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ANALYSIS OF THE CONFIGURATION OF THE ACOUSTIC FIELD OF LOUDSPEAKER SYSTEMS EXCITED WITH A SINUSOIDAL SIGNAL

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The paper discusses the accuracy of the approximation of the acoustic pressure distribution radiated by loudspeaker systems with the pressure distribution radiated by a flat circular membrane. The far and near field ranges of loudspeaker systems were determined and the effect of the irregularity of the acoustic pressure distribution in the near field of the systems on their amplitude and frequency characteristics was investigated.

1. Introduction

Determination of the acoustic potential function at a given measurement point of the acoustic field of the sources of disturbances can be performed using the Kirchhoff integration formula [5, 6]. In the case of radiation from a plane or a limited field on a plane, this formula becomes identical to the Huygens' integration formula.

Considering a vibrating element placed in a rigid baffle of infinite extent, the acoustic pressure at a point P (Fig. 1) can be determined from the formula

$$p(P) = \sigma \frac{\partial}{\partial t}\left[\frac{1}{2\pi}\iint_F \frac{e^{-ikr}}{r}\frac{\partial \psi}{\partial n}dF\right], \tag{1}$$

where σ is the density of the medium, r – the distance between the measurement point and an element of the source, k – the wave number, and ψ – the potential on the surface of a source of area F.

A detailed analysis [7] of formula (1) shows the necessity of distinguishing between the near field and the far field in the radiation field of the source of the disturbance.

In the far field the particle velocity of the medium is in phase with the acoustic pressure, and in the near field it is shifted by $\pi/2$. Accordingly, the near field does not contribute to the energy transmitted by the source to the medium. The imaginary component of the acoustic field characterizes the streaming of the medium near the source, where the medium not only moves in the direction of the radiation but also tangentially to the vibrating surfaces.

Determination of the analytical conditions differentiating the far field and the near field [7] leads to two inequalities which define the range of the far field:

$$R^2 \gg a^2 = x^2+y^2, \tag{2}$$

$$R^2 \gg \pi a^2/\lambda. \tag{3}$$

In the near field only the inequality

$$R^2 \gg a^2 \tag{4}$$

must be satisfied, with the condition $R \gg \lambda$ being valid for both near and far fields.

The radiation region that is directly adjacent to the vibrating surface, where inequalities (2) and (3) are not satisfied, has been called the *range of the very near field.*

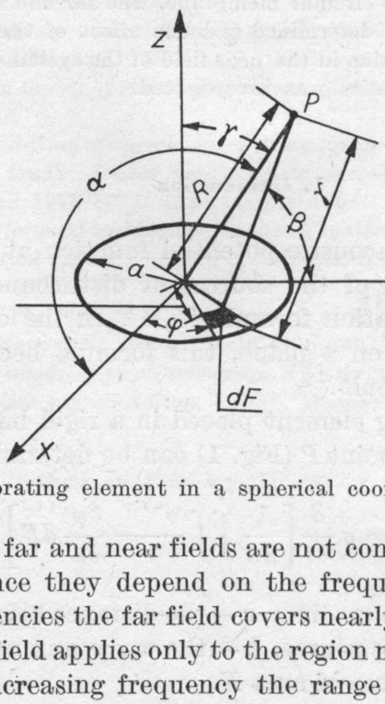

Fig. 1. A vibrating element in a spherical coordinate system

The ranges of the far and near fields are not constant quantiti s for a given vibrating element, since they depend on the frequency of the acoustic wave emitted. At low frequencies the far field covers nearly the whole of the radiation region, while the near field applies only to the region near the surface of the vibrating element. With increasing frequency the range of the near field expands. Fig. 2 shows the curves illustrating the acoustic pressure distribution along the axis of a circular membrane of a radius $a = 9$ cm, under the assumption that it performs piston-like simple harmonic motion in a direction perpendicular to the surface of the source. The calculations were made using formula (1).

It follows from the curves presented that for $(R/a^2)\lambda \geqslant 0.75$ they decrease monotonically, being proportional to $1/R$. The point for which $(R/a^2)\lambda = 0.75$

separates (for successive curves whose parameter is the ratio a/λ in the range 0.24-5.00) the region, where the phase and interference phenomena which occur affect the uniformity of the acoustic pressure distribution of the signal, from the region, where these phenomena do not occur.

