}$$

where $\Delta R_{mp} = R'_{mp}-R_{mp}$; $\Delta V = V'-V$; $\Delta Z_m = Z'_m-Z_m$.

It can be seen that the transmittance G_p depends on the product of two factors, the first of which defines the distribution of the standing pressure wave inside the tube and is a function of the variable x which takes values from the interval $\langle 0, l\rangle$ and of the mechanical quantities Z_m, Z_{mR}, R_{mp} and R_{mpR}; the second being related to changes in the parameters of the loudspeaker itself. It follows from its form that the relative pressure changes are in direct proportion to changes in the velocity and resistance of radiation, i.e. proportional to changes in the radiation resistance, but in inverse proportion to changes in the mechanical impedance of the loudspeaker. Since the mechanical parameters of the source and the phase shifts (the coefficients A and A_0) which occur in formulae (24), (25) and (33) depend on frequency, the transmittance G_p is also a function of it.

3. Experimental investigations

The measurements were carried out in a 4002 Brüel and Kjaer Kundt tube of 10 cm diameter, which permitted a plane wave shape, radiated by the loudspeaker over the frequency range 90-1800 Hz, to be obtained [4]. The

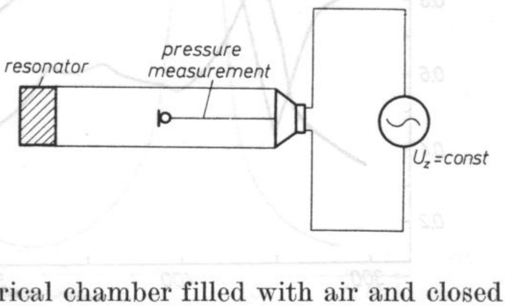

Fig. 5. A schematic diagram of the measurement system
U_z – the value of the voltage supply to the loudspeaker

resonator used had the form of a cylindrical chamber filled with air and closed at one end by an ideally rigid surface, i.e. with the impedance $Z = \infty$, and at the other, by a thin ($d = 1$ mm), perforated membrane clamped rigidly on the circumference (Fig. 5). The aim of the measurements was to determine the mean value of the modulus of the pressure amplitude inside the tube. Figs. 6 and 7 show the results of the measurements for two different resonance frequencies of the resonator, whereas Fig. 8 gives the results obtained in the case when the resonator was replaced with an ideally rigid plate. The results obtained were referred to the quantities measured when the loudspeaker radiated into unbounded space. The value of the impedance Z_m used in the calculations was determined from the list of typical mechanical and electric parameters

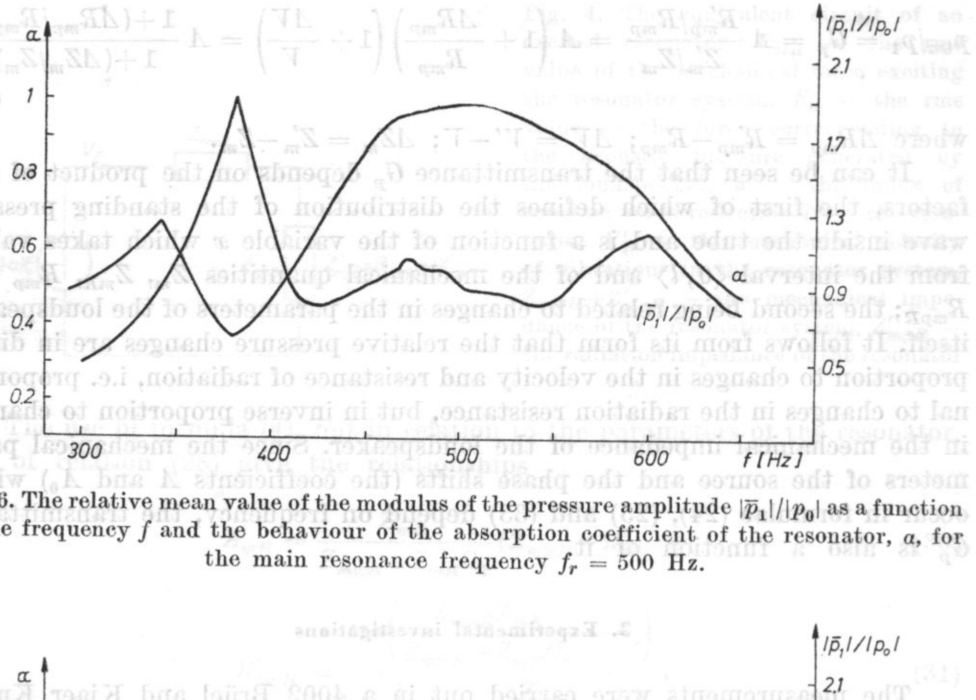

Fig. 6. The relative mean value of the modulus of the pressure amplitude $|\bar{p}_1|/|p_0|$ as a function of the frequency f and the behaviour of the absorption coefficient of the resonator, α, for the main resonance frequency $f_r = 500$ Hz.

