Proceedings of the Institute of Acoustics

THE ACTIVE BASS REFLEX ENCLOSURE

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ABSTRACT

Simple analysis of the low frequency behaviour of a conventional bass reflex loudspeaker system reveals coupling between the port response and the radiation load. This coupling, although almost insignificant in the context of free field loading, is a mechanism for loudspeaker / room interaction at the modal frequencies of a typical listening room. A bass reflex system with the port implemented using active techniques is presented. This active "port" has such high source impedance that it is not influenced by the radiation load, reducing the coupling with the room.

INTRODUCTION

The moving cone of a direct radiating loudspeaker intended to reproduce low frequencies generates acoustic pressures in the air adjacent to both its front and back surfaces. As these pressures are in anti-phase, the radiation from a bare driver can be approximated as an acoustic doublet. Such a radiator has very low power output at low frequencies, as the front and back radiation interfere destructively. To avoid the destructive interference, drivers are mounted in enclosures which separate the front and back radiation, most dramatically in the infinite baffle or closed box enclosure.

Unfortunately, the radiation load experienced by a finite source in free space falls with falling frequency, such that large source strengths are required to generate large pressures at low frequency. In order to meet this large source strength requirement, some enclosure families exploit the back radiation, passing it through acoustic networks which phase shift the backradiation such that it will interfere constructively with the front radiation over a range of frequencies in the low bass. Most familiar of these enclosure types is the bass reflex enclosure [1], which phase shifts the backradiation by passing it through a resonant acoustic network. The large number of bass reflex enclosures in use in all areas of reproduced sound testify to the success of the concept.

ACTIVE BASS REFLEX ENCLOSURE

Although the physics of operation of a bass reflex enclosure are well understood, the interaction of such an enclosure with the room in which it operates is significantly more complicated that the interaction of a loudspeaker in an infinite baffle. It is the purpose of the present paper to describe the coupling of a bass reflex enclosure with the modes of a room and to present a novel bass reflex system which is not sensitive to the coupling. The new loudspeaker, in which the resonant network is implemented using active techniques, is found to offer further practical advantages over the passive conventional enclosure.

BACKGROUND

The bass reflex loudspeaker (Figure 1) houses the low frequency driver in an enclosure which has an opening, or "port", cut into its wall. Sound radiated from the back of the driver can pass through the port to the listener. At low frequencies the movement of the loudspeaker cone does not cause acoustic wave motion in the enclosure or in the port; rather, pressure fluctuations in the air inside the cabinet are independent of position and the air in the port moves with one velocity. "Low frequencies" are those for which the acoustic wavelength is large compared with a characteristic dimension of the enclosure.

