Oct. 18, 1960 S. L. BOERSMA 2,956,636

LOUDSPEAKER

Filed June 11, 1956

FIG. 1

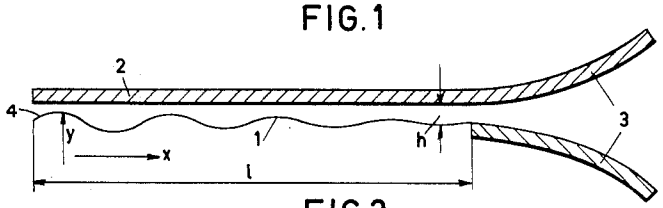


FIG. 2

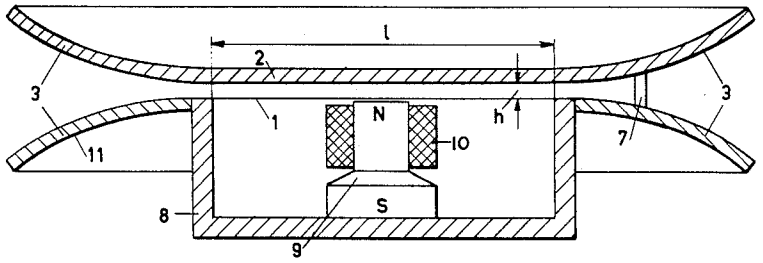


FIG. 3

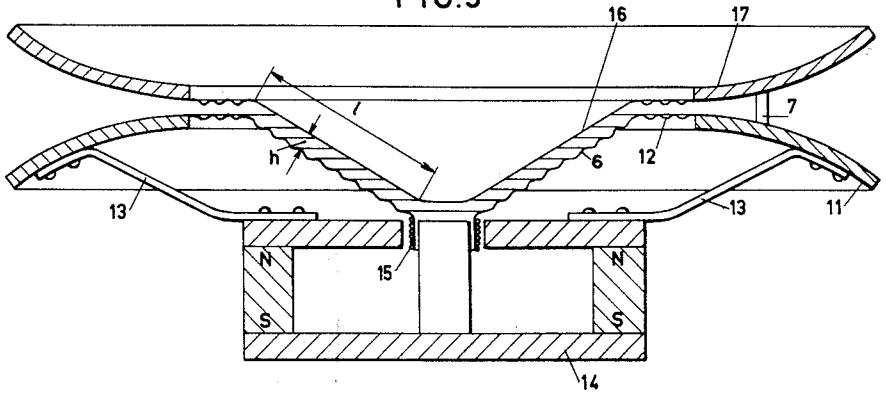
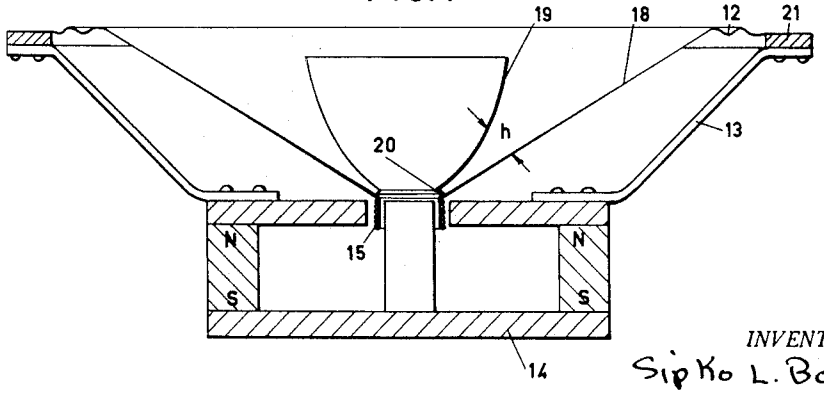


FIG. 4



INVENTOR:
Sipko L. Boersma

BY:
Michael S. Striker
agt

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LOUDSPEAKER

Sipko L. Boersma, 104 Oostsingel, Delft, Netherlands

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1 Claim. (Cl. 181—31)

My invention relates to a loudspeaker and its main object is an improved diaphragm which is adapted to reproduce a wide range of frequencies, especially the higher frequencies of the acoustical range with high efficiency.

A diaphragm is used in nearly all loudspeakers as a mechanical link to convert electric power in acoustic power.

These diaphragms, together with the way they are loaded, determine the frequency response of the loudspeaker. A very stiff diaphragm, which even at the highest frequency of the acoustical range moves as a piston, tends to be heavy. All accelerating forces add in phase to build up a heavy mass load on the driving mechanism and as a consequence thereof the high frequency response is poor, unless an elaborate horn provides a high acoustic load impedance.

A less stiff diaphragm (e.g. the normal paper cone) possesses a great number of resonant frequencies within the frequency range to be reproduced, and its frequency response is of an erratic and unpredictable character.

