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A BANDPASS LOUDSPEAKER ENCLOSURE

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Abstract

A loudspeaker enclosure whose acoustic response has a second order bandpass filter characteristic is described. The theoretical trade off between bandwidth, efficiency and box volume is given.

It is shown that when the system is fed through a suitable first order bandpass electrical filter, a third order acoustical bandpass characteristic can be achieved which is of practical value in certain sub-woofer applications.

Introduction

Recently there has been a renewed interest in the design of so called sub-woofer loudspeaker systems which are used to augment the low frequency response of very small enclosures. These systems normally cover a range of 1-3 octaves and are fitted with a low pass filter whose upper cut off frequency is usually less than 100Hz. The design of this low pass filter, using passive components, is often difficult because in practice the filter is not terminated by a pure resistance but by a loudspeaker system, whose input impedance varies significantly with frequency, particularly close to its resonance frequency. Even when satisfactory results are achieved, the resulting network requires large values of inductance and capacitance which make it both bulky and expensive. This problem can be avoided, at the expense of some additional complication and cost by using active or passive low level dividing networks placed ahead of separate power amplifiers for the sub-woofer and satellite systems.

This paper describes an alternative approach in which a second order bandpass response is achieved acoustically, and by the addition of a single first order bandpass electrical filter an overall third order response shape is obtained.

THEORY

The total acoustic output from a reflex or vented enclosure is given by the vector sum of the separate contributions from the drive unit and the vent, and this is shown for a lossless B4 alignment in figure 1. * It can be seen that the output from the vent has a second order bandpass characteristic, with its centre frequency equal to f_B, the resonance frequency of the vented enclosure.

If the output from the drive unit is isolated from that of the vent, then the resulting system has a natural bandpass characteristic whose response exceeds that of the original reflex enclosure below f_B. The general arrangement for such a system is shown in figure 2, together with its impedance type acoustical analogous circuit. The vent has been replaced by a passive radiator which, although it does not significantly affect the theoretical analysis, has certain advantages in a practical design. The system is seen to be a modified reflex enclosure of volume V_{B2} in which an additional enclosure of volume V_{B1} has been placed over the rear of the drive unit so that sound is only radiated from the passive radiator.

Analysis

For the purposes of analysis the following simplifications are made:

R_{AP} and R_{AB2}, the acoustic losses in the passive radiator and cavity 2, are assumed negligible.

Other circuit resistances are combined to give a single resistance, R_{AT}

$$\text{where } R_{AT} = \frac{B^2 l^2}{(R_g + R_E)\, S_D^2} + R_{AS} + R_{AB1} \qquad (1)$$

The acoustic compliance of the passive radiator C_{AP} is assumed to be very much greater than C_{AB2}, the acoustic compliance of cavity 2, and may be neglected.

C_{AS} and C_{AB1} are combined to give a single compliance C_{AT}

$$\text{where } C_{AT} = \frac{C_{AS} C_{AB1}}{C_{AS} + C_{AB1}} \qquad (2)$$

The simplified circuit is shown in figure 3.

* Ref. 1

Before analysing the circuit, it is useful to define a number of system parameters.

f_S, the free air resonance frequency of the drive unit is given by

$$f_S = 1/2\pi\sqrt{M_{AS}C_{AS}} \qquad (3)$$

V_{AS}, the volume of air having the same acoustic compliance as the drive unit suspension is given by

$$V_{AS} = \rho_o c^2 C_{AS} \qquad (4)$$

where ρ_o is the density of air in kg/m³ and c is the velocity of sound in m/s

$$\text{Let } \alpha = \frac{C_{AS}}{C_{AB1}} = \frac{V_{AS}}{V_{B1}} \qquad (5)$$

f_{C1}, the resonance frequency of the drive unit when loaded by the volume of cavity 1, V_{B1} is given by

$$f_{C1} = 1/2\pi\sqrt{M_{AS}C_{AT}} \qquad (6)$$

from equations (3) and (6)

$$f_{C1} = f_S\left[1 + \frac{C_{AS}}{C_{AB1}}\right]^{\frac{1}{2}}$$

$$\text{or } f_{C1} = f_S\,(1 + \alpha)^{\frac{1}{2}} \qquad (7)$$

M_{AP}, the acoustic mass of the passive radiator is arranged to resonate with the acoustic compliance of cavity 2, C_{AB2}, at a frequency f_{C2}. In order that the bandpass characteristic may be symmetrical f_{C2} is made equal to f_{C1}.

$$\text{Hence } f_{C2} = f_{C1} = 1/2\pi\sqrt{M_{AP}C_{AB2}} \qquad (8)$$

α_T, the total compliance ratio is defined from equations (6) (2) and (8) by

$$\alpha_T = \frac{M_{AP}}{M_{AS}} = \frac{C_{AT}}{C_{AB2}} = \frac{C_{AS}}{C_{AB2}}\,\frac{1}{(1 + \alpha)} \qquad (9)$$

$$\text{or } \alpha_T = \frac{V_{AS}}{V_{B2}}\,\frac{1}{(1 + \alpha)} = \frac{V_{B1}}{V_{B2}}\,\frac{\alpha}{(1 + \alpha)} \qquad (10)$$