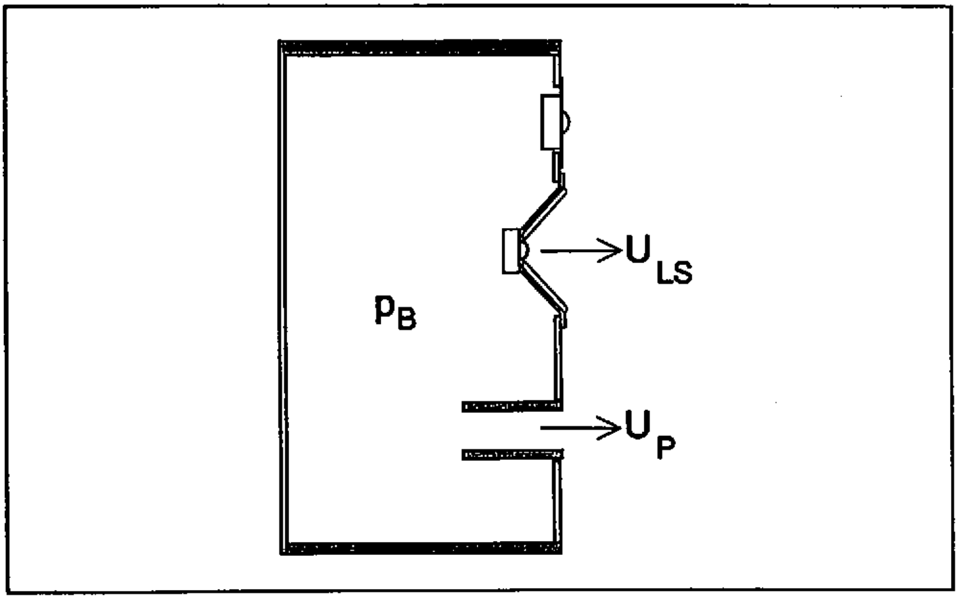

Figure 1 The conventional bass reflex enclosure.

Such uniform behaviour allows the enclosed volume of air in the enclosure and the air in the port to be approximated as lumped acoustic parameters [2]. The analysis of the bass-reflex enclosure using lumped acoustic parameters is attractive as it can be cast in terms of differential equations (potentially with equivalent electronic circuits) rather than the partial differential equations required to describe wave motion.

Neglecting cabinet leaks and motion of the cabinet walls, the pressure induced inside the enclosure, p_B, is caused by the movement of the cone and the lump of air in the port changing the effective volume of the enclosure. This causes a pressure change due to the stiffness of the enclosed volume of air, given by :

$$\frac{p_B}{U_{LS} + U_p} = \frac{j}{\omega C_A} \tag{1}$$

in which U_{LS} and U_p are the loudspeaker and port volume velocities, respectively, C_A is the compliance of the enclosed volume of air, ω is the angular velocity and j is the unit imaginary vector.

A simplified analysis

The port volume velocity, U_p is controlled by the difference between the pressure inside the enclosure, p_B, and the pressure outside. At low frequencies the pressure outside the enclosure is usually much smaller than p_B (a consequence of the low radiation load and the high impedance of the enclosed volume of air in the enclosure), so much so that the pressure outside the port is often neglected in simplistic analyses of the bass reflex enclosure. We shall make the same simplifying assumption here to provide a benchmark against which to evaluate the effects of including the external pressure in our subsequent analysis.

Neglecting the pressure outside the enclosure, the air in the port moves approximately as:

$$U_p = \frac{p_B}{j\omega M_A + R} \tag{2}$$

at low frequencies. M_A is the acoustic inertance of the air and R is the loss due to friction etc.. Both M_A and R are controlled by the dimensions and geometry of the port. Combining equations (1) and (2) and eliminating p_B gives a ratio between the source strengths of loudspeaker and port:

$$\frac{U_p}{U_{LS}} = \frac{1}{\omega^2 M_A C_A - jRC_A\omega - 1} \tag{3}$$

The magnitude and (inverted) phase of equation 3 are shown plotted as Figure 2 for values of acoustic inertance and compliance giving a port resonance at 50 Hz. Various values of acoustic resistance, R, have been used, giving the resonance a quality factor of 10, 3.16 and 1.

