Motional feedback with loudspeakers

J. A. Klaassen and S. H. de Koning

The use of negative feedback to reduce linear and non-linear distortion has long been standard practice in amplifier techniques. In audio equipment, however, the loudspeaker is an important source of distortion, and the distortion which it contributes remains unaffected by negative feedback in the electronic circuit. It is possible, however, to include the loudspeaker in the negative feedback loop. One method of doing this, which makes use of an acceleration transducer, has been investigated theoretically and experimentally by the authors.

Problems with small loudspeaker cabinets

Distortion in the electronic circuits of an audio system — microphone, amplifier, loudspeaker — has traditionally been dealt with by means of negative feedback. However, this feedback has no effect on the distortion produced outside the electronic circuits. This occurs mainly in the loudspeaker, in the conversion of an electrical current into a mechanical force and of a mechanical force into the movement of a diaphragm and the surrounding air. This is true both for distortion of the distribution of intensity over the frequency spectrum (linear distortion) and for the production of higher harmonics (non-linear distortion).

The diaphragm in an electrodynamic loudspeaker usually takes the form of a cone in a spring suspension. Mounted near the apex of the cone there is a cylindrical coil (the "speech coil"), which can move in a radial magnetic field. A varying current through the coil generates a varying force which sets the coil and cone in motion. In this process linear distortion may occur since the spring-mass system has its own resonant frequency. Non-linear distortion can occur because the resilience of the cone suspension system does not vary completely linearly with the displacement of the cone. Non-uniformity of the magnetic field can also cause non-linear distortion.

The air near the cone opposes the motion and thus constitutes a load on the cone. This load has a reactive part, the *radiation reactance* X_r, and a resistive part, *the radiation resistance* R_r. The latter is a measure of the power P which is radiated in the form of sound at a particular cone vibration velocity $\dot{x}$ ($P = \dot{x}^2 R_r$), where R_r depends on the dimensions of the cone and on the frequency (see *fig. 1*). If the air is prevented from moving from the front to the back of the cone, or vice versa, R_r is proportional at low frequencies to the square of the frequency. At high frequencies, however, R_r is virtually constant. This means that much greater velocities, and therefore much greater displacements of the cone, are needed to radiate a given power at low frequencies than at high frequencies. At low frequencies, therefore, the risk of non-linear distortion is greater.

Although, with many kinds of sound, the energy contained in the lower-frequency components is smaller than the energy in the middle range, there are sounds in which a considerable contribution is made at the lowest frequencies. To reproduce such sounds well the equipment must be able to deliver as much sound power at the low frequencies as at the high ones.

At low frequencies the radiated power decreases sharply if sound waves from the rear of the cone are able to interfere with waves radiated from the front. In practice an effective separation can only be achieved by mounting the loudspeaker in the wall of a cabinet which is otherwise completely closed. If, for the sake of compactness, we make the cabinet small, the enclosed air behaves like a spring, which has the effect of reducing the displacement of the cone — again to the detriment of the radiation at low frequencies — and increasing the resonant frequency. The designer generally attempts to keep the resonant frequency so low that it lies at the lower limit of the frequency range, but if a small loudspeaker cabinet is used the resonant frequency may well be within this range, giving severe linear distortion. Loudspeaker resonance is also a great nuisance in the reproduction of "step-function" sounds or sudden

Ir. J. A. Klaassen is with Philips Research Laboratories, Eindhoven; Ir. S. H. de Koning, formerly with Philips Research Laboratories, is now with the Philips Electro-Acoustics Division (ELA), Eindhoven.

transients. Furthermore, the resilience of the cushion of air behind the cone is not proportional to the cone displacement, and this again introduces non-linear distortion.

In most practical situations — even in high-fidelity equipment — linear and non-linear distortion can be kept within bounds by conventional means. It is interesting to note, however, that if the very best sound reproduction is required or if there is not much room for the loudspeaker, the sound reproduction can

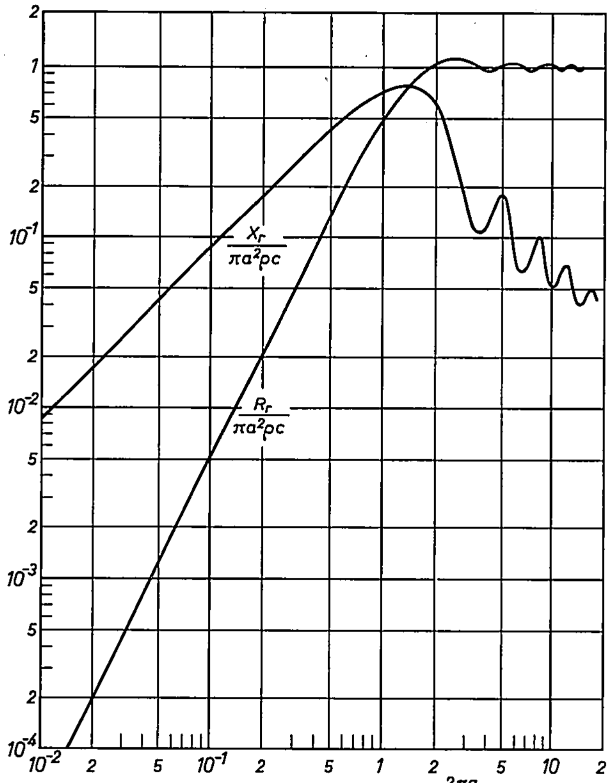

Fig. 1. The radiation reactance X_r and the radiation resistance R_r of a loudspeaker as a function of frequency f (on relative scales). a radius of the cone. ϱ air density. c velocity of sound in air. At high frequencies the radiation resistance per unit area approaches ϱc, the specific acoustic impedance of air. $X_r/2\pi f$ is known as the radiation mass.

be improved by extending the negative feedback we spoke of earlier to include the loudspeaker, and not limiting it to the electronic circuits.

This means that the voltage fed back to the input of the amplifier is related to the radiated sound rather than to the current or voltage supplied to the loudspeaker. This form of feedback, known as *motional feedback*, is the subject of this article. After looking at the theory we shall describe two systems in which use is made of motional feedback. Our measurements with these systems have shown that motional feedback does in fact give the improvement expected.