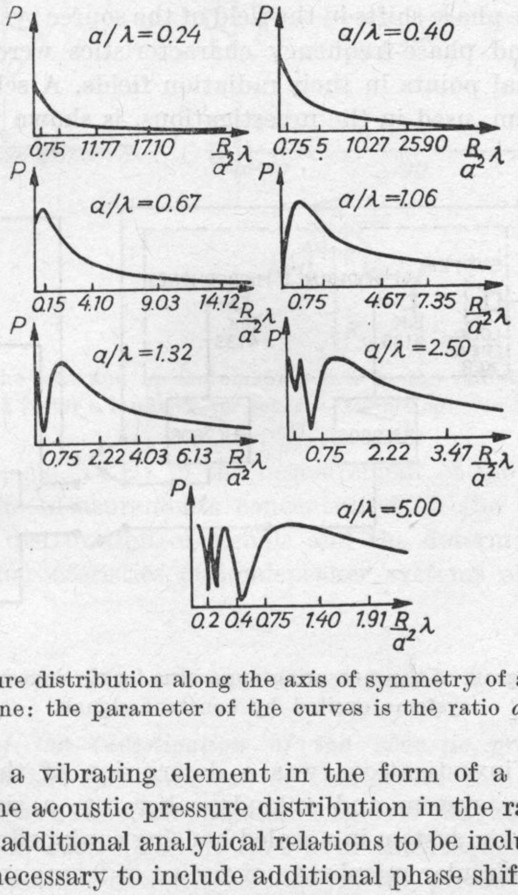

Fig. 2. Acoustic pressure distribution along the axis of symmetry of a circular piston membrane: the parameter of the curves is the ratio a/λ

In the case of a vibrating element in the form of a conical membrane, the calculation of the acoustic pressure distribution in the radiation field of the membrane requires additional analytical relations to be included in formula (1). In particular, it is necessary to include additional phase shifts due to the length and angle of inclination of the ruling of the cone. These additional phase shifts are also dependent on the form of the division of the loudspeaker membrane. For a loudspeaker set these problems become more complicated because of the parallel operation of several loudspeakers with different conical membranes.

Recognizing that there appeared to be no previous attempt at an analysis of all problems connected with a description of the acoustic field of a loudspeaker system over the whole radiation region, experimental investigations were begun which were aimed at the evaluation of the accuracy of the approximation of this type of system by a simple vibrating element (Fig. 1). At the same time the effect of the irregularities occurring in the acoustic pressure distribution in the radiation field of systems (very near field, near field) on the amplitude and frequency characteristics registered in these regions was determined.

2. Experimental method and measuring apparatus

The investigation of the configuration of the acoustic field of simple and complex loudspeaker systems was performed for sinusoidal excitation signals. In the framework of these investigations the acoustic pressure distribution and the magnitude of the phase shifts in the field of the source system were measured. Both amplitude- and phase-frequency characteristics were measured for the systems at individual points in their radiation fields. A schematic diagram of the measuring system, used in the investigations, is shown in Fig. 3.

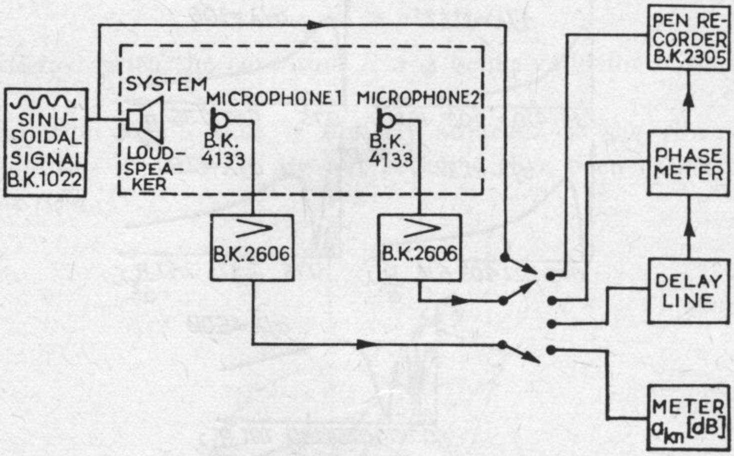

Fig. 3. A schematic diagram of the measuring apparatus for the investigation of loudspeaker systems excited by constant signals