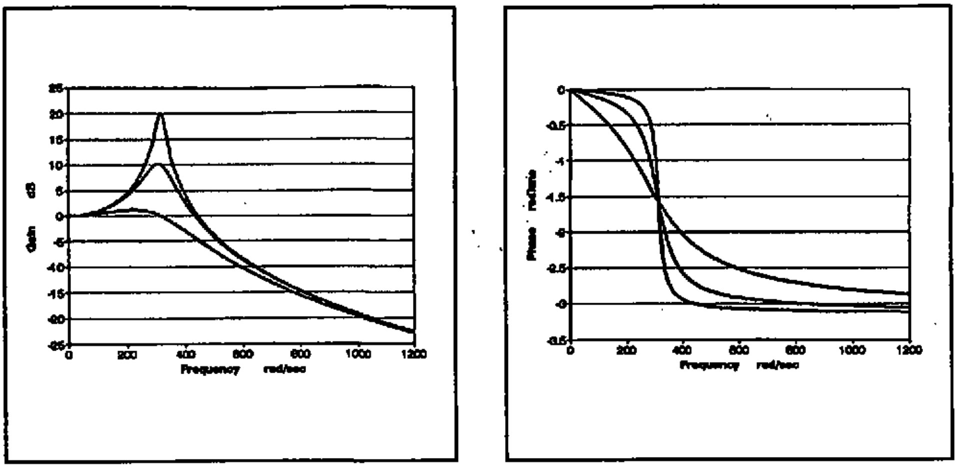

Figure 2 Ratio of port / speaker volume velocities ($-U_p/U_{LS}$) of the conventional bass reflex enclosure *neglecting external air load*

Note that the magnitude of the resonant peak is equal to the quality factor:

$$Q = \frac{1}{R\sqrt{\frac{C_A}{M_A}}} \tag{4}$$

Above the resonant peak the phase is seen to limit towards the required inversion (the bass reflex enclosure is a member of the "phase inverter" family) and at all frequencies from the resonance upwards, where the phase has been shifted through 90 degrees, the sound from the port interferes constructively with that from the loudspeaker.

Free field behaviour

The naive analysis described above neglects the air load outside the enclosure. If the air load is included, the approximate equation for the enclosure pressure (1) is not altered, but the equation for the motion of the air in the port (2) must be adjusted. The air outside the port, p_p, opposes motion of the air in the port, such that the low frequency port response is approximated by:

$$U_p = \frac{p_B - p_p}{j\omega M_A + R} \tag{5}$$

The external pressure, p_p, has two components; that due to the loudspeaker motion and that due to the motion of the air in the port itself:

$$p_p = U_{LS} . Z_{LS,p} + U_p . Z_p \tag{6}$$

in which $Z_{LS,p}$ is the transfer impedance between (the front of the) loudspeaker and the port and Z_p is the radiation impedance seen by the port. The modified port response (5) changes the ratio of speaker to port volume velocities to:

$$\frac{U_p}{U_{LS}} = \frac{\dfrac{j}{\omega C_A} - Z_{LS,p}}{j\omega M_A + R + Z_p - \dfrac{j}{\omega C_A}} \tag{7}$$

In free field conditions, the transfer and radiation loads represent low impedances compared to that of the enclosed air in the box, such that equation 7 is similar to equation 3. Figure 3 shows the magnitude and phase of (7) evaluated for a bass reflex system with a driver of 60mm radius, a port of 20mm radius and a driver to port centre spacing of 100mm. The driver transfer impedance was calculated assuming perfect hemispherical radiation and the port radiation load was calculated using the piston functions [3]. Comparison between Figures 2 and 3 shows that the air load experienced on the outside of the port in free field conditions has negligible effect on the operation of the phase inverter.

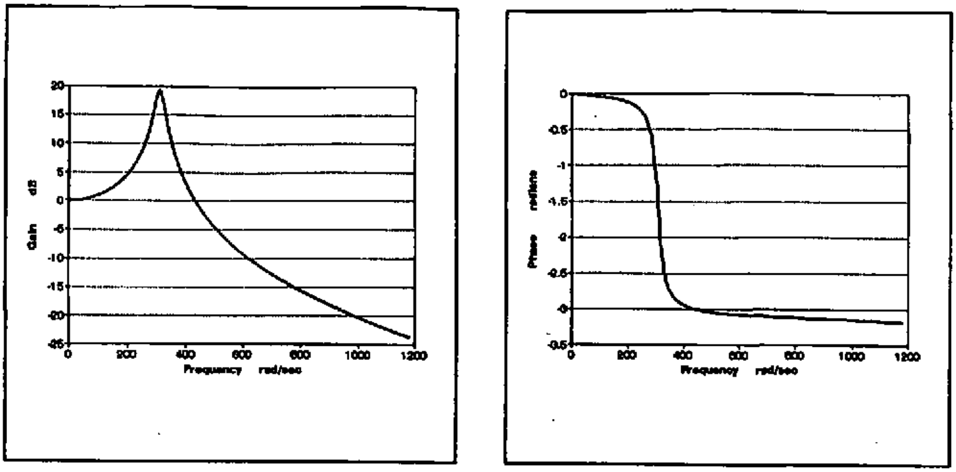

Figure 3 Ratio of port / speaker volume velocities ($-U_p/U_{LS}$) *including free field air load*