Motional feedback

History

Motional feedback requires the generation of a signal that is related to the radiated sound. This suggests in the first place that a microphone should be used. This would hardly be practical, however, because the transit time of the sound between loudspeaker and microphone introduces a considerable phase shift which is highly frequency-dependent.

At low frequencies (below about 500 Hz) a voltage related to the radiated sound can be derived from the movements of the coil. This is possible since the cone vibrates as a rigid body in this frequency range. (The surface of the cone is in "isophase motion". This is not the case at high frequencies.)

The movement of the speech coil can be converted into a signal voltage in various ways. A voltage may be derived from the *displacement* of the coil (e.g. by a capacitive method), from its *velocity* (e.g. by an inductive method), or from its *acceleration* (using inertial forces). For brevity, we shall use the terms displacement, velocity and acceleration feedback in this article. Two of these methods are significantly different in principle from the third: a stationary reference point is always needed for determining the position and velocity of a moving point, but not for determining an acceleration. We shall return to this point later.

A motional feedback system sometimes used today employs *velocity feedback*, the voltage used as a measure of the velocity of the speech coil being the e.m.f. induced in the coil by its motion in the magnetic field [1]. This voltage has of course to be separated from the voltage fed from the amplifier to the coil. Several methods are illustrated in *fig. 2*. In series with the loudspeaker in all these circuit diagrams there is an impedance Z_e whose phase angle is equal to that of the electrical impedance of the loudspeaker when the movement of the coil is prevented. Since the loudspeaker is not blocked in this way in reality, its impedance is dependent on the signal frequency. The voltage across Z_e can be subtracted from the loudspeaker voltage, for instance by means of an extra transformer (fig. 2*a*), an extra winding on the output transformer in the amplifier (fig. 2*b*), or with the aid of a bridge circuit (fig. 2*c*). The difference between these voltages is then fed back to the amplifier input.

A feedback method of this kind can also be regarded as a method of making the output impedance of the amplifier equal and opposite to the impedance of the loudspeaker in the blocked state. The amplifier is then

[1] See W. Holle, Gegenkopplung an Lautsprechern, Funk-Technik 7, 490-492, 1952.

said to have a *negative output impedance* [2]. In such an arrangement the amplifier functions as a voltage source which is loaded purely and simply by that part of the loudspeaker impedance which is due to the motion of the speech coil (motional impedance).

A difficulty in the methods referred to above is that the resistance of the speech coil is temperature-dependent. Another drawback is the non-uniformity of the magnetic field, as a result of which the voltage obtained does not give a true picture of the velocity of the coil. For these reasons circuits of this kind are not often used nowadays.

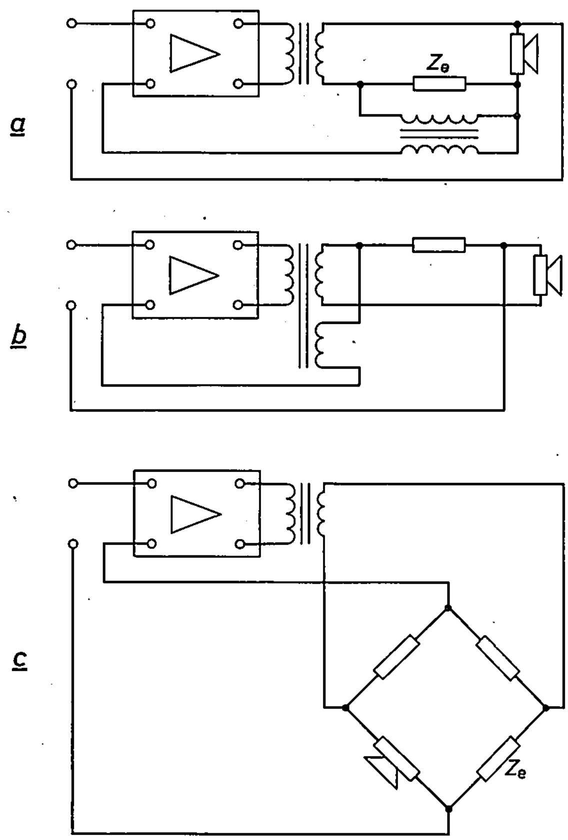

Fig. 2. Some methods of motional feedback, using the voltage induced in the speech coil itself by its movement in the magnetic field. Connected in series with the loudspeaker is an impedance Z_e, whose phase angle is equal to that of the impedance of the loudspeaker in the blocked state. The difference between the voltages across the loudspeaker and across Z_e are obtained by means of a separate transformer (*a*), with an additional winding on the output transformer (*b*), or with a bridge circuit (*c*). This difference voltage is added in the correct phase to the input signal.

In another method an extra coil is wound on to the former of the speech coil and the voltage induced in it is used as a measure of the velocity of the speech coil. This extra coil must be arranged in such a way that the mutual inductance between it and the speech coil is very low. It is also most important that there should be an absolutely stationary reference point. This is usually not the case because of vibrations from the loudspeaker itself and because of the radiated sound, which can excite mechanical resonances.

Displacement feedback by means of capacitance variations also has the disadvantage that a stationary reference point is required. Moreover, in this case non-axial movements of the speech coil also affect the voltage obtained.

The methods given above can in fact be used if the aim is to *measure* the movements of the speech coil, and account is taken of the errors introduced. For negative feedback, however, the signals obtained in this way have not been found suitable, because of the drawbacks mentioned earlier.

The various difficulties can be avoided if the feedback is effected by means of a device which measures the *acceleration* of the speech coil. The system described in this article makes use of this method. As the introduction of motional feedback at higher frequencies involves considerable problems, due to the difficulty of keeping the system stable, we have limited the frequency range so that the feedback operates only at low frequencies. Since, as we have shown, the distortion is most severe at low frequencies, this in itself gives a substantial improvement.

The voltage obtained from an acceleration transducer can be integrated once or twice, thus giving, without any of the drawbacks described above, a voltage which is proportional to the velocity or the displacement. A single transducer can therefore be used to give acceleration, velocity or displacement feedback, or any combinations of these.