When the acoustic compliance of the drive unit, C_{AS}, is negligible compared to the acoustic compliance of cavity 1, C_{AB1}, then equation (10) simplifies to

$$\alpha_T \doteqdot \frac{V_{B1}}{V_{B2}} \qquad (11)$$

Then the total system volume $V_T = V_{B1} + V_{B2}$

$$= V_{B1}\left[1 + \frac{1}{\alpha_T}\right] \qquad (12)$$

The total Q of the drive unit mounted in cavity 1, Q_{TC1}, is given by

$$Q_{TC1} = \frac{1}{2\pi f_{C1}C_{AT}R_{AT}} \qquad (13)$$

Frequency Response

The total system response is due only to the output from the passive radiator, and the sound pressure at a distance r is given by

$$|p_r| = \frac{f\rho_o}{2r}\,|U_p| \qquad (14)$$

where U_p is the volume velocity of the passive radiator

It is convenient to define a reference sound pressure $|p_r|_{ref}$

$$\text{where } |p_r|_{ref} = \frac{f\rho_o}{2r}\,|U_D|_{ref} \qquad (15)$$

$|U_D|_{ref}$ is the reference volume velocity of the drive unit in cavity 1, with cavity 2 and the passive radiator removed, at a frequency where $\omega^2 M_{AS}^2 >> R_{AT}^2$ i.e. the drive unit is mass controlled

$$|U_D|_{ref} = \frac{p_g}{2\pi f M_{AS}} \qquad (16)$$

$$\text{where } p_g = \frac{e_g Bl}{(R_g + R_E) S_D} \qquad (17)$$

The frequency response of the system is given by

$$\frac{|p_r|}{|p_r|_{ref}} = \frac{|U_p|}{|U_D|_{ref}} \qquad (18)$$

Substituting for $|U_D|_{ref}$ and determining the value of U_p from the circuit in figure 3 gives

$$\frac{|p_r|}{|p_r|_{ref}} = \frac{2\pi f M_{AS}}{p_g} \frac{p_g}{2\pi f M_{AP}} \left[\frac{\frac{1}{\gamma}}{\left[\frac{1}{q^2} + \left(\gamma - \frac{1}{\gamma}\right)^2\right]^{\frac{1}{2}}} \right] \qquad (19)$$

$$\text{where } \gamma = \left[\frac{f}{f_{C1}} - \frac{f_{C1}}{f}\right] \frac{1}{\sqrt{\alpha_T}} \qquad (20)$$

and noting that q in a bandpass filter corresponds to Q in a low pass filter, and is a measure of the degree of peaking before cut off. (Ref. 3 p.406,7)

Q_{TC1}, the Q of the series tuned circuit in figure 3 is related to q

$$\text{where } Q_{TC1} = \frac{q}{\sqrt{\alpha_T}} \qquad (21)$$

From equations (9) (19) and (21)

$$\frac{|p_r|}{|p_r|_{ref}} = \frac{M_{AS}}{M_{AP}} \left[\frac{\frac{1}{\gamma}}{\left[\frac{1}{\alpha_T Q_{TC1}^2} + \left(\gamma - \frac{1}{\gamma}\right)^2\right]^{\frac{1}{2}}} \right] \qquad (22)$$

$$= \frac{1}{\alpha_T} \left[\frac{\frac{1}{\gamma}}{\left[\frac{1}{\alpha_T Q_{TC1}^2} + \left(\gamma - \frac{1}{\gamma}\right)^2\right]^{\frac{1}{2}}} \right] \qquad (23)$$

Equation (23) is plotted in figure 4 for various values of α_T, for a maximally flat or Butterworth response, where q = 0.707

$$\text{i.e. } Q_{TC1}^2 \alpha_T = 0.5 \qquad (24)$$

$$\text{At } f = f_{C1},\ \gamma = 0 \text{ and } \frac{|p_r|}{|p_r|_{ref}} = \frac{1}{\alpha_T} \qquad (25)$$

At the upper and lower cut off frequencies, f_H and f_L, $\gamma = 1$ and the response is -3dB with respect to the passive radiator output at f_{C1} for a Butterworth response. From equation (20)

$$\left[\frac{f}{f_{C1}} - \frac{f_{C1}}{f}\right] = \pm \sqrt{\alpha_T} \text{ at } f_H \text{ and } f_L \qquad (26)$$

$$\text{and } f_{C1} = \sqrt{f_H f_L} \qquad (27)$$

$$\text{Hence } \frac{f_H}{f_L} = \frac{f_{C1}^2}{f_L^2} = \frac{f_H^2}{f_{C1}^2} \qquad (28)$$

From equations (26) and (28)

$$\left[\frac{f_H}{f_L}\right]^{\frac{1}{2}} = \frac{f_H}{f_{C1}} = \frac{f_{C1}}{f_L} = \frac{\sqrt{\alpha_T} + \sqrt{\alpha_T + 4}}{2} \qquad (29)$$

Values of Q_{TC1} for a Butterworth response are given in table 1 for various values of α_T, together with bandwidth f_H/f_L, relative sensitivity and total box volume V_T.

