Frequency Response of an Electrostatic Horn-Tweeter with Electret

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Abstract

The practical design method of electrostatic loudspeakers with D.C. bias is known. In this paper, the frequency characteristics and the efficiency of horn-loaded electret tweeter are presented.

The tweeter has a very thin diaphragm (palladium is vacuum-evaporated on polyester of 4μ thick) between two perforated back plates on which perforated electret films (125μ thick) are laminated. Its frequency response mainly depends upon the ratio of the surface area of the perforated electret to the area of the diaphragm (called perforating ratio). Regarding this characteristic of dependence, the results of analysis and experiments are given to clarify the various characteristics of horn-loaded electret tweeter.

Introduction

An electrostatic tweeter using electret instead of D.C. bias has been known for long. Pickup for gramphones was invented by Mr. Eguchi in 1920, and microphones by Mr. Rugherford in 1934. Both of them used Carnauba Wax electrets for the fixed electrodes.

In the 1960's, high polymer films made a rapid development, and high pplymer electrets were studied, and a microphone using electret films as the diaphragm was devised [2]. These motivated the rapid commercialization of today's electret microphones. Electret has been also applied only to head-phones [3]. There is, however, almost no example of application of electret to loudspeakers.

Unlike a microphone, a loudspeaker requires the concersion to acoustic power.

Therefore, we employed an electret fixed electrode method in which the electrical characteristics of electret can be separated from the mechanical characteristics of electret and also the degree of freedom in design can be increased. Thus we developed horn-loaded electret tweeter.

The only merit of this electret fixed electrode method is that the thickness of electret can be freely increased in proportion to the air gap necessary for large amplitude. This needs the technique of perforating electret and we have successfully developed the technique.

1. Analysis

Fig. 1 shows the push-pull type in the electret fixed electrode method and its mechanical equivalent circuit is shown in Fig. 2.

When input signal voltage is e_o , the driving force F on the diaphragm can be obtained from the following formula.

$$F = \frac{\varepsilon_o \, Seff}{(g + d/\varepsilon^*)^2} \left(\frac{\sigma d}{\varepsilon} \right) e_o$$

Where, $Seff = (1 - \beta) S_D$ effective area of fixed electrode

S_D : area of diaphragm

β : perforating ratio

σ : surface charge density of electret

d : thickness of electret

ε : dielectric permitivity of electret

$\varepsilon = \varepsilon^* \varepsilon_o$

g : length of air gap

e_o : signal voltage

Perforating an electret will cause the reduction of its total surface charge due to decrease in surface area.

Therefore, driving force F will also decrease as shown by equ. (1). However, viscosity resistance R_F of the air gap and in the holes of the back electrode will decrease more than the electric charge, it is predicted that there exists an optimum point of β for the velocity V fo diaphragm.

From Fig. 2, the velocity V of diaphragm can be obtained as follows:

$$V = \frac{F}{Rth + 2R_F + j(Xth + \omega M_M - \frac{1}{\omega C_M} - \frac{1}{\omega C_B} + \frac{1}{\omega C_N})} \qquad (2)$$

Where,

$Rth = \frac{\rho_o C S_D}{\alpha} \cdot \sqrt{1 - (\frac{f_c}{f})^2}$ radiation resistance of horn

$Xth = \frac{\rho o C S_D}{\alpha} \cdot \frac{fc}{f}$ radiation reactance of horn

$C_B = \frac{V_B}{\rho_o C^2 S_D^2}$ compliance of back cavity

$C_M = \frac{1}{S_M}$ compliance of diaphragm

$S_N = \frac{1}{C_N} = \frac{2\varepsilon o S_{eff}}{(g+\alpha/\varepsilon^*)^3} \left(\frac{\alpha d}{\varepsilon}\right)^2$ negative stiffness of diaphragm

$M_M =$ Mass of diaphragm

$\alpha = \frac{S_{th}}{S_D}$ ratio of throat area of horn to S_D

$f_c =$ cutoff frequency of horn

Viscosity resistance R_F [4] of gap in equ. (2) is

$$R_F = \frac{12\eta S_D^2}{\pi N g^3} \left(\frac{1}{4}\ln(\beta)^{-1} - \frac{3}{8} + \frac{\beta}{2} - \frac{\beta^2}{8} \right) \quad \ldots\ldots (3)$$

Where, η is viscosity coefficient of air,

N is the number of holes in electret.