Theoretical considerations

At low frequencies the coil and cone of a loudspeaker can be treated as a single spring-mass system. Its resonant frequency will be referred to briefly as the resonant frequency of the loudspeaker. The motion of this spring-mass system is described in the following equation:

$$m\ddot{x} + r\dot{x} + sx = F, \quad \ldots \quad (1)$$

where F is the force acting on the coil, x the displace-

[2] See R. L. Tanner, Improving loudspeaker response with motional feedback, Electronics **24**, No. 3, 142 etc., 1951; R. E. Werner, Loudspeakers and negative impedances, IRE Trans. **AU-6**, 83-89, 1958; H. W. Holdaway, Design of velocity-feedback transducer systems for stable low-frequency behavior, IEEE Trans. **AU-11**, 155-173, 1963.

[3] The resonant frequency is understood here to be the frequency at which the mechanical impedance of the loudspeaker is resistive.

[4] The amplitude characteristic is the curve representing the amplitude of the sound pressure, measured along the axis of the loudspeaker in a free sound field, as a function of frequency, for constant voltage across the loudspeaker terminals.

ment from the position of equilibrium, m the mass, r the frictional resistance and s the spring constant. The resonant frequency of such a system [3] is given by:

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{s}{m}}, \quad \ldots \quad (2)$$

and the Q (quality factor) by:

$$Q_0 = \omega_0 \frac{m}{r} = \frac{\sqrt{ms}}{r}. \quad \ldots \quad (3)$$

When acceleration feedback is applied the current through the speech coil, and hence the force F proportional to it, are reduced by a term proportional to $\ddot{x}$. If the proportionality factor is indicated by m', the equation of motion can then be written:

$$m\ddot{x} + r\dot{x} + sx = F - m'\ddot{x}$$

or:

$$(m + m')\ddot{x} + r\dot{x} + sx = F. \quad \ldots \quad (4)$$

The *mass* is thus effectively increased. As a result of this the resonant frequency is lower and the Q higher. Similarly it can be demonstrated that velocity feedback effectively increases the *damping term*; the resonant frequency remains unchanged, but the Q is reduced. Displacement feedback effectively increases the *spring constant s*, thereby increasing the resonant frequency and also the Q.

If the three feedback systems are combined we can choose the resonant frequency of the loudspeaker and the Q independently of one another, so that we can control the shape of the amplitude characteristic [4] at low frequencies.

The resonant frequency and the Q of a system using motional feedback can be calculated with the aid of an equivalent circuit. *Fig. 3* illustrates this with the diagram of an output amplifier represented by a voltage source of e.m.f. ge (g voltage gain, e input voltage) and an internal impedance R_i. The loudspeaker is represented by an electrical analogue in the form of a parallel circuit, in which the capacitance is the analogue of m, the inductance is the analogue of $1/s$ and the resistance the analogue of $1/r$ (see equation 1). The radiation mass is assumed to be included in m and the radiation resistance in r. The force F acting on the speech coil is now the analogue of the current supplied to the circuit. Since this force is equal to Bli (B magnetic flux density, l length of wire, i current), the transition from electrical to mechanical quantities can be indicated in the circuit by an ideal transformer of turns ratio Bl:1. The output circuit of the amplifier also includes the resistance R_s of the speech coil. (Since this equivalent circuit is only used at low frequencies, we can neglect the inductance of the speech coil.)

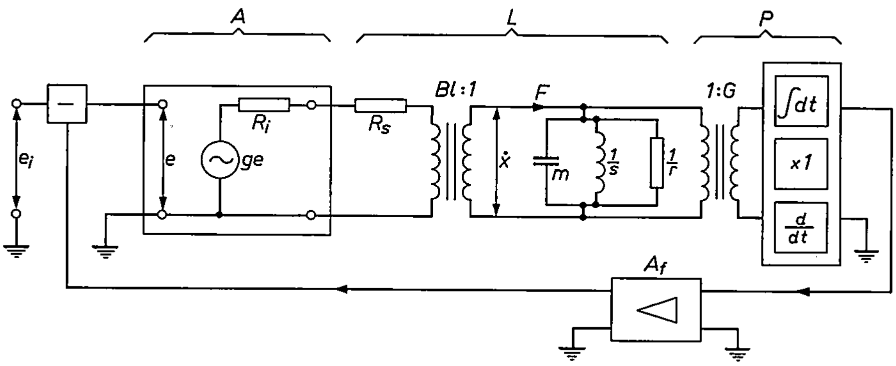

Fig. 3. Equivalent circuit diagram of a system consisting of an output amplifier A with loudspeaker, using motional feedback. The loudspeaker L is replaced by an electrical analogue in the form of a parallel circuit connected by means of two ideal transformers to the amplifier and the transducer P. The voltage across the circuit is now the analogue of the velocity $\dot{x}$ of the speech coil and cone. Depending on its type the transducer delivers a signal proportional either to $\int\dot{x}dt = x$, to $\dot{x}$ or to $d\dot{x}/dt = \ddot{x}$.

The voltage appearing across the circuit is now seen to be the analogue of the velocity $\dot{x}$ of the speech coil. The equivalent circuit of the transducer contains another ideal transformer of turns ratio 1 : G (G being a measure of the sensitivity). The transducer delivers a signal which is proportional either to $\int\dot{x}dt = x$, to $\dot{x}$ or to $d\dot{x}/dt = \ddot{x}$, depending on whether it is a displacement, velocity or acceleration transducer. (Accordingly, the turns ratio G takes different dimensions.) The input impedance of the transducer is considered to be infinite, and its mechanical characteristics are assumed to be included in the quantities m, s and r of the loudspeaker. The output signal from the transducer is amplified A_f times and fed back to the amplifier input.

With the aid of fig. 3 we can examine the effect of the feedback on the resonant frequency and the Q of the system. If we represent the resonant frequency and the Q without feedback by $\omega_0/2\pi$ and Q_0 respectively, we arrive at the results summarized in *Table I*. This table gives a quantitative representation of the effect of motional feedback on the resonant frequency and the Q.

Table I. Resonant frequency and Q of a loudspeaker with motional feedback.