PORT INTERACTION WITH A ROOM MODE

The discrete low frequency modes of small listening spaces occur at frequencies close to the port resonances of typical bass reflex enclosures. Each of the modes of a room have resonant behaviour, centred at frequency ω_n, described by a frequency domain factor of form:

$$\frac{j\omega}{\omega_n^2 + jR_n\omega - \omega^2} \qquad (8)$$

The lowest modes of small rooms can have modes with quality factors of greater than 50 [4].

Although it has been demonstrated that the phase inversion achieved by a bass reflex enclosure is not appreciably influenced by free field loading, the presence of a high quality resonant mode can significantly influence the port velocity. To illustrate this effect, a single resonance (8) was added to the free field radiation loads described above. The resonant frequency was deliberately chosen as 55 Hz, close to the 50 Hz port resonance of the bass reflex system discussed above. The magnitude radiation load seen by the port was as shown in Figure 4.

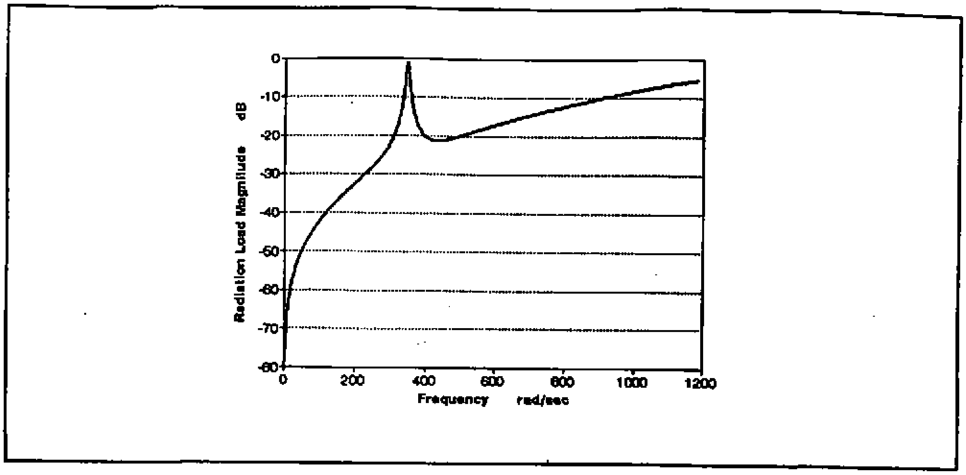

Figure 4 Simulated magnitude radiation load with a single resonant mode

Introduction of the single resonant factor in the radiation load seen by the loudspeaker disrupts the port motion, as reported in Figure 5. In addition to modifying the vector summation of the output from the loudspeaker and port (relative to the idealized case reported in Figure 2), the resonant component of the radiation load will lengthen the impulse response of the system.