Fig. 3 shows the calculated F, V, R_F, Z in relation with β where g = 50μm, volume back cavity = 25cc, electret is 125μm thick, Z is the total mechanical impedance. Acounstic power W of loudspeaker can be obtained as $W = |V|^2 \cdot R_{th}$. Therefore, the maximum value of acoustic power can be also obtained with perforating ratio β, the same value as that giving the maximum value of diaphragm velocity V as in Fig. 3. From equ. (2), acoustic power W is

$$W = \frac{F^2 \cdot R_{th}}{(R_{th}+2R_F)^2 + \left(X_{th}+\omega M_M - \frac{1}{\omega C_M} - \frac{1}{\omega C_B} + \frac{1}{\omega C_N}\right)^2} \quad (4)$$

Thus, acoustic power in equ. (4) is the function of driving force F and viscosity resistance R_F depending upon the perforating ratio β of electret. It is well known that radiation resistance Rth depends upon the ratio of the throat area of horn to the diaphragm area. To increase Rth too much in equ. (4) (to decrease the ratio α) will cause the reduction of acoustic power W. So, the flat response of the acoustic power, that is, the range of resistance control will become wide.

The result of calculation of equ. (4) under the same condition in Fig. 3 is shown in Fig. 4. Here, to get the optimum acoustic power, the ratio α is given as follows when dw/dα=0 [5].

$$\alpha = \frac{1}{2R_n\sqrt{1+\left(\dfrac{\omega_o M_M(\omega/\omega_o-\omega_o/\omega)-\dfrac{1}{\omega C_B}+\dfrac{1}{\omega C_N}}{2\,\rho_o C S_D R_n}\right)^2}} \qquad (5)$$

Where, $R_F = \rho_o C S_D R_n$

$\alpha=1/2R_n$ when resistance control range is

$$R_{th}+2R_n \gg X_{th}+\omega M_M-\frac{1}{\omega C_M}-\frac{1}{\omega C_B}+\frac{1}{\omega C_N}$$

The above result agrees with the design condition of the optimum ratio α for dynamic horn speakers.

The design of this type is, therefore, easier than that of a dynamic horn speaker because impedance density R_n of the both sides of diaphragm can be estimated from equ. (3).

Regarding the frequencies where resistance component of the total mechanical impedance becomes equal to capacitive reactance and mass reactance, low limiting frequency f_L and high limiting frequency f_H are

$$f_L = \frac{1}{2\pi\left(\frac{\rho_o C S_D}{\alpha} + 2R_F\right)}\left(\frac{1}{C_M} - \frac{\rho_o C S_D}{\alpha} 2\pi f_c + \frac{1}{C_B} - \frac{1}{C_N}\right) \quad \ldots (5)$$

$$f_H = \frac{1}{2\pi M_M}\left(\frac{\rho_o C S_D}{\alpha} + 2R_F\right) \quad \ldots\ldots (6)$$

The results of calculation of equ. (5) and equ. (6) in relation to α are shown in fig. 5.

Next, let's determine the thickness of electret film. Maximum amplitude η_m of diaphragm can be estimated from the frequency range and the maximum sound pressure level. For air gap g, it should be $g > \eta_m$. Furthermore, air gap g should be determined so that $S_M > S_N$ where S_N is negative stiffness depending upon coulomb force between diaphragm and electrets; and S_M is stiffness of diaphragm.

Once g has been determined, the optimum thicknes of electret film that maximizes the driving force can be obtained from equ. (1).

By differentiating equ. (1) with respect to d, to make it zero, we obtain

$$\frac{dF}{d\alpha} = \varepsilon o S eff \left(\frac{\sigma}{\varepsilon} e_o\right) \frac{g - \alpha/\varepsilon^*}{(g + \alpha/\varepsilon^*)^3}$$

Therefore,

$$d = \varepsilon^* g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where, ε^* is dielectric constant of electret.

Since dielectric constant of FEP teflon ε^* is 2.1, electret thickness is to be 2.1 times air gap g.

2. Measurement and results

The acoustic power response and the sound pressure response of test products calculated using the values in Table 1 are shown in Fig. 6 and Fig. 7 respectively.

Dotted lines stand for calculated response.