The relative sensitivity is expressed in dB as

$$\frac{\text{spl of double cavity system at } f=f_{C1}}{\text{spl of drive unit with cavity 2 removed at } f>>f_{C1}}$$

$$= 20 \log_{10}\alpha_T \qquad (30)$$

Table 1

α_T	Q_{TC1}	Bandwidth f_H/f_L	Rel. Sensitivity $20\log_{10}\alpha_T$	Total Volume V_T/V_{B1}
0.5	1.0	2.0	+6dB	3.0
1.0	0.71	2.62	0dB	2.0
2.0	0.5	3.73	-6dB	1.5
3.0	0.41	4.79	-9.5dB	1.33
4.0	0.35	5.85	-12dB	1.22

From Table 1 it can be seen that as α_T increases the system bandwidth also increases at the expense of lower relative sensitivity.

Efficiency

It is useful to compare the efficiency of this bandpass system with that of a closed box system having the same lower cut off frequency and box volume and a Butterworth high pass response.

η_{rel}, the relative efficiency is defined as

$$\eta_{rel} \; \frac{\text{Efficiency of bandpass system}}{\text{Efficiency of equivalent closed box system}}$$

$$\text{or } \eta_{rel} = \left| \frac{p_r \;\; \text{double cavity at } f = f_{C1}}{p_r \;\; \text{closed box at } f >> f_{C1}} \right|^2$$

It can be shown from equations (12),(25),(29) and [eq.(24) Ref.4]

$$\eta_{rel} = \frac{\left(\sqrt{\alpha_T} + \sqrt{\alpha_T + 4}\right)^3}{8(1 + \alpha_T)\sqrt{\alpha_T}} = \frac{1}{(1+1/\alpha_T)}\left[\frac{1 + \sqrt{1+4/\alpha_T}}{2}\right]^3 \qquad (31)$$

η_{rel} is evaluated for various values of α_T and shown in table 2. These values of η_{rel} represent the maximum values obtainable and η_{rel} will in practice be somewhat lower due to losses in the acoustic lining in V_{B2} which have been ignored in the analysis for the sake of simplicity and clarity.

Table 2

α_T	η_{rel} (max)	$10\log_{10}\eta_{rel}$
0.5	2.67	+4.26dB
1.0	2.12	+3.26dB
2.0	1.70	+2.30dB
3.0	1.51	+1.80dB

From Table 2 it can be seen that as α_T increases, and the system bandwidth increases, so the relative efficiency decreases. There is still a useful theoretical gain of 70% for α_T = 2 where the bandwidth is nearly 2 octaves.

Third order response with Auxiliary Electrical Filter

The electrical equivalent circuit of the double cavity bandpass system fed through a first order bandpass electrical filter is shown in figure 5, and has been derived from the circuit given in figure 3 using the relationship

$$Z_E = \frac{(Bl)^2}{Z_A S_D^2}$$

where Z_A is the impedance of an element in the impedance type acoustical analogous circuit, and Z_E is the impedance of the corresponding element in the electrical equivalent circuit.

In figure 5

C_{MES} corresponds to M_{AS}

L_{CET} corresponds to C_{AT}

R_{ES} corresponds to $R_{AS} + R_{AB1}$

L_{CEB2} corresponds to C_{AB2}

C_{MEP} corresponds to M_{AP}

R_{EL2} corresponds to R_{AL2}

where R_{AL2} is an additional element representing the acoustic resistance of leakage losses in cavity 2.

For the purposes of analysis, or simulation, R_{AL2} can be adjusted to provide a convenient frequency-invariant approximation to the actual acoustic losses in cavity 2 due to absorption R_{AB2}, leakage R_{AL2}, and the passive radiator suspension R_{AP}, which in practice all vary with frequency (Ref. 5).

L and C are the external inductor and capacitor used to provide the first order bandpass electrical filter and are chosen so that

$$LC = L_{CET}C_{MES} = L_{CEB2}C_{MEP} = \frac{1}{(2\pi f_{C1})^2} \qquad (32)$$

Again for simplicity this circuit is analysed assuming that $R_{ES} = \infty$ and $R_{EL2} = 0$. In practice of course, these losses cannot be ignored and their effect will be included in system simulations shown later in the paper.