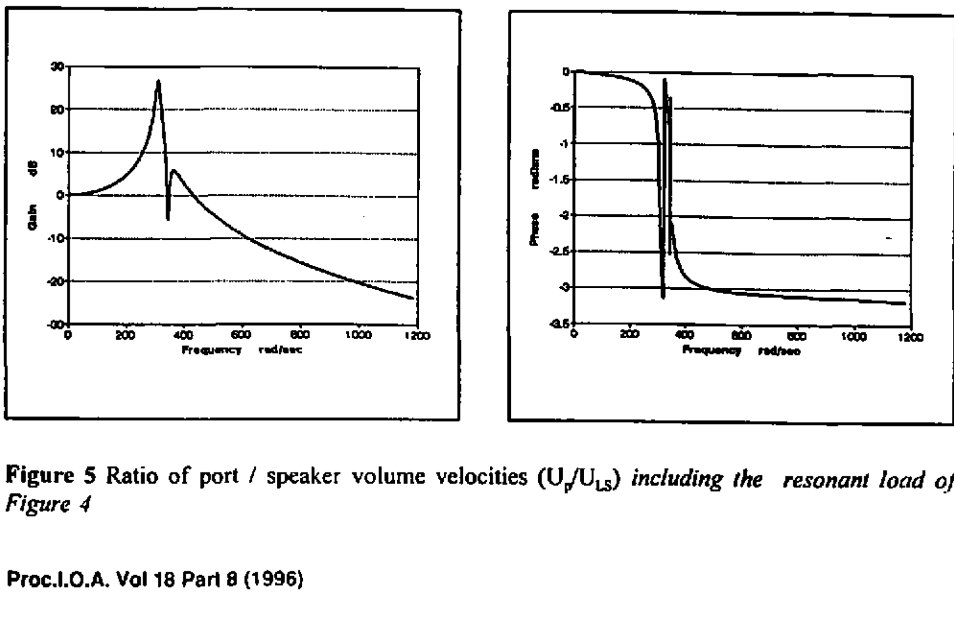

Figure 5 Ratio of port / speaker volume velocities (U_p/U_{LS}) *including the resonant load of Figure 4*

A NOVEL ACTIVE BASS REFLEX ENCLOSURE

The bass reflex enclosure interacts with the acoustic environment in which it operates by virtue of the source impedance of the port. The loudspeaker unit has reasonably high source impedance and is relatively unaffected by the room (indeed loudspeakers are modelled as a first order approximation as constant velocity sources, which have infinite source impedance). The port, having lower source impedance, is influenced strongly by the room, allowing the loudspeaker / room interaction described in equation 7. If the source impedance of the port can be increased, the loudspeaker / room coupling mechanism can be reduced; the remainder of this paper introduces an enclosure with a port with effectively infinite source impedance.