Axial sound pressure P can be obtained from acoustic Power W, that is,

$$P = \sqrt{\frac{\rho o . C W}{4\pi r^2 (DI)}} \quad \ldots\ldots\ldots\ldots\ldots \quad (9)$$

Where, (D I) is directivity index, r is axial distance from sound source.

From the above results, we find that the measured values of acoustic power and axial sound pressure well agree with the calculated values.

The fixed electrodes used here made of stainless steel plates (60 mm in diameter, 0.5 mm in thickness) provided with 351 holes (1.8 mm in diameter) by photo etching technology.

Then, an electret film is perforated by a dies having the same pattern as the above plate's and laminated on them, in this case the ratio β is 0.42.

For the method of polarization, it is possible to polarize the film either before or after the lamination on the plate.

In this production method, we have got the surface potential Vs of electrets before perforating Vs=1380 volts and the potential Vs' after perforating Vs'=770 volts.

The potential ratio (Vs'/Vs=0.56) is nearly equal to the surface area ratio ($S_{eff}/S_D = 1 - \beta = 0.58$).

Conclusion

The following points have been clarified with respect to electrets used for the fixed electrode of an alectrostatic tweeter.

(1) If required air gap is provided, the thickness of electret that maximizes the driving force can be given by ε^*g.

(2) There exists perforating ratio β of the electret that maximizes the acoustic power. From numerical calculation, the optimum value is $\beta = 0.35 \sim 0.45$.

(3) When a horn is loaded, the condition for the optimum ratio α can be obtained with a given β.

Through the analysis and experiments of an electret fixed electrode method which minimizes the mechanical impedance of diaphragm as much as possible and maximizes the driving force, it has become possible to practically apply electrets to loudspeakers.

However, electret is not suitable for high power loud-speakers because of air breakdown that is inherent to an electrostatic transducer. It is, therefore, suited for indoor reproduction in a home but not for outdoor reproduction or in a large hall or studio.

Acknowledgement

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References

1) U.S. Patent 2, 024, 705 ('35)

2) U.S. Patent 3, 118, 022 ('64)

3) Pioneer SE-100, Matsushita EAH-80

4) Z.Skvor, Acustica 19 P.295('67/68)

5) N.Sakamoto, "Loudspeaker and its system" (Nikkan Kogyo Shinbun Japan, 1967)

Table 1 Actual design values

Driver section		Horn section	
Diaphragm diameter	59 mm$^{\phi}$	Ratio of throat area of horn to diaphragm area α	0.6
Air gap g	50 μm	Cutoff frequency f_c	1 kHz
Thickness of electret film d	125 μm	Horn type	exp.
Mass of diaphragm M_M	25 mg	Throat diameter	46.4 mm$^{\phi}$
Electret perforating ratio β	0.42	Radiation resistance of horn	1.89 mechΩ
Volume of back cavity V_B	25 cc	Radiation reactance of horn	0.38 mechΩ
Electret surface charge dencity σ	9×10^{-9} c/cm^2		
Number of holes in electret N	351		
Signal voltage e_0	300 Vrms		

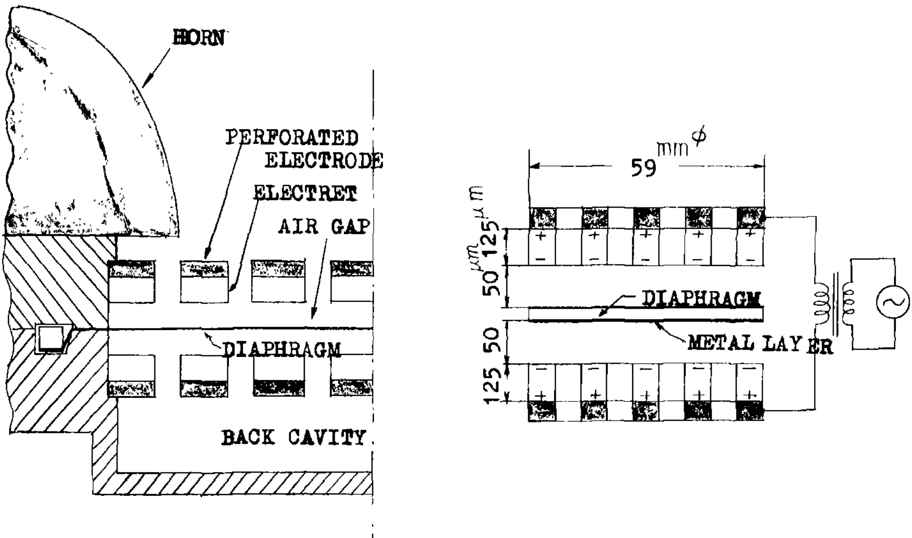
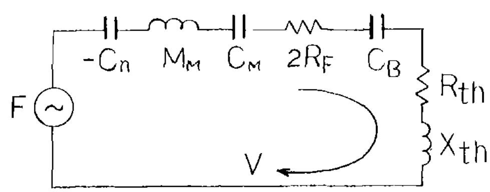