It is impossible to design a paper cone having a desired frequency response at the desk stage of the development and in fact the development of paper cone diaphragms for loudspeakers is a trial and error affair.

It is a further object of my invention to create a loudspeaker diaphragm which can be designed at the desk stage and has a high efficiency, which is nearly constant over the entire frequency range.

The diaphragm can be used in combination with a horn, but as the diaphragm can be made large, the horn can be small. A more detailed object of my invention is the deliberate use of travelling transverse waves, which emerge from the part of the diaphragm which is acted on by the driving system and from there travel towards the border of the diaphragm and transfer their energy to the surrounding air.

A still more detailed object is to construct the diaphragm from a material with well defined elastic properties and low internal losses, such as metal.

With these and other objects in view, my invention and the novel features thereof will be pointed out in the claim and described and illustrated in the following description and the accompanying drawings.

Fig. 1 outlines the principle of the invention.

Fig. 2 shows a sectional view of a ferromagnetic loudspeaker with a steelfoil diaphragm.

Fig. 3 shows a sectional view of an electrodynamic cone speaker.

Fig. 4 shows a sectional view of an electrodynamic cone speaker.

The principle of the present invention is shown in Fig. 1 for the case of one-dimensional wave propagation. **1** is a vibrating diaphragm, **2** is a stationary wall, **3** is a horn. A stress mechanism (not shown) generates a constant tensile stress S in the x direction of the diaphragm. As the diaphragm possesses a mass m per unit area de-

flections will be propagated along the x coordinate with the velocity

$$\sqrt{\frac{S}{m}}$$

A driving mechanism (not visible) forces the line shaped end **4** of the diaphragm in vertical motion. The stress S in the diaphragm can be made so high that the velocity

$$\sqrt{\frac{S}{m}}$$

equals the velocity of sound in the air in the airgap h between diaphragm **1** and stationary wall **2**. The travelling diaphragm deflection y generates a sound wave in the airgap h.

If it is assumed that h is small compared to the wavelength and the deflection y is small compared to h the following relations exist:

$$m\frac{\partial 2_y}{\partial t^2}-S\Delta y+P=0 \tag{1}$$

$$\text{grad } P+\rho\frac{\partial V}{\partial t}=0 \tag{2}$$

$$\text{div } (hV)-\frac{\partial y}{\partial t}+\frac{h}{\rho c^2}\frac{\partial P}{\partial t}=0 \tag{3}$$

List of symbols:

y=diaphragm deflection
h=thickness of airgap
P=sound pressure in airgap
V=velocity of air in gap
m=mass per unit area of diaphragm
S=tensile stress per unit length in diaphr.
ρ=density of the air in gap
c=velocity of sound in gap
t=time

If we assume h to be constant, not varying with place, the equation for the diaphragm deflection y for harmonic vibrations is:

$$\Delta^2 y+(1^2+k^2)\Delta y+k^2(1^2-a^2)y=0 \tag{4}$$

with

$$k=\frac{\omega}{c}$$

wherein ω=frequency of sound in radiance per second

$$L=\frac{\omega}{c'},\ c'=\sqrt{\frac{S}{m}}$$

sound velocity in diaphragm and

$$a=\sqrt{\frac{l}{h}\frac{\rho c^2}{mc'^2}}$$

In the one dimensional case of Fig. 1 a solution for high frequencies

$$y=\cos\frac{x}{2}\sqrt{\alpha^2k^2+a^2}\ \exp j\left[\omega t-k\left(1+\frac{\alpha}{2}\right)x\right] \tag{5}$$

with

$$\alpha=\frac{1}{2}\left(\frac{c^2}{c'^2}-1\right)$$

If we make c equal to c' (by correctly choosing S), the deflection of the diaphragm is:

$$y=y_0\cos\frac{a}{2}x.\exp j(\omega t-kx) \tag{6}$$

According to this particular solution

$$y \text{ at } x=\frac{\pi}{a}$$

is equal to

$$\text{zero at } x=\frac{\pi}{a}$$

for all frequencies for which the condition $k>>a$ is valid, so that this solution can be considered as representing the actual motion of a diaphragm clamped at

$$x=\frac{\pi}{a}$$

As according to this particular solution the waves are propagated in one direction no reflection of energy takes place so that no standing waves occur and the frequency characteristic is substantially flat, at least at the higher frequencies.

At the point

$$x=\frac{\pi}{a}$$

all of the sound energy is accumulated in the airgap that can feed it into a horn which radiates it in the surrounding atmosphere. From Equation 5 it will be seen that the distance

$$\frac{\pi}{a}$$

is independent of the frequency if $c=c'$ and

$$\frac{\pi}{a}\gg\lambda$$

λ being the wavelength.

The mechanical impedance of the diaphragm feed point (line) 4, is for the higher frequencies a constant and purely resistive: $Z=mc$ ohms/meter.