The object of investigations was a description of the acoustic field of a single loudspeaker system and a loudspeaker set: a single Isophon type PSL 203/25 loudspeaker system in a sealed housing equipped with one broadband loudspeaker with a circular membrane of radius of 9 cm; and a Klein-Hummel loudspeaker set consisting of two identical broadband loudspeakers and one high-tone loudspeaker, installed in a sealed housing. The spacing of measurement points in the acoustic field of both systems is shown in Fig. 4 (the investigation was performed in an anechoic chamber). Each loudspeaker system was excited by acoustic generators. A signal from the loudspeaker system was simultaneously received by two microphones, with microphone M-2 being always at the same place (the signal received from this microphone was used as a reference signal), and microphone M-1 changing its position in the course of the measurements. Signals from the microphones were supplied, through amplifiers, to recording systems for further processing.

The excitation level of the system, corresponding to a specific value of SPL, was established at a measurement point (a, $R = 180$ cm) for a signal at

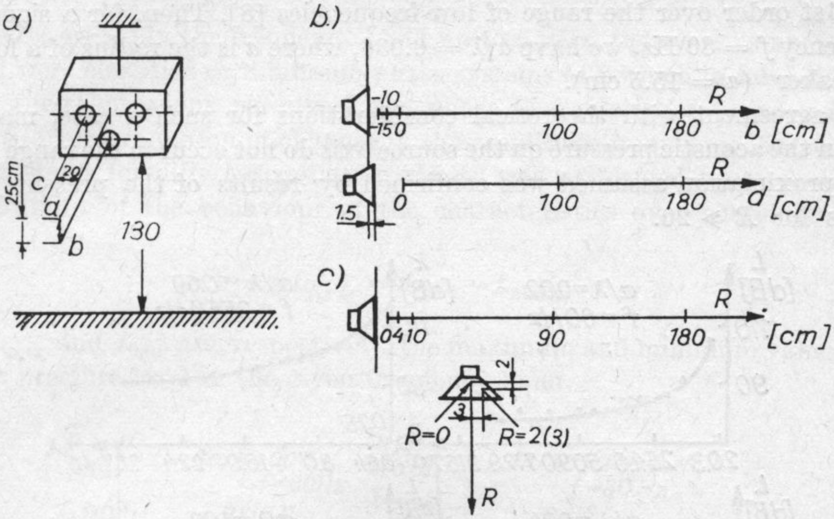

Fig. 4. Position of the axis and measurement points in the radiation fields of loudspeaker systems: *a*, *b* — for a loudspeaker set, *c* — for a single loudspeaker system

a given frequency, e.g. 1 kHz in the measurement of the amplitude-frequency characteristics. The measurements concentrated on the determination of the acoustic pressure distribution of signals and the determination of the amplitude frequency characteristics of loudspeaker systems along the loudspeaker axes.

3. Analysis of results of the experimental investigations

(a) *Results of the investigation of the acoustic pressure distribution of signals*. Results of the measurement of changes in the level of the acoustic pressure of a signal as a function of distance R, over the radiation field of a single loudspeaker system, show (Fig. 5) that over the frequency range, where the ratio $a/\lambda \ll 1$, there is a uniform decrease in the pressure level for $R \geqslant 10$-20 and for an exciting voltage giving SPL $= 80$ dB (an increase in the excitation of the single loudspeaker system to a level corresponding to SPL $= 90$ dB caused significant changes in this behaviour, in particular, for frequencies $f > 150$ Hz and $R < 70$). When the ratio $a/\lambda \geqslant 1$, the greatest irregularities occur for small values of R. A uniform decrease in the acoustic pressure level then occurs for $R \geqslant 40$-60.

In the evaluation of variation of the acoustic pressure level L as a function of R for a loudspeaker set (Fig. 6), an essential difficulty occurs in the determination of ranges of the near and far fields, connected with the fact that a loudspeaker set is a complex radiating system in which several sources operate at the same time. Neglecting all complex phase and interference phenomena in the first approximation, such a system can be considered as a spherical source of the 1st order over the range of low frequencies [8]. Then, for a signal with a frequency $f = 80$ Hz, we have $a/\lambda = 0.036$, where a is the radius of a low-tone loudspeaker ($a = 15.5$ cm).

In agreement with theoretical considerations for such a case, maximum values in the acoustic pressure on the source axis do not occur in the range $R \gg a$. The approximation assumed was confirmed by results of the present measurements for $R \gg 20$.