Fig.1 Cross section view of horn-loaded electrostatic loudspeaker with electret



$$R_{th} = \frac{\rho_0 c S_D}{\alpha}\sqrt{1-\left(\frac{f_c}{f}\right)^2}$$

$$X_{th} = \frac{\rho_0 c S_D}{\alpha}\,\frac{f_c}{f}$$

$$C_B = \frac{V_B}{\rho_0 c^2 S_D^2}$$

$$C_n = \frac{(g + d/\varepsilon^*)^3}{2\varepsilon_0 S_{eff}\left(\frac{\sigma d}{\varepsilon}\right)^2}$$

M_M EFFECTIVE MASS OF DIAPHRAGM

C_M COMPLIANCE OF DIAPHRAGM

C_B COMPLIANCE OF BACK CAVITY

$-S_n = -\frac{1}{C_n}$ NEGATIVE STIFFNESS OF DIAPHRAGM

R_{th} RADIATION RESISTANCE

X_{th} RADIATION REACTANCE

R_F RESISTANCE DUE TO VISCOUS LOSS IN AIR GAP

Fig.2 Mechanical equivalent circuit

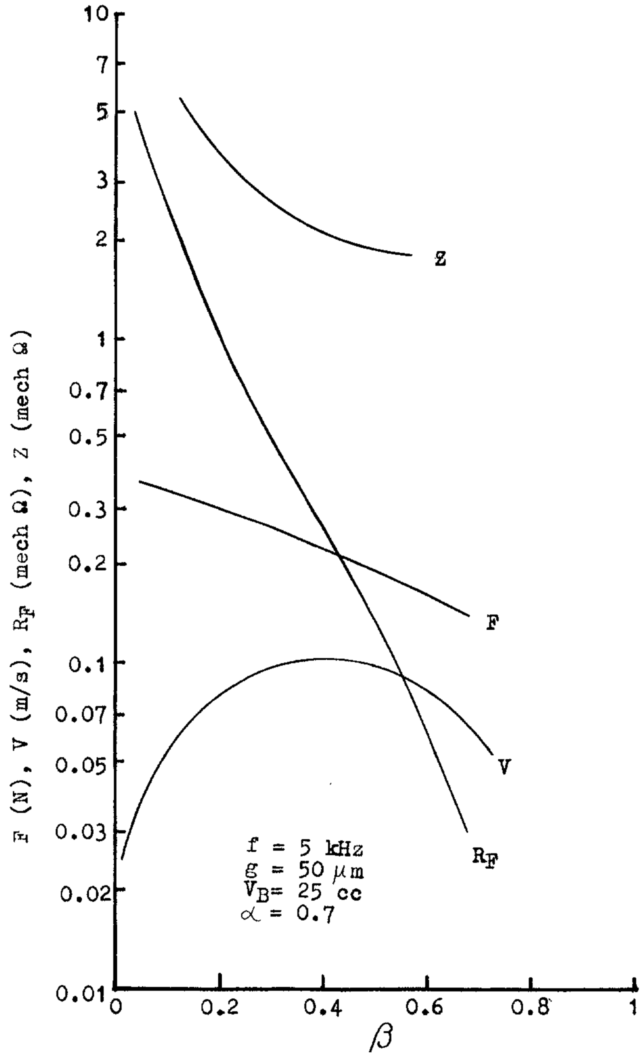


Fig.3 Dependence of force F, velocity V, resistance R_F and mechanical impedance Z on the ratio of the total area of holes in electrode to the diaphragm area