	Acceleration feedback	Velocity feedback	Displacement feedback
Resonant frequency	$\dfrac{\omega_0/2\pi}{\sqrt{1+\dfrac{gA_fGBl}{m(R_i+R_s)}}}$	$\dfrac{\omega_0}{2\pi}$	$\dfrac{\omega_0}{2\pi}\sqrt{1+\dfrac{gA_fGBl}{s(R_i+R_s)}}$
Q	$Q_0\sqrt{1+\dfrac{gA_fGBl}{m(R_i+R_s)}}$	$\dfrac{Q_0}{1+\dfrac{gA_fGBl}{B^2l^2+r(R_i+R_s)}}$	$Q_0\sqrt{1+\dfrac{gA_fGBl}{s(R_i+R_s)}}$

Choice of type of feedback

Since the sound pressure generated at low frequencies is proportional to the acceleration of the cone, a flat amplitude characteristic in this range can be obtained if the *acceleration* of the cone is made independent of the frequency. This can be done by means of acceleration feedback. A drawback of this method, however, is that the resonance becomes more noticeable. Whilst the feedback lowers the resonant frequency, the Q increases, so that there is a peak in the amplitude characteristic. This situation can be improved by the simultaneous application of velocity feedback, which, as we have seen, reduces the Q.

An attractive feature of acceleration feedback is that the feedback factor increases with rising frequency (since, with a constant displacement amplitude, the acceleration increases with frequency). Because of this the higher harmonics generated by non-linear distortion are more strongly suppressed than with displacement or velocity feedback.

The transducer

As was stated earlier, we have used an acceleration transducer. This consisted primarily of a disc of piezoelectric material, fixed on one side to the coil former of the loudspeaker. When this disc is set in vibration, inertial forces are set up in it which produce a voltage between the end faces of the disc, and this voltage is a measure of the acceleration of the coil former. The mass must be kept down to avoid affecting the reproduction at higher frequencies.

For a given mass the highest signal power is obtained with a piezoelectric element whose longest dimension lies in the direction of acceleration. The impedance may then be so high, however, that an amplifier connected to the element would be upset by leakage currents. The arrangement would also be very susceptible to interfering voltages. Although an optimum configuration can be found with a stack of thin piezoelectric elements connected in parallel and stacked in the direction of acceleration, simplicity dictated the use of one thin element, of not too low a capacitance, with a loading mass on the side turned away from the coil. In the examples discussed below the capacitance was approximately 600 and 3000 pF.

In the first experiments the piezoelectric element was attached to the edge of the coil former with adhesive. It was then found that non-axial forces also occurred in the coil, giving rise to unwanted output signals. The mounting of the transducer was later changed so as to prevent those forces from affecting the piezoelectric element.

Another possible source of unwanted voltages in the piezoelectric element is the variation in air pressure to which it is subjected during its movements. This can be remedied by enclosing the element in a completely sealed housing. If this is made of metal it can provide electrical screening at the same time.

The efficiency of a loudspeaker

Uniform reproduction from a normal loudspeaker can only be obtained in a frequency range that lies *above* the resonant frequency. Below this frequency the efficiency quickly deteriorates. This is illustrated by curve a in *fig. 4*, representing the acoustic power radiated at constant input voltage. This curve relates to a loudspeaker with a Q of 1. We see that at a frequency equal to half the resonant frequency f_0 the radiated power has dropped by 12 dB (a factor of 16) compared with that at f_0. To obtain at the frequency $\frac{1}{2}f_0$ an acoustic power that is equal to that at frequencies higher than f_0, the amplifier must thus be capable of delivering an

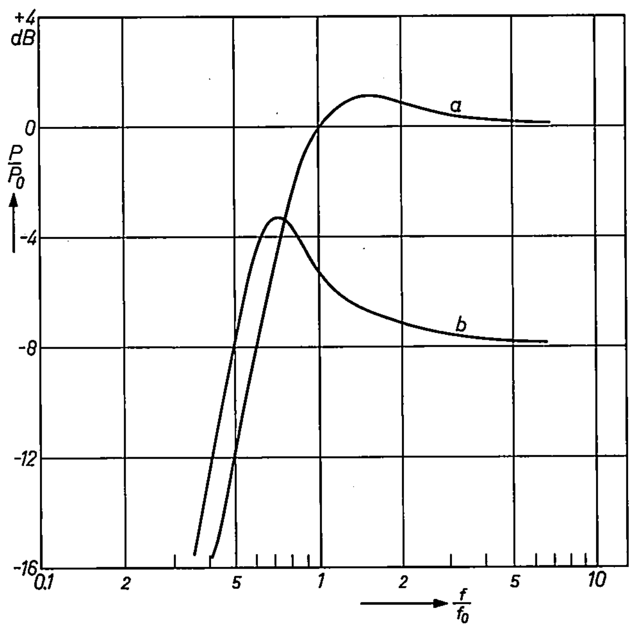

Fig. 4. The power P radiated by a loudspeaker, at constant input voltage, as a function of frequency f, both on relative scales. P_0 power at the resonant frequency f_0. The curve a is for $Q = 1$. In this case the power at the frequency $\frac{1}{2}f_0$ is 12 dB lower than that at f_0 and above. Increasing the mass of cone and speech coil by a factor of 2.5 (curve b) makes the power at $\frac{1}{2}f_0$ equal to that at higher frequencies. The Q is then $\sqrt{2.5} = 1.58$.

electrical power 16 times greater than is needed at higher frequencies.

A more uniform distribution of the required power is possible if the moving mass of the loudspeaker is increased. Although this reduces the radiated power for frequencies above f_0, it increases the power for lower frequencies. In fig. 4 curve b shows the acoustic power for the same loudspeaker as for curve a, but with the moving mass now increased by a factor of 2.5. The Q has now been increased by a factor of $\sqrt{2.5} = 1.58$, and the acoustic power at higher frequencies has dropped by 8 dB, while the power at $f = \frac{1}{2}f_0$ has increased by 4 dB, so that these two powers are now at the same level. Thus, if this loudspeaker is to be used down to a frequency of $\frac{1}{2}f_0$, the electrical power needs to be increased not by 12 dB but only by 8 dB. The resonant frequency has now been shifted to $f_0/\sqrt{2.5} = 0.63 f_0$. It should be noted that this method of obtaining a more uniform efficiency can only be used for low-frequency loudspeakers. Increasing the moving mass in full-range loudspeakers generally gives poorer reproduction at the higher frequencies.