Analysing the circuit shown in figure 5, shows that for a Butterworth response

$$Q_{TC1} = \frac{4}{3\sqrt{2\alpha_T}} \qquad (33)$$

The external electrical components may be calculated from

$$\text{Series inductance, } L = \frac{L_{CEB2}}{3} \qquad (34)$$

$$\text{Series capacitance, } C = 3C_{MEP} \qquad (35)$$

The new -3dB frequencies f_H' and f_L' are given by

$$\left[\frac{f}{f_{C1}} - \frac{f_{C1}}{f}\right] = \pm\sqrt{2\alpha_T} \quad \text{at } f_L' \text{ and } f_H' \qquad (36)$$

$$\text{Hence } \left[\frac{f_H'}{f_L'}\right]^{\frac{1}{2}} = \frac{f_H'}{f_{C1}} = \frac{f_{C1}}{f_L'} = \frac{\sqrt{2\alpha_T} + \sqrt{2\alpha_T + 4}}{2} \qquad (37)$$

As before (see page 7), the relative efficiency is defined as follows

$$\eta_{rel}' \; \frac{\text{Efficiency of third order bandpass system}}{\text{Efficiency of equivalent closed box system}}$$

It can be shown that

$$\eta_{rel}' = \frac{3\sqrt{2}}{2} \; \frac{1}{(1 + 1/\alpha_T)} \left[\frac{1 + \sqrt{1 + 2/\alpha_T}}{2}\right]^3 \qquad (38)$$

The required values of Q_{TC1} for a third order Butterworth response are given below in Table 3 for various values of α_T, together with the resulting bandwidth f_H'/f_L', and the relative efficiency, η_{rel}'

Table 3

α_T	Q_{TC1}	Bandwidth f_H'/f_L'	η_{rel} (max)	$10\log_{10}\eta_{rel}$
0.5	1.33	2.62	3	+4.7dB
1.0	0.94	3.73	2.7	+4.32dB
2.0	0.67	5.83	2.49	+3.96dB
3.0	0.54	7.87	2.39	+3.79dB

Comparing the values shown in table 3 with those given previously in tables 1 and 2, it can be seen that the third order bandpass system is always more efficient than the second order, and increasingly so for higher values of α_T.

For $\alpha_T = 3$ the bandwidth is nearly 3 octaves, and the system has a theoretical efficiency of more than twice that of the equivalent closed box.

EXPERIMENTAL RESULTS

A third-order bandpass system having a total internal volume of 65 litres was constructed from 300mm diameter cardboard tube having a wall thickness of 12mm.

System Parameters

Cavity 1 lined with bonded acetate fibre wadding

V_{B1}	29 litres (300mm diameter x 400mm long)
f_{C1}	44Hz
Q_{TC1}	0.98
Drive unit area, S_D	0.022m²
V_{B2}	35 litres (300mm diameter x 480mm long)
Passive radiator area	0.033m²
Total compliance ratio, α_T	0.65
Series L	11mH
Series C	1200µF

Frequency Response

The frequency response of the bandpass system was measured using the nearfield sound-pressure method (Ref. 6) and also using the equivalent method of measuring the acceleration of the passive radiator diaphragm by means of a miniature accelerometer bonded to its front face. The equivalence and accuracy of these two methods was confirmed by means of free field pressure measurements taken at a distance of 1 metre out of doors with the system mounted on a small platform raised 10 metres above the ground.

The frequency response of the system with no lining in cavity 2 is shown in figure 6, together with the calculated response. There is very poor agreement above 140Hz. The assumption in figure 3 that the compliance of cavity 2 can be represented by a single capacitance C_{AB2}, is only justified for frequencies where the wavelength of sound is greater than sixteen times the length i.e. where $f < 45$Hz (Ref. 2 p129). Cavity 2 may be represented by a series mass and compliance for frequencies where the wavelength of sound is greater than eight times the smallest dimension i.e. $f < 144$Hz (Ref. 2 p217).

It can be seen from the measured response in figure 6 however, that there is still significant output above 144Hz with high-Q resonant peaks at 330Hz, 660Hz and 990Hz, so an even more complex representation of cavity 2 seems to be required. A quasi-distributed impedance-type acoustical analogous circuit for cavity 2 is likely to be of the form shown in figure 7. The system frequency response has been re-calculated from the simplified circuit shown in figure 3, using the distributed representation for cavity 2 in place of the simple capacitor and this is shown, together with the corresponding measured response, in figure 8.

In an effort to damp out these resonances, cavity 2 was loosely filled with 300mm discs made from 50mm thick glass fibre. The absorbent material was selected for its high absorption at frequencies above 150Hz and it was hoped that by allowing the discs to move at low frequencies that the loss of efficiency of the system in its pass band would be minimised.