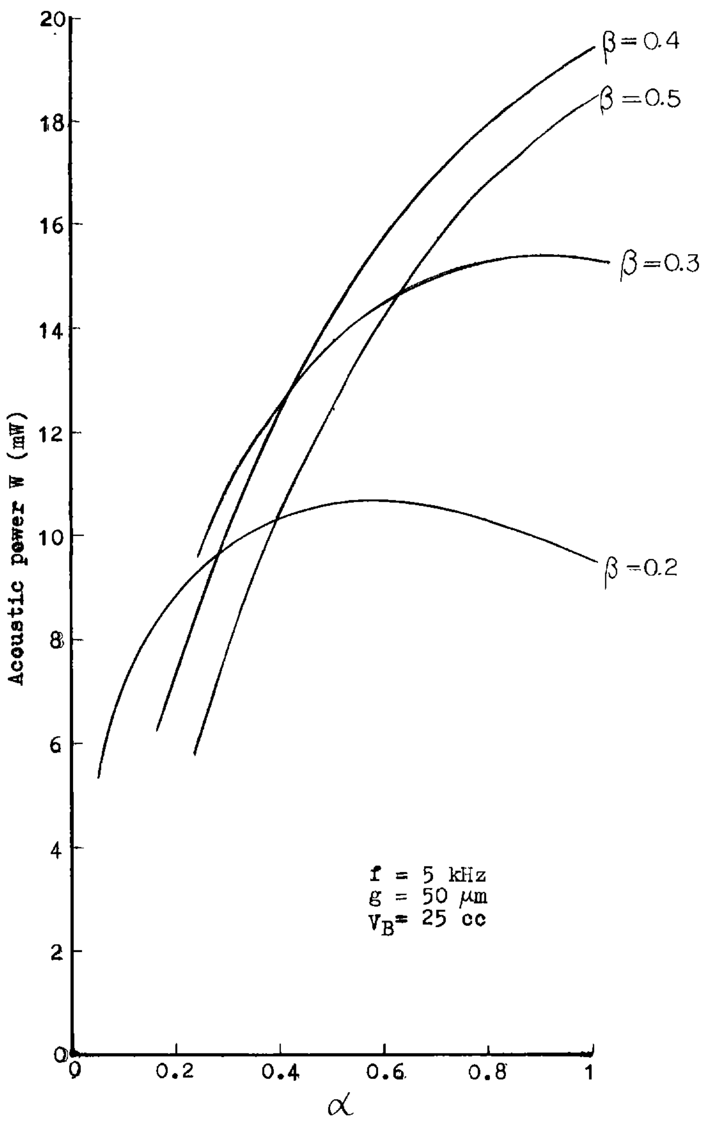


Fig.4 Dependence of acoustic power on the ratio of the throat area to the diaphragm area

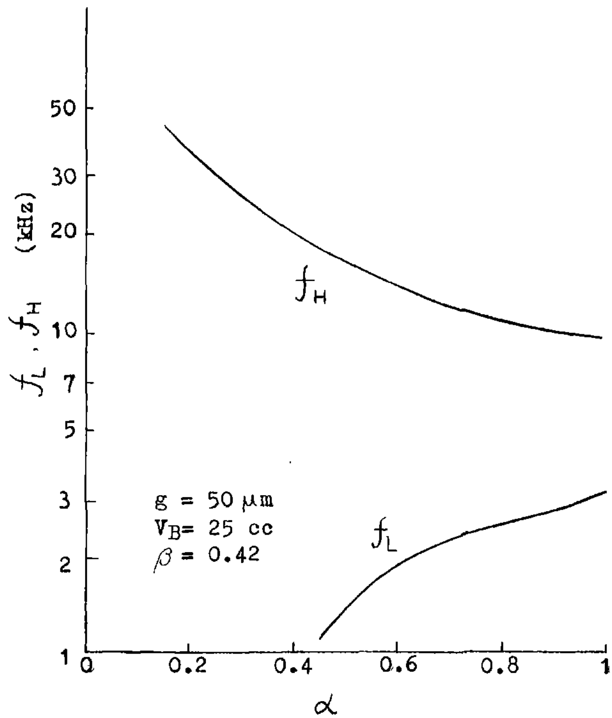


Fig.5 Relationship between f_H and f_L for the rati of the throat area to the diaphragm area