Two loudspeakers for motional feedback

We have applied motional feedback on the principle described above in experimental circuits using two loudspeakers. One of them was a bass loudspeaker (type 9710 A), the other a full-range loudspeaker (type 9710 AM) [5]. Both loudspeakers were mounted in a closed cabinet whose internal volume was 10 litres. The part of the cone inside the coil was cut away to simplify the attachment of the acceleration transducer. This part of the cone does not affect the radiation of sound, but serves only for damping the spring-mass system. This damping is not required when motional feedback is used.

As we noted earlier, the transducers contain a disc of piezoelectric material [6], loaded with a certain mass. The transducer for the full-range loudspeaker (*fig. 5*) is made as light as possible in order to minimize its effect on the reproduction at the higher frequencies. For the bass loudspeaker (*fig. 6*) a larger piezoelectric disc and a larger loading mass were used. The effect of this is twofold: it improves the efficiency at low frequencies as demonstrated above, and increases the

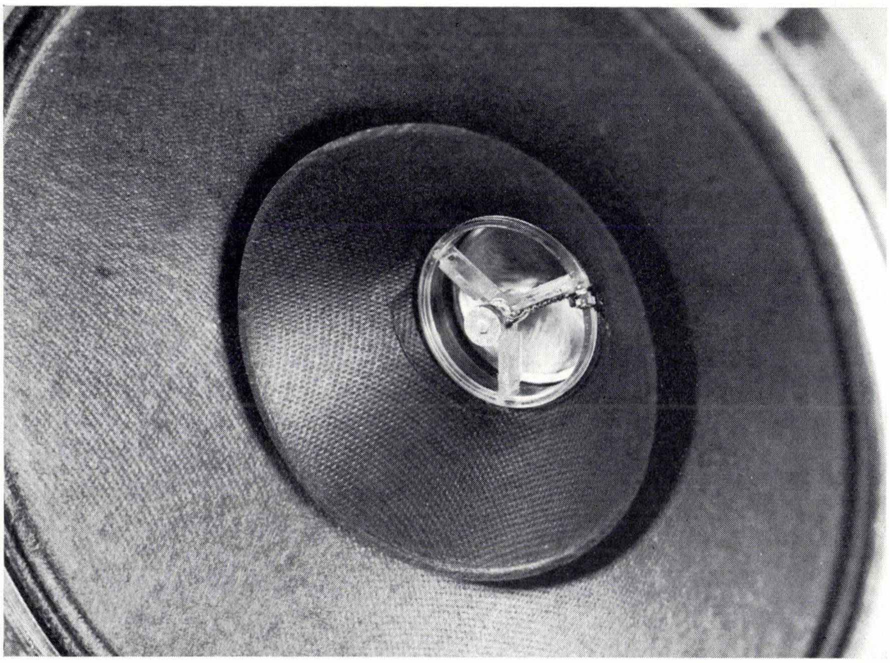

Fig. 5

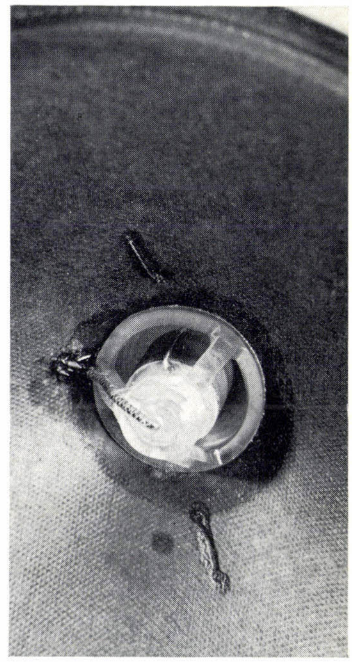

Fig. 6

Fig. 5. Method of attaching the acceleration transducer to the full-range loudspeaker, type 9710 AM.

Fig. 6. Method of attaching the acceleration transducer to the bass loudspeaker, type 9710 A.

[5] The difference between the two loudspeakers is that type 9710 A has a single cone while type 9710 AM has a double cone.

[6] Philips type designation PXE-5. This material was chosen in consultation with C. M. van der Burgt of this laboratory.

sensitivity of the transducer. *Table II* lists the main characteristics of the two transducers.

The total mass in this table relates to the complete transducer (piezoelectric element, loading mass and base); the output voltages relate to an acceleration of 126 m/s². This acceleration is reached when the displacement of the coil, at a frequency of 40 Hz, is so great that the coil only just stays within the magnetic field. If the loudspeaker has a flat frequency response, the acceleration is the same at all frequencies; the output voltages shown thus correspond to the displacement limit when the lowest frequency to be reproduced is 40 Hz.

Table II. Transducer data.

Loud-speaker	piezoelectric element				loading mass	total mass	output voltage
	dia.	thickness	cap.	mass			
9710 AM	5 mm	0.5 mm	620 pF	76 mg	300 mg	2 g	26 mV
9710 A	16 mm	1.1 mm	2880 pF	1.69 g	29 g	37 g	500 mV

The circuit

Fig. 7 shows a block diagram of the circuit we used for applying motional feedback to a type 9710 AM loudspeaker connected to an output amplifier *A* (output power 10 W). The acceleration transducer *P* drives a cathode follower *K*, which is placed in the loudspeaker cabinet so that the connecting leads can be short. The valve used is a nuvistor (type 7586). The cathode follower is followed by an amplifier *A'*, whose output signal is an electrical representation of the acceleration of the speech coil. *Fig. 8* shows the variation of this signal voltage in amplitude and phase with varying frequency of the (constant) input signal. The feedback loop here is open and the curve thus corresponds to the Nyquist diagram of the feedback system. It is known that an amplifier is stable only if the curve does not enclose the point —1. In the figure the position of this point is indicated for the case where the acceleration feedback has been increased until the resonant frequency — 97 Hz without

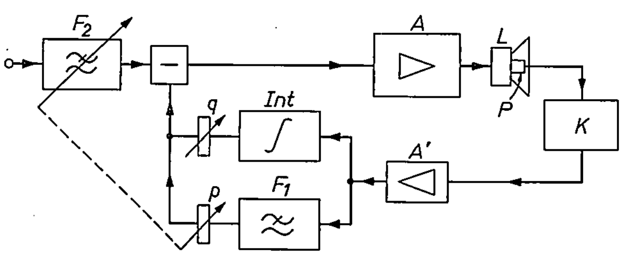

Fig. 7. Block diagram of a circuit for applying motional feedback to a full-range loudspeaker. *A* output amplifier (output power 10 W). *L* loudspeaker. *P* acceleration transducer. *K* cathode follower. *A'* amplifier. F_1 and F_2 low-pass filters. *Int* integrator. *p* and *q* variable attenuators.