The system response, with glass fibre discs in cavity 2, is shown in figure 9 and was obtained using a constant sinusoidal input of 6V rms. The response shape appears nearly ideal, having a flat pass band with -3dB frequencies at 26 and 76Hz, and a smoothly falling characteristic above 140Hz, the previous peaks having been damped out by the lining. The system response was then rechecked, this time using the fast Fourier transform to calculate its frequency response from a digital measurement of its impulse response taken in the nearfield (Ref. 7). To facilitate comparison, this is shown super-imposed upon the analogue measurement in figure 9.

It can be seen that the curves differ considerably below 50Hz, the digital measurement peaking by 1dB at 40Hz before cutting off nearly 1/3 octave earlier at 32Hz. Removing the lining from cavity 2 and remeasuring the response using both sinewave and impulse excitation revealed no difference, so it was deduced that the discrepancy must have been caused by the lining. It was suspected that at low frequencies the sinewave excitation was high enough to overcome the static friction between the glass fibre discs and the inside of the tube, so that part of the lining moved with the passive radiator thereby adding to its effective mass. The impulse excitation however, had insufficient energy to overcome the static friction, so that the effective moving mass of the passive radiator was lower, causing mistuning of the system. This hypothesis was later confirmed, for when the glass fibre discs were constrained by interleaving them with fixed wire grids, the response curves, measured by both methods agreed, as shown in figure 10.

Given in figure 11 is the complete electrical equivalent circuit which uses the quasi-distributed representation of cavity 2, including its lining, and contains an additional electrical element L_{CEP} corresponding to C_{AP}, the acoustic compliance of the passive radiator suspension. Finally the calculated and measured response curves for the complete third order double cavity system, given in figure 12, show excellent agreement from 20-500Hz.

Conclusions

The theory and design of a third-order bandpass loudspeaker system which employs only a first-order bandpass electrical filter has been described. Theory shows that even for bandwidths up to three octaves, this system still has a pass-band efficiency of more than twice that of the equivalent closed-box having the same lower cut-off frequency and total internal volume.

It has been shown that the usual representation of the internal volume of an enclosure by a simple capacitor in the impedance-type acoustical analogous circuit fails to predict the presence of high Q resonances, which in practice appear at the output of the bandpass system at frequencies where the wavelength of sound is less than eight times the smallest dimension of the second cavity.

These resonant peaks, although usually obscured for the reasons given below, have been observed before, in experimental nearfield measurements made on vented loudspeaker systems, the discrepancies between the measurements and the theoretical predictions for the vent output being incorrectly attributed to cross talk from the drive unit (Ref. 6).

In a vented enclosure, the general vent output at high frequencies is usually sufficiently below that of the drive unit that these high Q resonances are unlikely to be detected from a visual examination of the steady-state amplitude frequency response characteristic, although their presence often imparts a distinct colouration to the perceived sound quality. This colouration can only be adequately attenuated by using so much internal lining material that the overall low-frequency efficiency of the system is so impaired that many of the theoretical advantages of reflex loading are negated.

Attempts to restore the low frequency efficiency by allowing the internal lining to move can result in a form of dynamic non-linear distortion, in which the frequency response shape changes significantly with level. Transient stimuli, such as bass drums and tympani, will then appear to have a restricted low frequency response with some peaking, resulting in overhang, whereas nearly steady state signals such as organ pedal notes will not reveal this problem.

Acknowledgement

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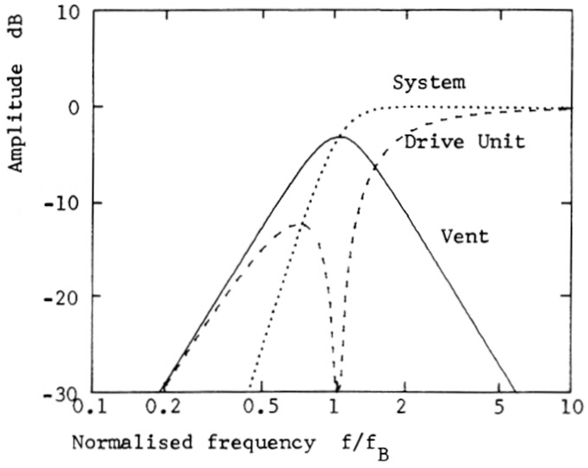
LIST OF SYMBOLS

Bl	Force factor
c	Velocity of sound in air
C_{AB1}	Acoustic compliance of cavity 1
C_{AB2}	Acoustic compliance of cavity 2
C_{AP}	Acoustic compliance of passive radiator suspension
C_{AS}	Acoustic compliance of drive unit suspension
C_{AT}	Total acoustic compliance of drive unit and cavity 1
e_g	Open circuit output voltage of amplifier
f	Frequency
f_{C1}	Resonance frequency of drive unit in cavity 1
f_{C2}	Resonance frequency of passive radiator in cavity 2
f_H	Upper cut off frequency of bandpass system
f_L	Lower cut off frequency of bandpass system
f_S	Free air resonance frequency of drive unit and air load
M_{AS}	Acoustic mass of diaphragm assembly and air load
M_{AP}	Acoustic mass of passive radiator including air load
P_g	Strength of acoustic pressure generator
p_r	Acoustic pressure at a distance r from the loudspeaker system
Q_{TC1}	Total Q of drive unit at f_{C1} due to all system resistance
r	Distance from sound source to measuring point
R_{AB1}	Acoustic resistance of absorption losses in cavity 1
R_{AB2}	Acoustic resistance of absorption losses in cavity 2
R_{AL2}	Acoustic resistance of leakage losses in cavity 2