So this loudspeaker diaphragm has no mass reaction at the higher frequencies. The upper frequency limit is determined by the mass of the driving mechanism (voice coil) or by the wavelength being no longer great compared with the width of the air gap.

In Fig. 2 a practical embodiment of a loudspeaker is shown schematically. The diaphragm is of stressed steel foil and is at its outer rim attached to the housing 8 in which a magnet 9 and a coil 10 are located.

The wall of the horn 3 consists of the stationary parts 2 and annular frame means 11. The part 2 is supported by the part 11 by means of supports 7 of which only one is shown. The diaphragm is circular and the horn is of circumferential form.

The acoustical energy is fed into the horn through the air gap at the rim of the diaphragm between the parts 2 and 11

In order to make the sound velocities in diaphragm and air equal one can choose the correct, rather high, foil stress or one can lower the sound velocity in the air by cutting concentric grooves (not shown) in the stationary wall 2. In the latter case an air filled delay line is formed.

The dimensions can be: diaphragm thickness 0.002", diameter 10", air gap 0.16", tensile stress 200 lbs./inch, frequency response 1–20 kc./s. The driving mechanism possesses no material mass, but the electrical self inductance and the ratio of pole diameter/wave length set a limit to the frequency response. With a diaphragm clamped at the edge the lower frequency limit is near the lowest resonant frequency of the free swinging diaphragm. An elastically suspended edge can make this limit much lower although of course radiation at these low frequencies is no longer determined by the travelling wave mechanism described.

Fig. 3 shows an electrodynamic loudspeaker with a quite conventional elastic cone suspension. The cone 6

is fixed to the flange 11 by means of a conventional flexible coupling 12, the flange 11 being supported by supporting rods 13 fixed to the magnet system 14. The cone 6 is provided with a voice coil 15, located in the airgap of the magnet. A second diaphragm 16 of substantially the same dimensions and form as the diaphragm 6 is supported by the flange 17 which itself is supported by the flange 11 by means of supports 7.

The flanges 11 and 17 constitute the walls of the horn. The cone 6 is corrugated in order to make the sound velocity in it equal to the sound velocity in air. The cone 16 is located symmetrically with respect to the cone 6 so that between these cones a conical passage is formed. In operation the cone 16 remains stationary at the higher frequencies, where the travelling waves feed the sound to the circumferential horn, constituted by the flanges 11 and 17. At the lower frequencies the cone 16 will move in phase with the cone 6 and operate in the normal way.

Fig. 4 shows a further embodiment of the invention applied to an electrodynamic loudspeaker. The magnet 14 is of the same conventional type as in Fig. 3.

The conical diaphragm 18 which is driven by the voice coil 15 is made of material decreasing in thickness from the apex to the outer rim, that is, the conical diaphragm 18 is made from material in which the mass per unit area decreases with increasing distance from the apex.

The voice coil further carries a cup-like member 19, which by means of a flexible elastic coupling 20 is coupled with the voice coil. The diaphragm 18 is by means of a flexible coupling 12 in the conventional way fixed to a ringshaped member 21, carried by the supporting rods 13, which themselves are supported by the magnet 14. The decrease in thickness of the material of the cone may follow an exponential law.

Between the conical diaphragm 18 and the cup-like member 19 an airgap h is formed.

In order to obtain the travelling wave action of the present invention it is necessary for the airgap h to increase with the radius according to the inverse law, so that the product of thickness of material and airgap is approximately constant.

At higher frequencies operation is in the traveling wave mode. The mechanical impedance at the voice coil is mc per unit length, m being the mass per unit area of the thick material in the immediate vicinity of the voice coil.

At the lower frequencies cone 18 and member 19 move in phase due to the elastic coupling between them. In a good baffle enclosure the voice coil impedance is here $\pi R^2\rho c$ ohms.

The elastic coupling 20 is adjusted so as to leave the cup-like member 19 stationary for the higher frequencies, while preventing relative motion between the diaphragm 18 and the cup-like member 19 for the lower frequencies.

Grading the thickness of the cone material gives the designer an extra constructional degree of freedom that can be used to equalize the mechanical impedance at the voice coil edge for both modes of operation, without the cone becoming so heavy as to disturb the piston mode of operation at the cross-over frequency.

I claim as my invention:

A loudspeaker comprising, in combination a driven conical diaphragm in which the velocity of transverse waves for the higher frequencies is equal to the sound velocity in the surrounding medium, said conical diaphragm being made of material of which the mass per unit area decreases with increasing distance from the apex, a cup-like member forming with said conical diaphragm an airgap of which the width increases with increasing distance from the apex, the product of thickness of the material of said diaphragm and airgap being substantially constant, and an elastic coupling connecting said cup-like member with said conical diaphragm, said elastic coupling being so adjusted as to leave the cup-like mem-

ber stationary for the higher frequencies, while preventing relative motion between the diaphragm and the cup-like member for the lower frequencies.

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