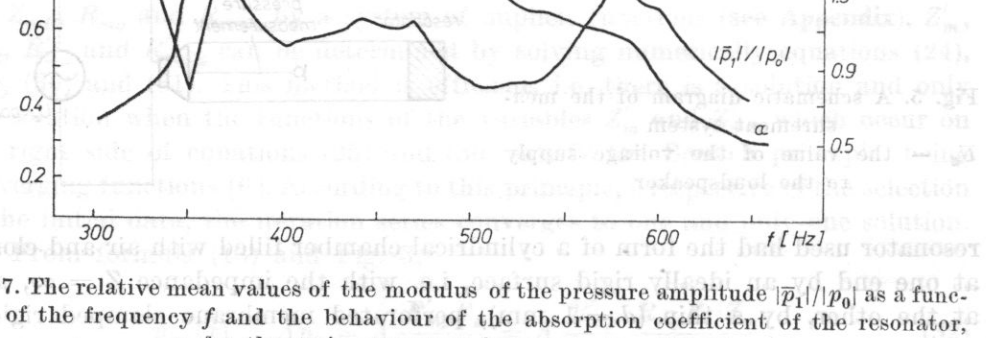

Fig. 7. The relative mean values of the modulus of the pressure amplitude $|\bar{p}_1|/|p_0|$ as a function of the frequency f and the behaviour of the absorption coefficient of the resonator, α, for the main resonance frequency $f_r = 420$ Hz.

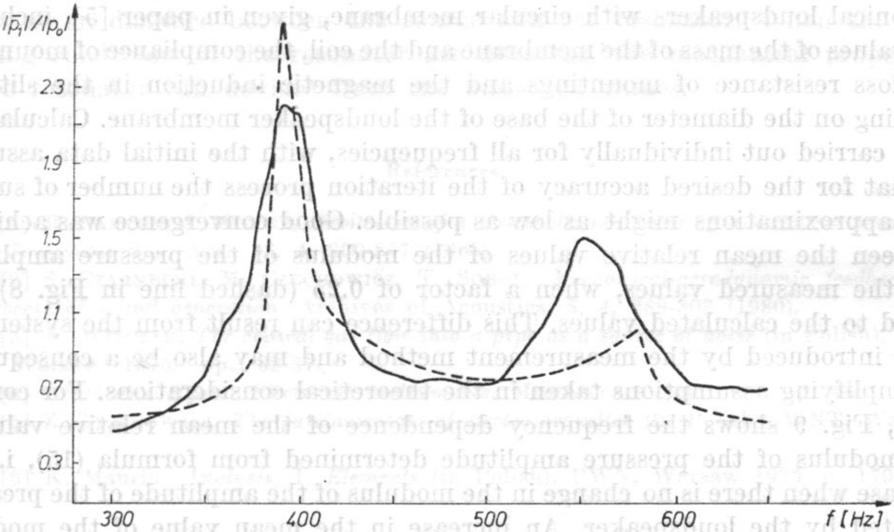

Fig. 8. The measured (solid line) and calculated (dashed line) relative mean values of the modulus of the pressure amplitude $|\bar{p}_1|/|p_0|$ as a function of the frequency f in the case when the tube is closed by a rigid surface.