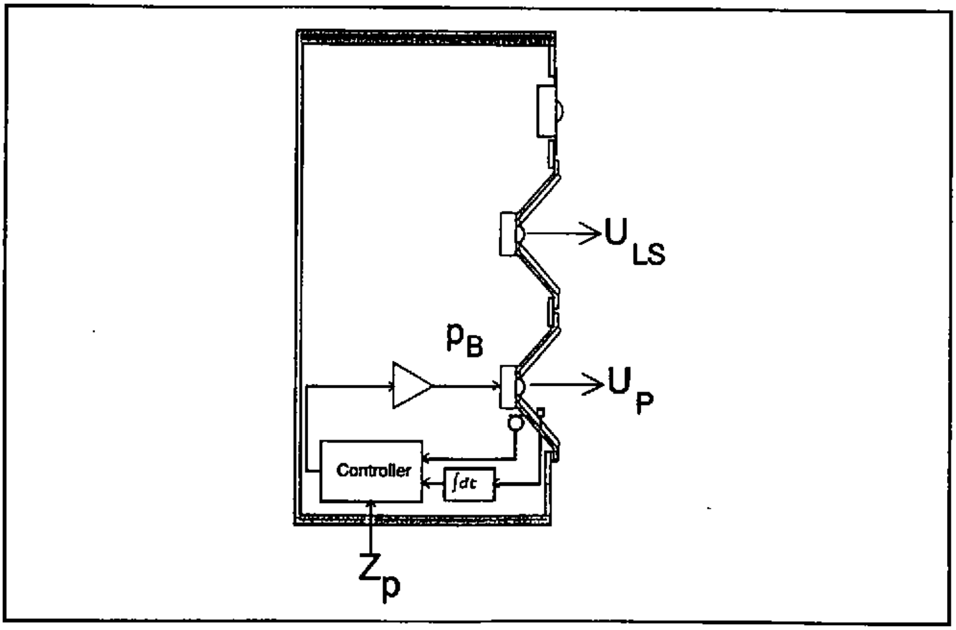

Figure 6 The Active bass reflex enclosure

The system depicted as Figure 6 has a second loudspeaker unit in the position previously occupied by the port in the conventional bass reflex enclosure. In the absence of electrical input to the second loudspeaker unit, it's cone will be forced into motion by the difference between the pressure inside and outside the cabinet.

If the mechanical parameters of the cone and suspension of the second loudspeaker are chosen appropriately, the system will still have a resonance between the enclosed volume of air in the cabinet and the cone's inertance - the system will still have bass-reflex action (indeed such systems have been commercially produced - the second driver is sometimes called an auxiliary bass radiator). However, the motion of the second cone is still influenced by the pressure outside the system. This influence can be avoided by controlling the motion of the second loudspeaker electronically, as shown in Figure 6.

If a loudspeaker cone is instrumented with a miniature pressure microphone and an accelerometer it is possible to control the cone motion such that the surface impedance is forced to a pre-specified value [5]. If, as shown in Figure 6, the pressure is detected inside the enclosure, then the impedance at the back of the second driver can be forced to a pre-specified value, Z_{port}. Under such control, the ratio of the source strengths of the two loudspeakers (the second loudspeaker now being interpreted as an active port) is:

$$\frac{U_P}{U_{LS}} = \frac{1}{\frac{Z_{port}\,\omega C_A'}{j} - 1} \tag{9}$$

If the impedance of the back of the active port is forced to:

$$Z_{port} = j\omega M + R \tag{10}$$

then equations (3) and (9) are identical. This shows that an enclosure with an actively implemented port would not suffer the room load interactions possible for a conventional bas reflex system.

Experimental verification

Experimental versions of the active bass reflex system proposed have been constructed. In the development systems, the (110mm diameter) active port has been controlled to offer an approximation of a mass load and achieves the performance shown in Figure 7.

The measured impedance, Figure 7, shows the expected rising magnitude and 90 degree phase advance over a wide frequency range (the system was low pass limited at 150Hz by filters in the analog signal conditioning electronics).

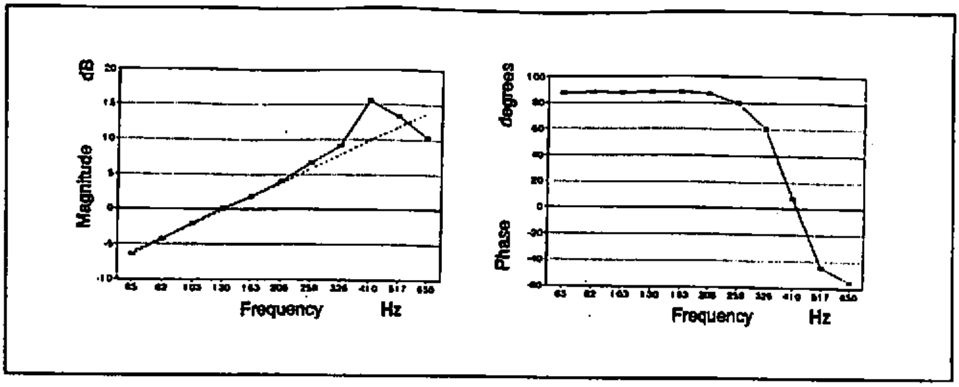

Figure 7 Measured impedance of an active port controlled to offer mass load.

Figure 8 shows a typical measured far field frequency response of an active bass reflex system, constructed in a 17 litre enclosure with 110mm units as both main and "port" drivers. The Figure shows both the response with the control system on and the response measured with both units driven in parallel. The system exhibits the bass extension and increased roll off below resonance expected of the bass reflex configuration.