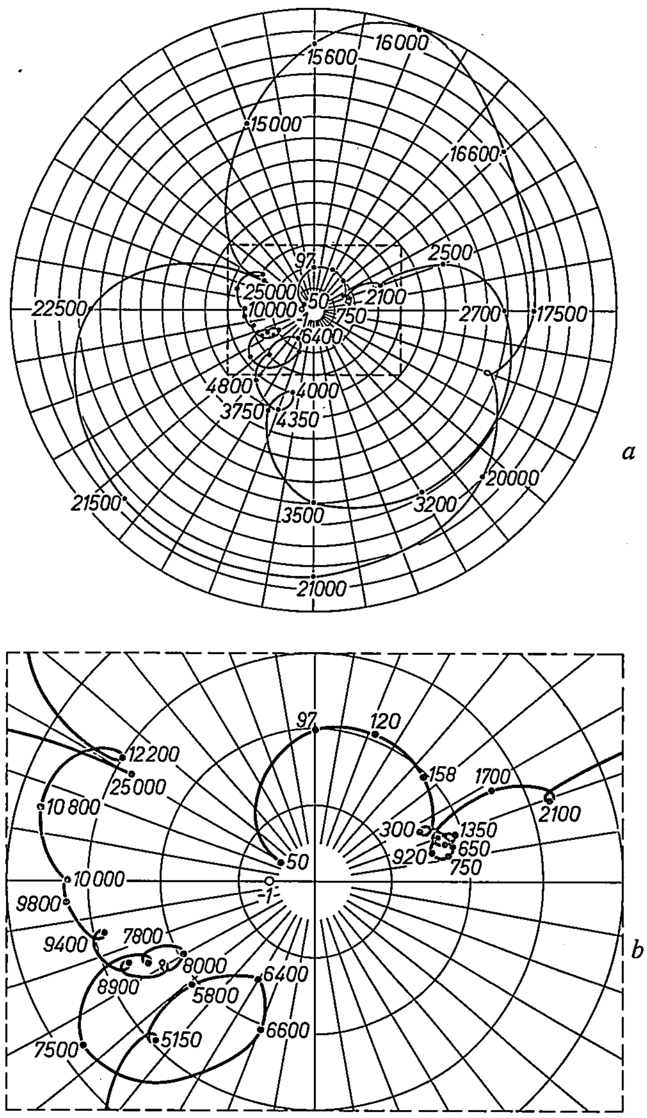

Fig. 8. *a*) Nyquist diagram for a feedback system like that of fig. 7 when the filter F_1 and the integrator *Int* are not included in the circuit. The feedback is made so large that the resonant frequency — 97 Hz without feedback — is shifted to 42 Hz. The figures along the curve indicate the frequency in Hz. Since the curve encloses the point —1, this system is not stable.
b) A magnified view of the region bounded by the dashed line in (*a*).

feedback [7] — is shifted to 42 Hz. Since, as the figure shows, the curve does enclose the point —1, the system will not be stable as it stands. Stability can be achieved by incorporating a low-pass filter F_1 in the feedback circuit, as shown in fig. 7. As we have seen, the application of motional feedback in this form is only worth while at the lower frequencies, so there is no objection to the use of a low-pass filter in the feedback circuits. The cut-off frequency of the filter is 250 Hz and the attenuation above cut-off is 12 dB per octave. The filter is followed by a variable attenuator p, used for adjusting the amount of acceleration feedback. The Nyquist diagram resulting from the introduction of

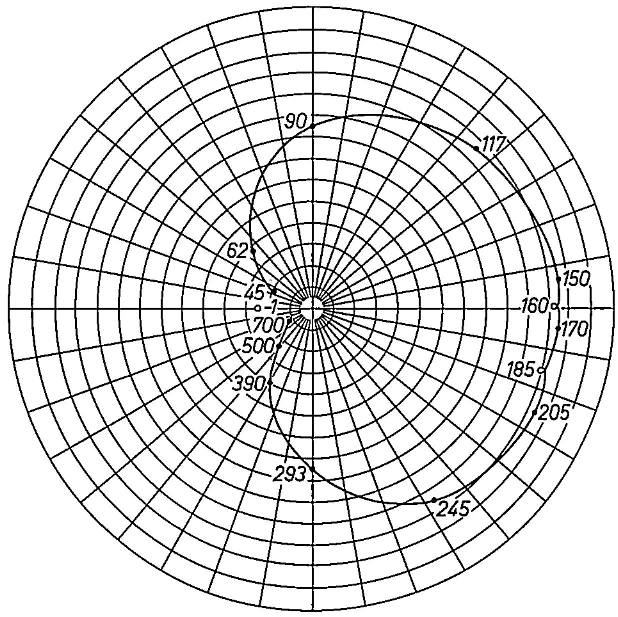

Fig. 9. The introduction of the low-pass filter F_1 makes the circuit in fig. 7 stable, as can be seen from the fact that the Nyquist diagram no longer includes the point —1.

the filter F_1 is shown in *fig. 9*. It can be seen that the circuit is now stable. The fact that there is feedback at low frequencies and not at high frequencies causes a difference in level, which is compensated for by the low-pass correction filter F_2 (fig. 7). The extent to which this filter attenuates at high frequencies can be adjusted, the adjustment being coupled with that of the attenuator p.