R_{AP}	Acoustic resistance of port or passive radiator
R_{AS}	Acoustic resistance of drive unit suspension losses
R_E	Drive unit dc resistance
R_g	Amplifier output resistance
S_D	Effective area of drive unit diaphragm
U_D	Volume velocity of the drive unit in cavity 1
U_P	Volume velocity of passive radiator
V_{B1}	Volume of cavity 1
V_{B2}	Volume of cavity 2
V_{AS}	Volume of air having same acoustic compliance as drive unit suspension
V_T	Total volume of double-cavity system ($V_{B1} + V_{B2}$)
α	Compliance ratio C_{AS}/C_{AB1}
α_T	Compliance ratio C_{AT}/C_{AB2}
η	Efficiency
ρ_o	Density of air

fig 1

Frequency response of reflex system showing separate contributions made by drive unit and vent.



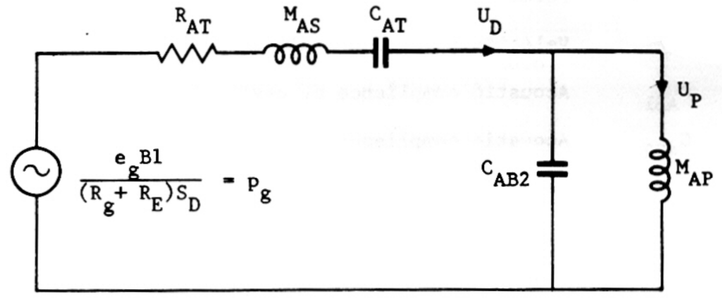


fig 3 Simplified analogous circuit for Double Cavity System.

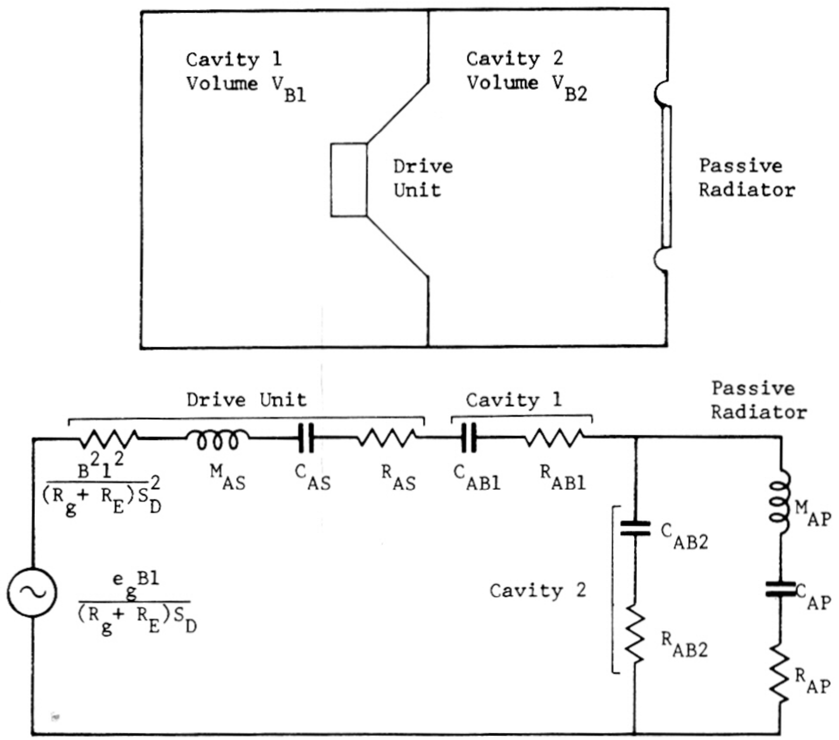


fig 2 Double Cavity bandpass loudspeaker system and impedance type acoustical analogous circuit.