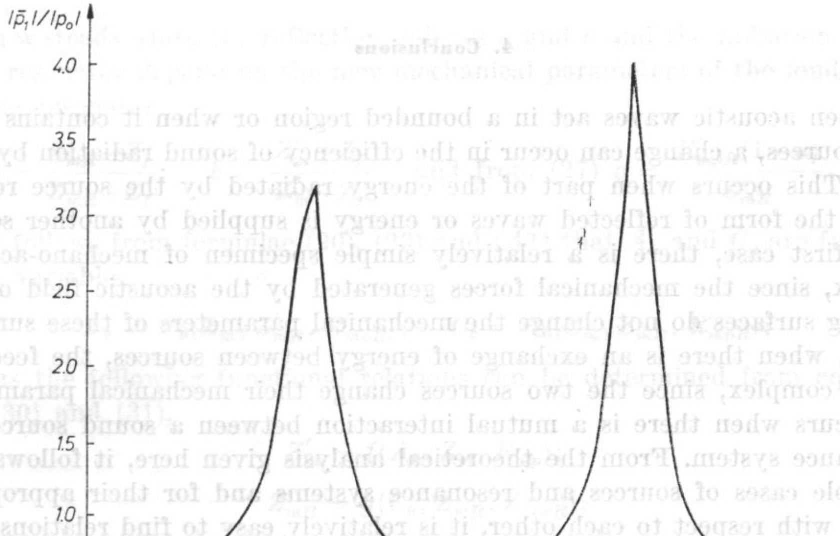

Fig. 9. The relative mean values of the modulus of the pressure amplitude $|\bar{p}_1|/|p_0|$ as a function of the frequency f obtained from formula (15), i.e. under the assumption of a lack of change in the mechanical parameters of the source.

of conical loudspeakers with circular membrane, given in paper [5], including the values of the mass of the membrane and the coil, the compliance of mountings the loss resistance of mountings and the magnetic induction in the slit, depending on the diameter of the base of the loudspeaker membrane. Calculations were carried out individually for all frequencies, with the initial data assumed so that for the desired accuracy of the iteration process the number of successive approximations might as low as possible. Good convergence was achieved between the mean relative values of the modulus of the pressure amplitude and the measured values, when a factor of 0.25 (dashed line in Fig. 8) was added to the calculated values. This difference can result from the systematic error introduced by the measurement method and may also be a consequence of simplifying assumptions taken in the theoretical considerations. For comparison, Fig. 9 shows the frequency dependence of the mean relative value of the modulus of the pressure amplitude determined from formula (15), i.e. in the case when there is no change in the modulus of the amplitude of the pressure radiated by the loudspeaker. An increase in the mean value of the modulus of the pressure amplitude results in all the cases presented from the resonance of the Kundt tube itself, whose frequency depends on the length of the tube and on the mechanical parameters of the loudspeaker and the resonator.

4. Conclusions

When acoustic waves act in a bounded region or when it contains other sound sources, a change can occur in the efficiency of sound radiation by their source. This occurs when part of the energy radiated by the source returns to it in the form of reflected waves or energy is supplied by another source. In the first case, there is a relatively simple specimen of mechano-acoustic feedback, since the mechanical forces generated by the acoustic field on the bounding surfaces do not change the mechanical parameters of these surfaces. In turn, when there is an exchange of energy between sources, the feedback is more complex, since the two sources change their mechanical parameters. This occurs when there is a mutual interaction between a sound source and a resonance system. From the theoretical analysis given here, it follows that for simple cases of sources and resonance systems and for their appropriate position with respect to each other, it is relatively easy to find relations from which, using numerical methods, changes in the mechanical properties of the source and the resonator can be found.

Another conclusion can be drawn about the measurement method using the Kundt tube. The measurement by this method, e.g. of the absorption coefficient or the resonance frequency of a resonance system, gives correct results only under some specific measurement conditions, i.e. a specific sound source and a given distance between the source and the resonator. When the real working conditions of the resonator are different, the mechanical properties of the resonator can deviate from the measured values.

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Appendix

In a steady state the reflection indexes a and b and the radiation index c of the resonator depend on the new mechanical parameters of the loudspeaker and the resonator:

$$a = \frac{Z'_{mR} - Z_f}{Z'_{mR} + Z_f}; \quad b = \frac{Z'_m - Z_f}{Z'_m + Z_f} \quad \text{and from (27)} \ c = \frac{R'_{mpR}(1-a)}{Z'_{mR}}. \tag{A1}$$

It follows from formulae (20), (29) and ($A1$) that A_0 and C_0 are functions of the variables

$$A_0 = F_0(Z'_m, Z'_{mR}, R'_{mpR}); \quad C_0 = G_0(Z'_m, Z'_{mR}, R'_{mpR}); \tag{A2}$$

whereas the following functional relations can be determined from equations (25), (30) and (31),

$$\begin{aligned} Z'_m &= f(A_0, Z_m, R_{mp}); \\ Z'_{mR} &= g(C_0, Z_{mR}, Z_{mwR}); \\ R'_{mpR} &= h(C_0, Z_{mR}, Z_{mwR}). \end{aligned} \tag{A3}$$

Substitution of ($A3$) in relations ($A2$) gives

$$\begin{aligned} A_0 &= F_1(A_0, C_0, Z_m, Z_{mR}, Z_{mwR}, R_{mp}); \\ C_0 &= G_1(A_0, C_0, Z_m, Z_{mR}, Z_{mwR}, R_{mp}). \end{aligned} \tag{A4}$$

Thus, system ($A4$) represents a pair of functions implicit in terms A_0 and C_0.