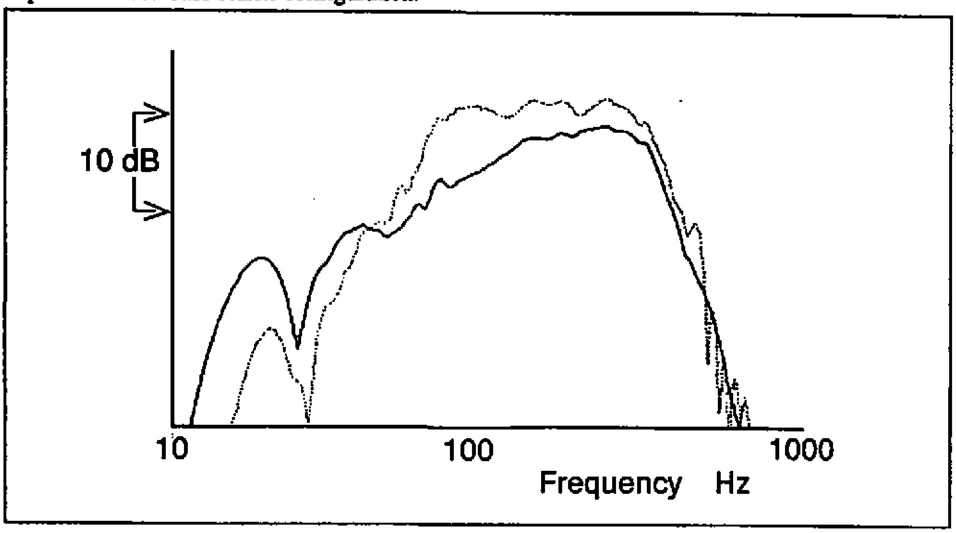

Figure 8 Far field response of an experimental active bass reflex system. (Heavy line; both l.f. units driven in parallel, light line; one l.f. unit controlled as "active port").

FUTURE DEVELOPMENTS

As well as isolating the motion of the "port" from the loading effects of the room, the active bass reflex enclosure offers another significant advantage over the conventional passive system - programmability. The impedance of the active port can be specified (in the computer control system) to be any combination of mass and damping. This offers an additional degree of freedom at the design stage, allowing, for example, the specification of a port which would be too large to physically fit within the enclosure if realised in conventional passive means.

The active port impedance need not represent just inertance and damping - any impedance that can be represented by a physical filter inside the control algorithm can be implemented, allowing entirely new loudspeaker tunings, many of which would be impossible or impractical using passive means.

The programmability of the enclosure could also be exploited to adapt the acoustics of the system, perhaps moving the resonant frequency of the active port in real time. Using this technique it would be possible to make a system which continuously tunes itself to allow single instantaneous frequency bass reproduction with the highest possible efficiency. The identification of the frequency to which the system should be tuned could be readily achieved using linear predictive coding techniques. Unfortunately, a high quality factor resonance, necessary for high efficiency, requires a large port volume velocity (equation 4). This cannot be achieved using a main loudspeaker and active port loudspeaker of equal radius without excessive throws on the active port. For this reason the active port would generally be implemented using a driver of larger radius than the main loudspeaker.

CONCLUSIONS

The operating source impedance of a low frequency loudspeaker drive unit is often so high that its motion is not significantly influenced by normal air loading. If it is desired to further uncouple the loudspeaker drive unit, "motional feedback" control techniques can force it to behave as a true constant velocity source. This is not true of the motion of the air in the ports of vented loudspeaker enclosures, which may be strongly influenced by irregularities in the radiation load presented by the listening space. This paper has presented a simple demonstration of that coupling mechanism and has introduced a new active phase inverting loudspeaker system. This new system could be constructed with infinite source impedance, making it completely independent of low frequency room interaction.

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