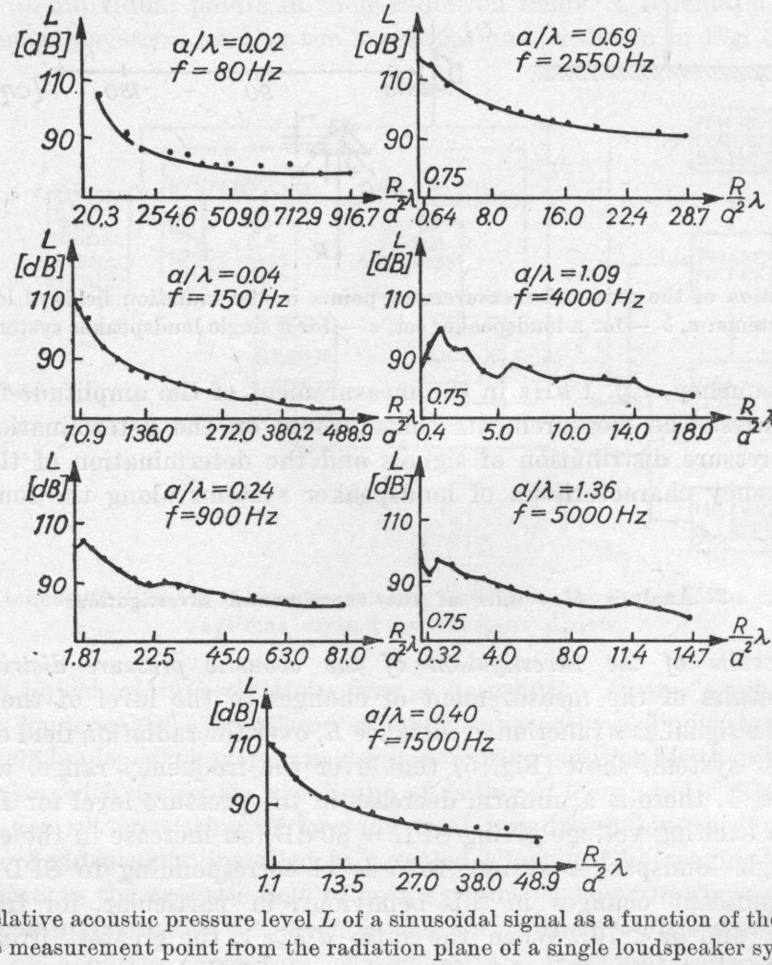

Fig. 5. Relative acoustic pressure level L of a sinusoidal signal as a function of the distance R of the measurement point from the radiation plane of a single loudspeaker system; SPL = 80 dB

This simplification is not valid for signals of higher frequencies ($f = 1000$ Hz and $f = 2000$ Hz). In this case the system should be considered as a group of sources with individual directional characteristics during the calculation of the ratio a/λ, and a is the linear size of the housing of loudspeaker set.

(b) *The results of the investigation of the amplitude-frequency characteristics.* Based on the comparison of the behaviour of the amplitude- and phase-frequency characteristics [1] in the frequency band up to 5 kHz, the systems under investigation were classified as minimum phase systems [4], which in further evaluation of their behaviour permitted the phase characteristics to be neglected. A quantitative evaluation of changes in the amplitude-frequency characteristics of the systems for different radiation ranges was performed by measuring the nonuniformity of the behaviour of the characteristics over chosen frequency ranges,

$$\Delta L_{f_1-f_2} = L_{\max} - L_{\min}, \tag{6}$$

where $L_{\max}$ and $L_{\min}$ are, respectively, the maximum and minimum values of the acoustic pressure level in the given frequency band.