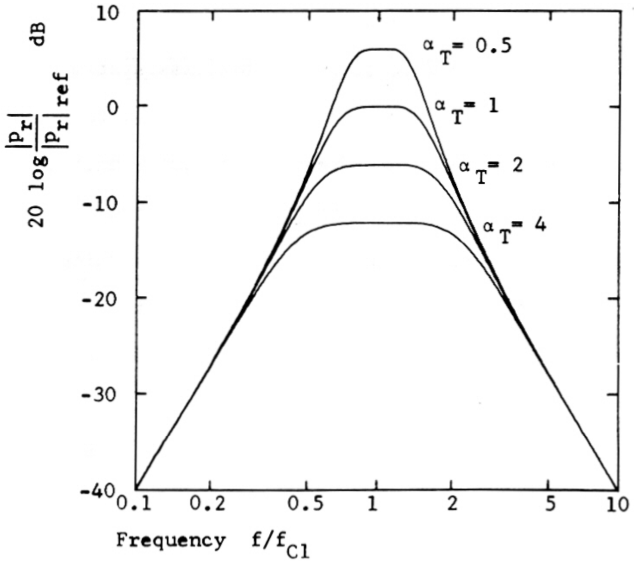


fig 4 Butterworth responses of Double Cavity System for various values of α_T.

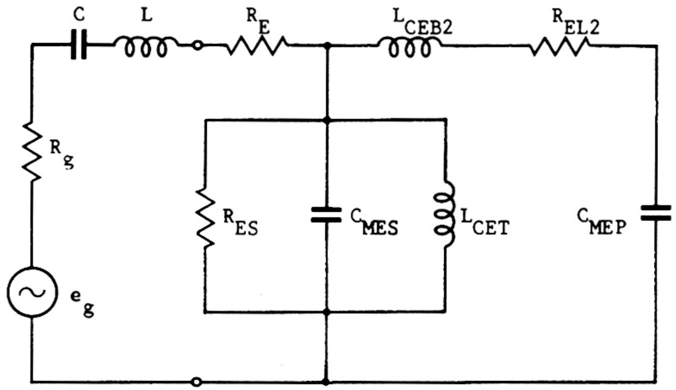
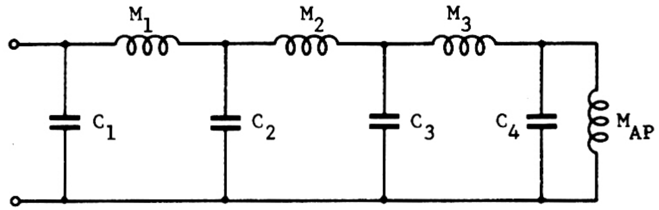


fig 5 Simplified electrical equivalent circuit of third-order Double Cavity loudspeaker system.



$$M_1 + M_2 + M_3 = 0.1\ M_{AP}$$

$$C_1 + C_2 + C_3 + C_4 = C_{AB2}$$

fig 7 Quasi-distributed impedance-type acoustical analogous circuit for cavity 2 (without lining).

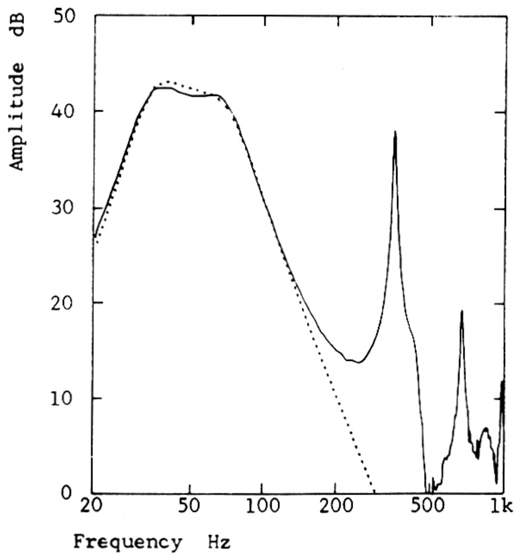


fig 6 Frequency response of third-order Double Cavity system
......calculated - using simplified equivalent circuit
——— measured - experimental system (cavity 2 unlined).

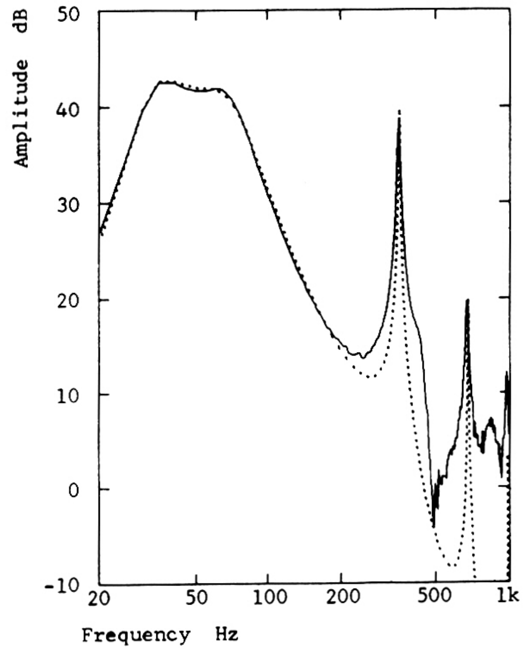


fig 8 Frequency response of third-order Double Cavity system with cavity 2 unlined
......calculated - using quasi-distributed representation of cavity 2
——— measured - experimental system.