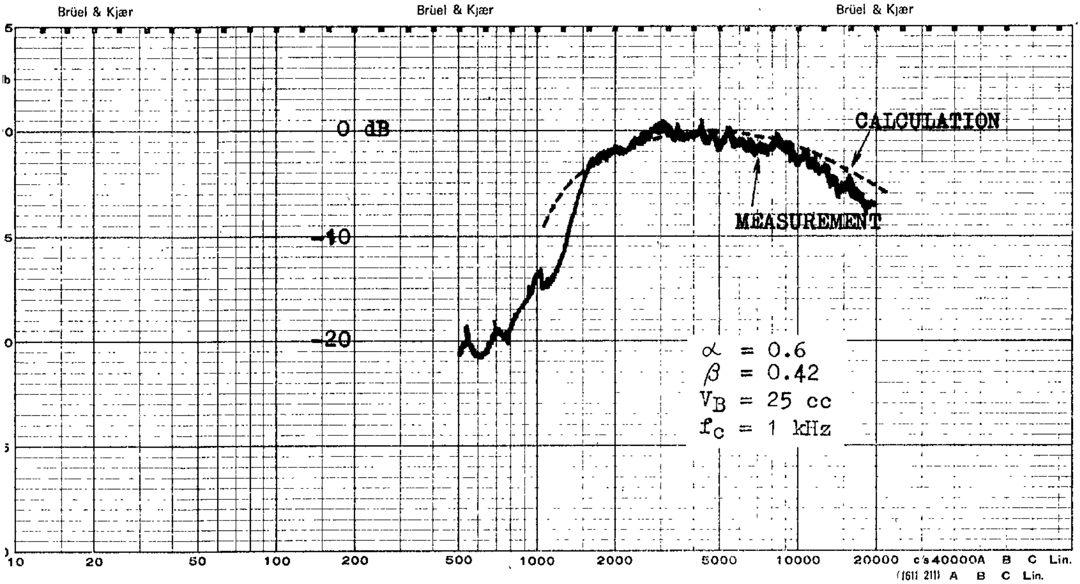


Fig.6 Frequency response of acoustic power

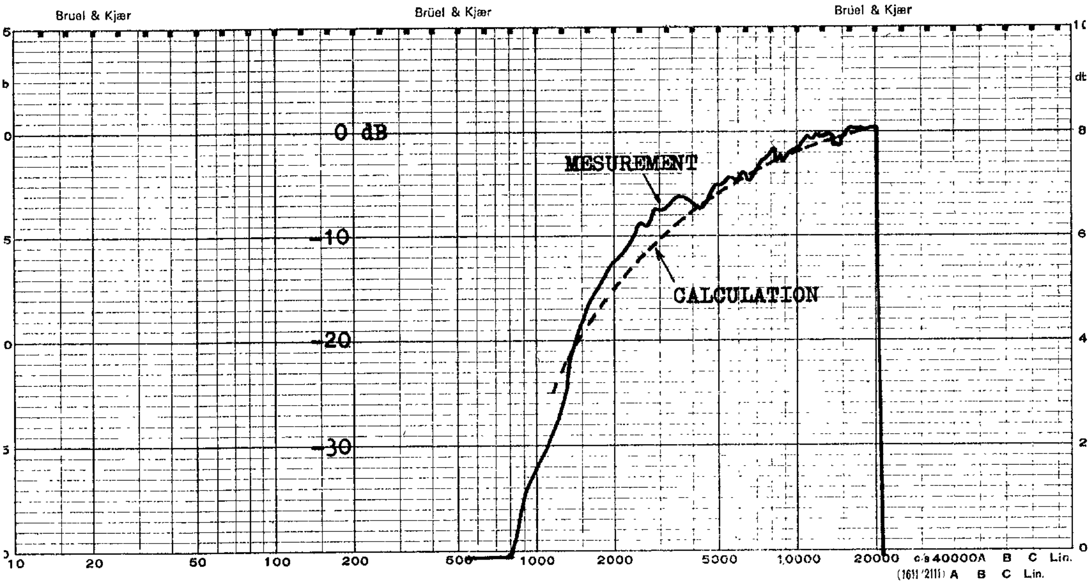


Fig.7 Frequency response of sound pressure on axis