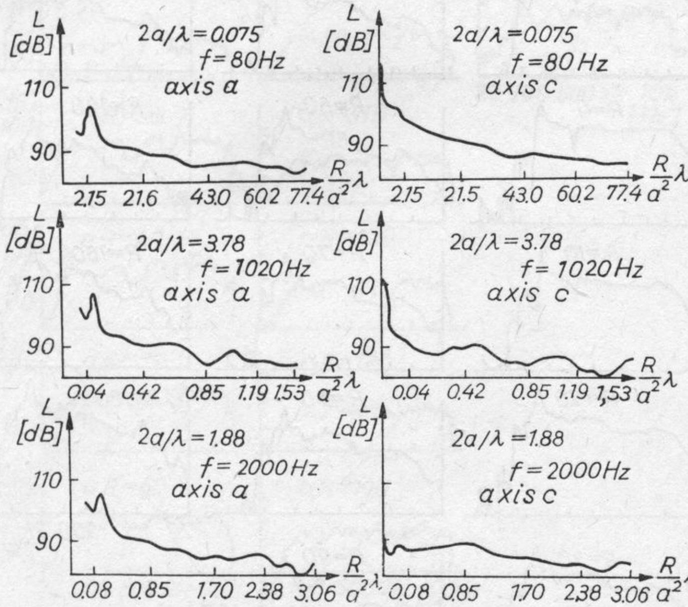

Fig. 6. Relative acoustic pressure level L of a sinusoidal signal as a function of the distance R of the measurement point from the radiation plane of a loudspeaker set; SPL = 80 dB

It was found that the maximum changes of $\Delta L_{f_1-f_2}$ with increasing distance R of the measurement point from the radiation plane occur in the frequency band f_1-f_2 = 3-5 kHz. In the acoustic field of a single loudspeaker system these changes are largest for $R \leqslant 10$, when the excitation level of the system corresponding to an output SPL = 80 dB and may reach 17-25 dB (Fig. 7). For the lower frequency band the ranges of R, where the changes in $\Delta L_{f_1-f_2}$ occur, are the same as before with the numerical value of $\Delta L_{f_1-f_2}$ being lower than the maximum noted above.

An increase in the distance of the measurement point from the axis of symmetry of the system for low R ($R = 2/3$) gave a visible decrease in the absolute value of $\Delta L_{f_1-f_2}$ in the highest frequency band (closely approximating the values of $\Delta L_{f_1-f_2}$ for high R), while this was not observed at low frequencies. In the evaluation of these changes in the radiation field of the loudspeaker set (Fig. 8,9) it can be noted that they are not only a function of the distance R, but also of the position of the measurement axis.

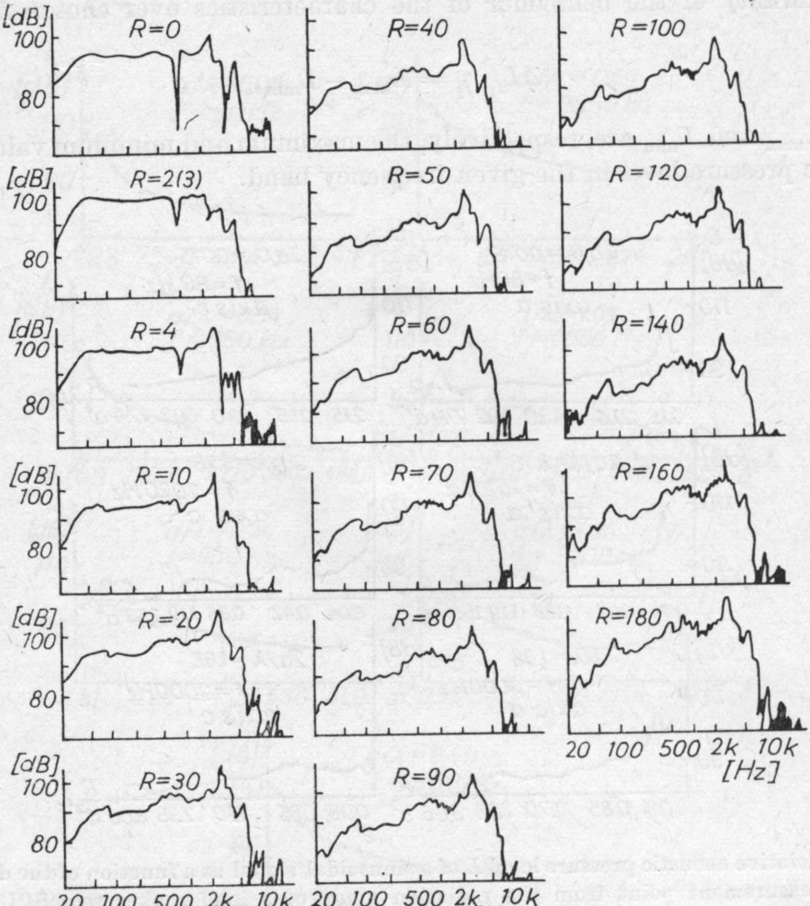

Fig. 7. Amplitude-frequency characteristics of a single loudspeaker system for different values of R; SPL = 80 dB