To prevent the resonance effect from having too great an effect on the amplitude characteristic because of the acceleration feedback (which, as we have seen, increases the Q), velocity feedback is also used. A voltage proportional to the velocity of the speech coil is derived from the acceleration signal by means of the integrator *Int*. This voltage is added to the acceleration signal via a variable attenuator q.

Fig. 10 shows the block diagram of the circuit used for applying motional feedback to the bass loudspeaker 9710 A. (The upper-frequency range is reproduced by means of a separate amplifier and loudspeaker.) Basically, the circuit is the same as that shown in fig. 7.

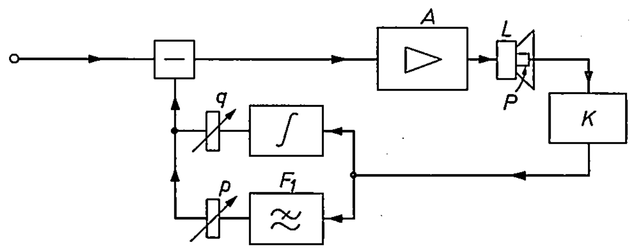

Fig. 10. Block diagram of a circuit in which motional feedback is applied to a low-frequency loudspeaker, type 9710 A. The letters have the same significance as in fig. 7.

However, since the sensitivity of the transducer used with this loudspeaker is greater, no amplifier is needed here after the cathode follower. In addition, a low-pass filter with a higher cut-off is used because, with the bass loudspeaker, the accelerations at high frequencies are lower than for the full-range loudspeaker. This frequency has therefore been fixed at 600 Hz, which means that the feedback is effective over a wider frequency range. Finally, if the motional feedback is only applied to the bass loudspeaker, there is no need for a correction filter like that shown in fig. 7 for equalizing the level at high and low frequencies.

Results of measurements

Amplitude characteristics

In *fig. 11* curve *a* is the amplitude characteristic of the full-range loudspeaker 9710 AM mounted in a closed cabinet whose internal volume is 10 litres. The resonant frequency is 97 Hz. Curve *b* shows the characteristic obtained when the maximum permissible acceleration feedback for stability was applied with the circuit of fig. 7 (attenuator q at zero). The resonant frequency is now at 42 Hz. Curve *c* shows the characteristic obtained when velocity feedback is applied as well to reduce the effect of the resonance. If we compare this with *a*, we see clearly the improvement in the reproduction of the lower frequencies obtained by the application of motional feedback.

[7] The mechanical resonance of the loudspeaker can be seen to be at this frequency since the phase angle of the acceleration is here 90°. The phase angle of the velocity is then zero.

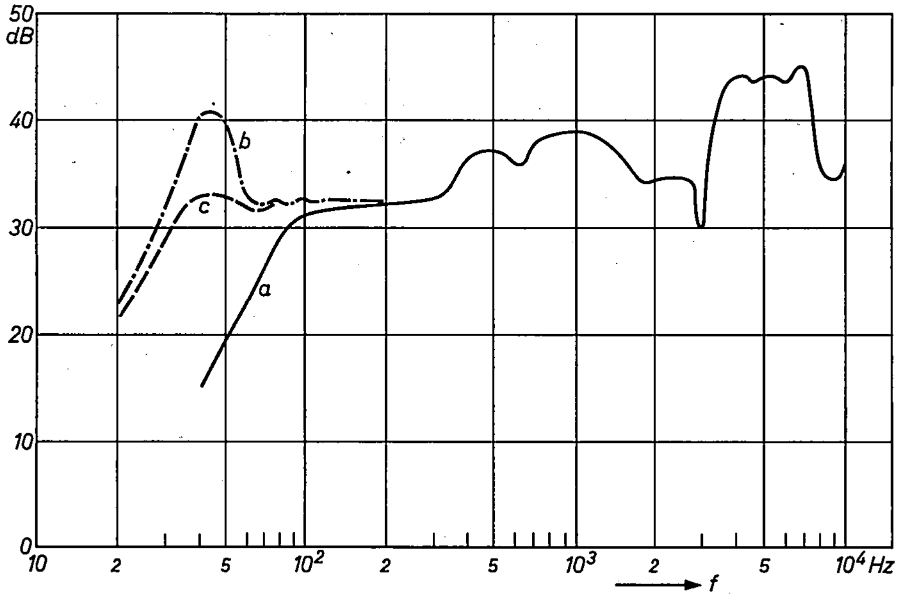

Fig. 11. Amplitude characteristics measured on the system of fig. 7, the loudspeaker being mounted in a completely closed cabinet with a volume of 10 litres, *a*) without motional feedback, *b*) with acceleration feedback, *c*) with both acceleration and velocity feedback.

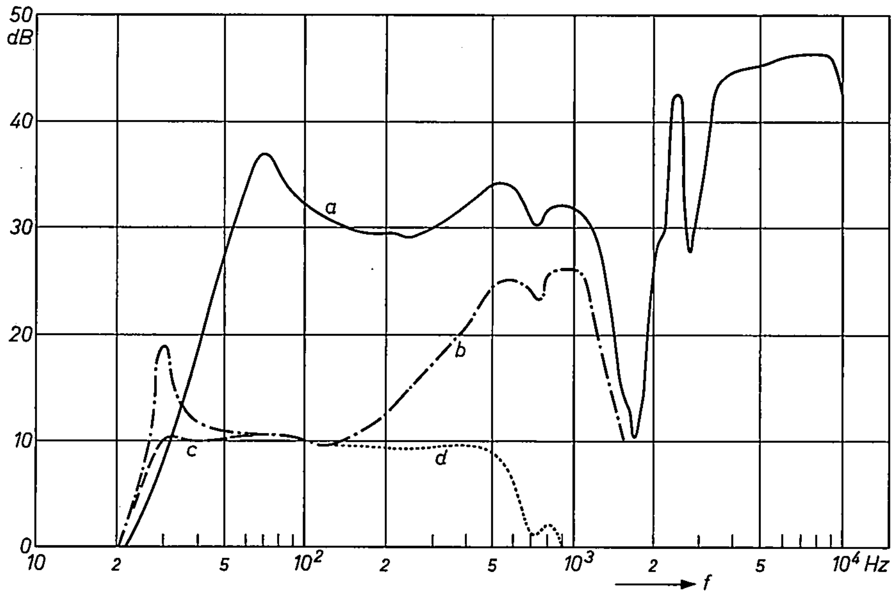

Fig. 12. Amplitude characteristics measured on the system of fig. 10, *a*) without motional feedback, *b*) with acceleration feedback, *c*) with both acceleration and velocity feedback, *d*) with the addition of a filter for separating high and low frequencies.