.....analogue measurement using sinewave excitation.

——digital measurement via FFT of measured impulse response.

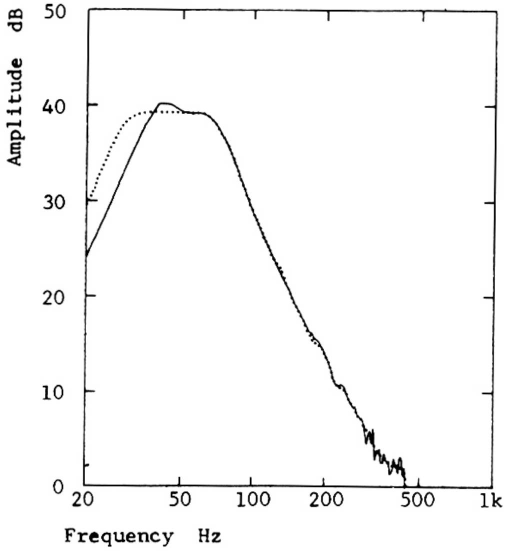
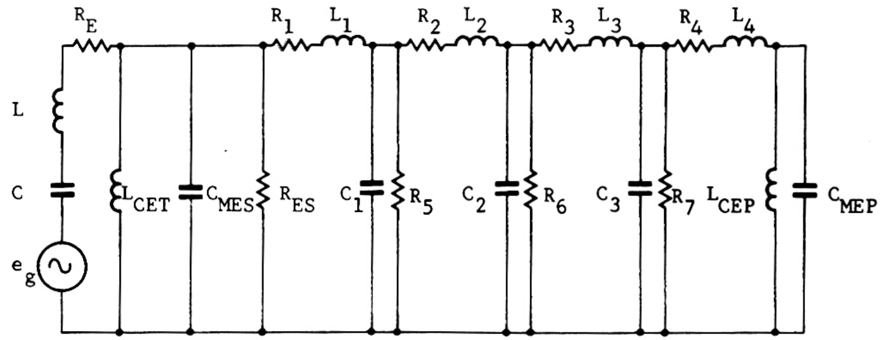


fig 9 Frequency response of third-order Double Cavity system with unconstrained lining in cavity 2.



$C_1 + C_2 + C_3 = 0.1\ C_{MEP}$

$L_1 + L_2 + L_3 + L_4 = L_{CEB2}$

R_1 to R_7 correspond to absorption and leakage losses in cavity 2.

fig 11 Complete electrical equivalent circuit for third-order Double Cavity system.

.....analogue measurement using sinewave excitation.

——digital measurement via FFT of measured impulse response.

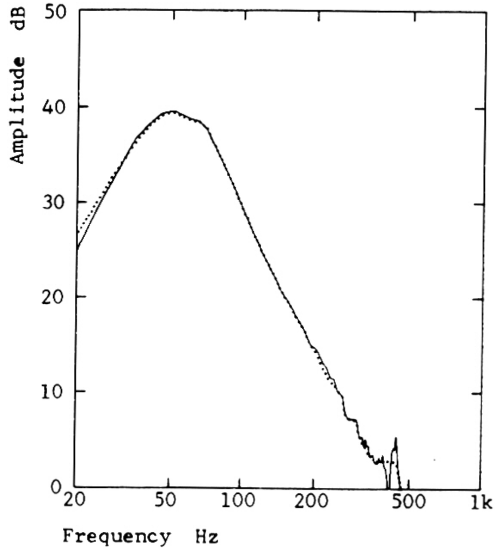


fig 10 Frequency response of third-order Double Cavity system with constrained lining in cavity 2.

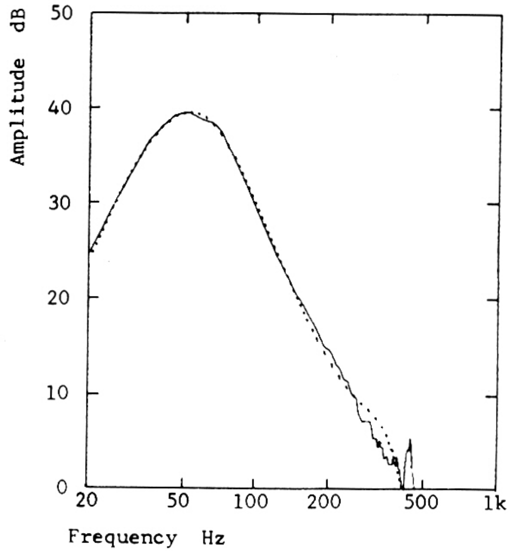


fig 12 Frequency response of third-order Double Cavity system
......calculated - using complete electrical equivalent circuit
——measured - via FFT of measured impulse response.