The greatest differences in the behaviour of the characteristics occurred for a shift of the measurement axis with respect to the axis of symmetry of the system in a vertical plane, and the smallest ones for a shift in a horizontal plane. With the location of the measurement points along the axis of symmetry of the set (the a-axis), it was found that the values of $\Delta L_{f_1-f_2}$ in the low frequency band are practically constant functions of the distance R. At higher frequencies the values of $\Delta L_{f_1-f_2}$ become constant for $R \geqslant 30$. Changes in the values of $\Delta L_{f_1-f_2}$ along the b- and c-axes are strongly dependent on frequency; they also

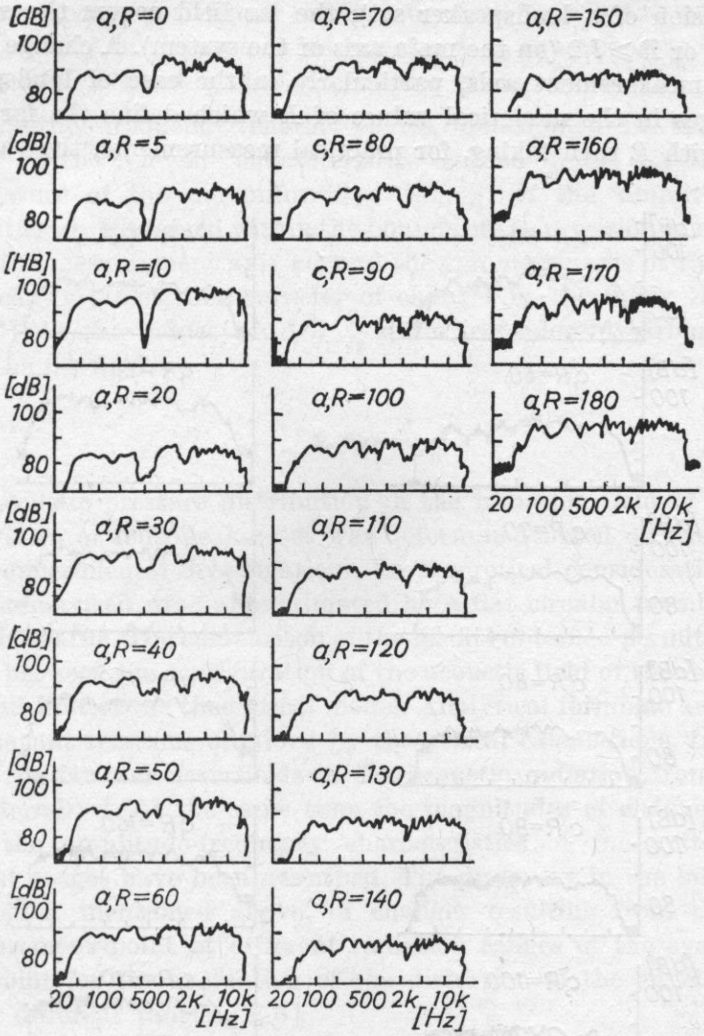

Fig. 8. Amplitude-frequency characteristics of a loudspeaker set determined on the *a*-axis; SPL = 80 dB

occur at $f = 80$ Hz for $R = -10$. The values of $\Delta L_{f_1-f_2}$ become constant at higher frequencies for $R \geqslant 30$-50, with an increase in the excitation level of the set having a great effect on the increase of the limiting value of R beyond which the values of $\Delta L_{f_1-f_2}$ become constant.

4. Conclusions

1. The following rules, which specify the relations given in formulae (2) and (3), can be used to define the far field of loudspeaker systems:

at low frequencies, for which the inequalities $a < 0.50\,\lambda$ or $l < \lambda$ are valid (a – the radius of membrane in a single loudspeaker system, l – the maximum linear dimension of a loudspeaker set), the far field covers the range R for which $R \geqslant a$ or $R \geqslant l/2$ (on the main axis of the system). A change in the position of the measurement axis, particularly in the case of loudspeaker sets, causes changes in the numerical values of R which define the far field range to change, with R then taking, for practical measurements, the values $R \geqslant 2a$ or $R \geqslant l$;