Fig. 12 shows the effect of acceleration feedback on the bass loudspeaker 9710 A, also mounted in a closed 10-litre cabinet. Here again, curve *a* relates to the case where no feedback is used, and curve *b* to the application of acceleration feedback within the limits of stability. We see that the resonant frequency of 70 Hz is shifted to 30 Hz. Curve *c* is the result of applying velocity feedback as well as acceleration feedback. Using an appropriate filter to separate the high and low frequency channels, we obtain the amplitude characteristic *d*, which is flat to within $\pm$ 1 dB from 23 to 500 Hz.

Non-linear distortion

The reduction of non-linear distortion that can be brought about by motional feedback depends, like the feedback factor, upon the frequency. We have already seen that the distortion caused by the loudspeaker

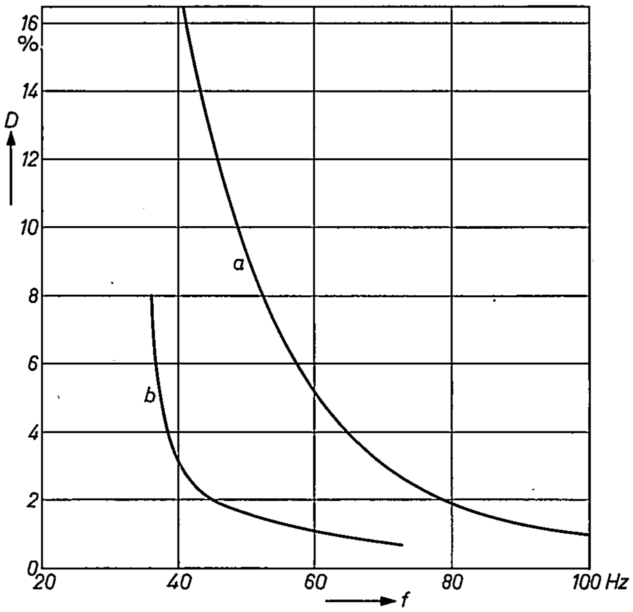

Fig. 13. Non-linear distortion D as a function of frequency f for loudspeaker 9710 AM. The radiated power is kept the same at all frequencies; the electrical power supplied to the loudspeaker is 4.5 W at 40 Hz. Curve *a* is obtained with no motional feedback, and curve *b* is obtained when acceleration and velocity feedback are combined in such a way as to give the amplitude characteristic *c* of fig. 11.

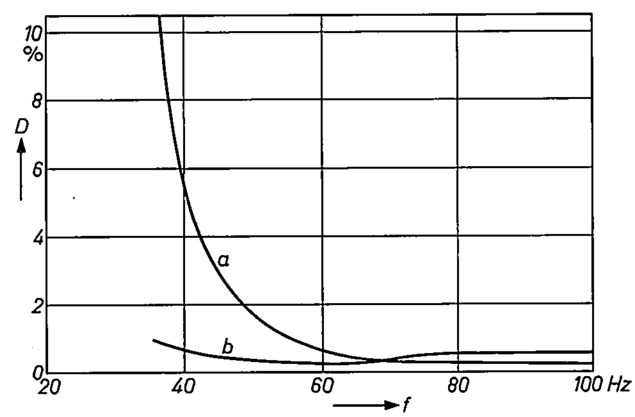

Fig. 14. Non-linear distortion D as a function of frequency f for the bass loudspeaker 9710 A under the same conditions as for fig. 14, *a*) without motional feedback, *b*) with motional feedback adjusted to obtain the amplitude characteristic *d* of fig. 12.

mechanism is greatest in the reproductions at low frequencies; motional feedback here is therefore of special importance. Figs. 13 and 14 give some results of measurements. *Fig. 13* shows the percentage distortion as a function of frequency, for the 9710 AM loudspeaker and at constant radiated power. The electrical power supplied to the loudspeaker is 4.5 W at 40 Hz. Curve *a* shows the distortion without motional feedback (but using electrical feedback in the amplifier), and curve *b* gives the result of using the motional feedback that produces the amplitude characteristic in fig. 11*c*. It can be seen from this figure that at 40 Hz the distortion has decreased from 17% to 3%. *Fig. 14* gives the corresponding curves for the bass loudspeaker 9710 A. Curve *b* here corresponds to the amplitude characteristic *d* in fig. 12.

These results show that the method of motional feedback which we have described can in fact yield substantial improvements in sound reproduction, and that it will be of great assistance in achieving good reproduction in a very wide frequency range with highly compact equipment.

Summary. One of the main causes of distortion in an electro-acoustical system consisting of an amplifier and a loudspeaker is to be found in the mechanism of the loudspeaker, particularly if the loudspeaker is mounted in a small, closed cabinet. This distortion is not affected by the electronic negative feedback conventionally used for reducing distortion. With motional feedback, the loudspeaker is included in the feedback loop. This article discusses various forms of motional feedback. A method specially developed for feedback at low audio frequencies has been tested experimentally. In this method an acceleration transducer containing a piezoelectric element is fixed to the moving coil of a normal loudspeaker; this gives a feedback signal proportional to the acceleration of coil and cone. A signal proportional to the velocity is also obtained by integration and a certain fraction of this is added to the first feedback signal. In this way an amplitude characteristic can be obtained which is flat down to below the mechanical resonant frequency of the loudspeaker, and the non-linear distortion in this frequency range is substantially reduced. The sound pressure and the non-linear distortion have been measured as a function of frequency for two loudspeakers with motional feedback, one being a loudspeaker for the bass range and the other a loudspeaker for the full audio range. They showed a substantial improvement in reproduction of the bass.