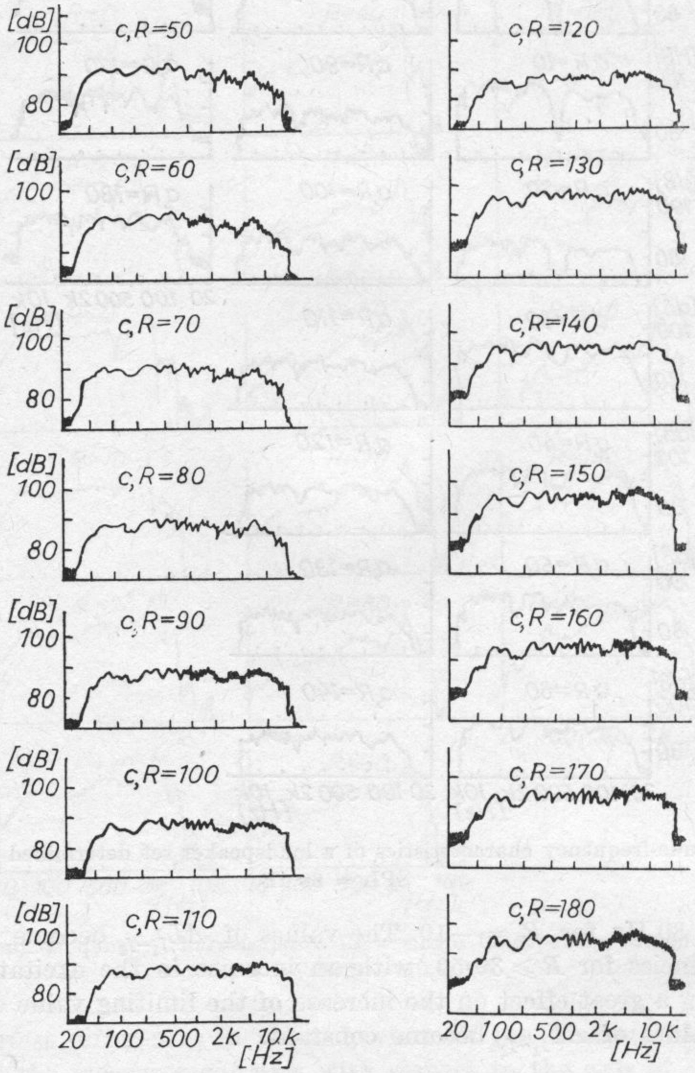

Fig. 9. Amplitude-frequency characteristics of a loudspeaker set determined on the c-axis; SPL = 80 dB

at high frequencies, for which the inequality $a \geqslant 0.50\lambda$ or $l \geqslant \lambda$ is satisfied, the far field covers the range where $R \geqslant \pi a^2/\lambda$ for a single loudspeaker system and $R \geqslant 0.75 \cdot (l/2)^2/\lambda$ for a loudspeaker set (on the main axes of the systems).

A change in the position of the measurement axis in the systems investigated, particularly in the case of loudspeaker sets, causes changes in the numerical values of R defined by the inequalities given above.

2. Amplitude-frequency characteristics, determined in the near fields, are similar to the relevant characteristics defined in the far fields. Changes in the measure of the nonuniformity, $\Delta L_{f_1-f_2}$, of the amplitude-frequency characteristics are contained within the bounds of the precision of measurements. A shift of the measurement axis beyond the symmetry axis of the system does not significantly affect the character of changes in the index $\Delta L_{f_1-f_2}$. In the very near field the values of $\Delta L_{f_1-f_2}$ differ considerably from the relevant values in the far field.

5. Summary

The acoustic pressure distribution in the radiation field of a single loudspeaker system or lousdpeaker set was determined based on theoretical equations and experimental investigations. In theoretical considerations the loudspeaker systems used were approximated by a flat circular membrane installed in an infinite baffle. The comparison of the results obtained permitted differences to be seen between the configuration of the acoustic field of the real loudspeaker systems and that of the theoretical model. Analytical formulae are given, which specify relevant relations obtained by theoretical calculations, from which the ranges of the far and near fields in the acoustic radiation from loudspeakers can be determined. At the same time the magnitudes of changes in the behaviour of the amplitude-frequency characteristics of the systems measured at different ranges have been described. The discovery in the behaviour of the characteristics, mentioned above, of changes resulting from the position of the measurement point at different radiation ranges of the systems, was the starting point for the evaluation of the distortion of the envelopes of pulsed signals at different ranges [2, 3].

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