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DIRECT ASSESSMENT OF ACOUSTIC QUANTITIES WITHIN ACTIVE MATERIALS

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ABSTRACT

An active material with variable acoustic properties comprises an electrodynamic actuator with a double feedback, one on the acoustic pressure and the other on the velocity of the diaphragm. The whole disposal allows the modification of the acoustic properties of the transducer diaphragm, without the use of any external sensor (microphones, accelerometers). This paper presents a general methodology for assessing the acoustic quantities at the voicing face of the active material by way of all-electric measurements.

I INTRODUCTION

When it comes to designing active acoustic control disposals, one of the main issues relies on the sensing of the desired acoustic quantities. For active noise control (ANC) devices as well as for active structural acoustic control (ASAC) disposals, the so-called secondary path, corresponding to the transfer function between the actuator (loudspeaker) and the sensor (microphone) induces feedback control problems: the frequency response of this secondary path is hardly flat and free of phase shift because it contains both 1) the electroacoustic response of the loudspeaker, 2) the acoustic characteristics of the path between the loudspeaker and the microphone, and 3) the electroacoustic response of the microphone. These characteristics can be taken into account within the design of a dedicated feedback controller, but this design is much depending on the acoustic load [1]. In the present work, the focus is put on the design of implicit acoustic sensing on the loudspeaker itself, aiming at lowering the influence of the secondary path for ensuring broadband performances, causality and stability of an active material disposal.

II THE ACTIVE MATERIAL PRINCIPLE

Generally speaking, the active impedance control concept presented in this paper is based on a combined collocated pressure $\underline{p}_d$ – velocity $\underline{v}_d$ sensing at the transducer's diaphragm, the sensitivity of which are σ_p [V/Pa] and σ_v [V/m/s] ([2]). These two signals are the inputs of a double feedback disposal, whose gains are denoted Γ_p and Γ_v (corresponding feedback voltages $\underline{V}_p$ and $\underline{V}_v$). The total feedback voltage is denoted $\underline{V}_{FB} = \Gamma_v \underline{V}_v + \Gamma_p \underline{V}_p$, as illustrated on Figure 1.

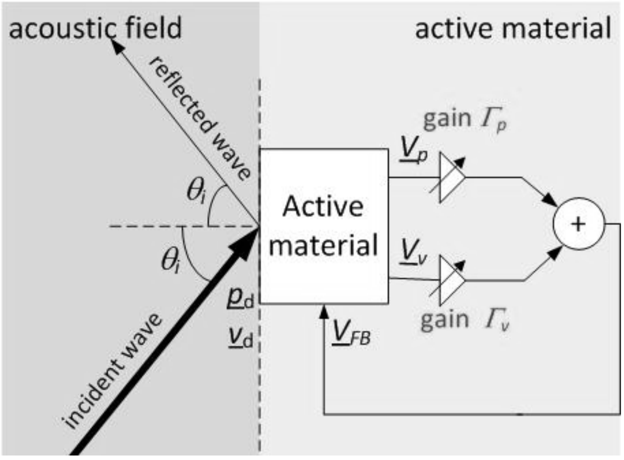

Figure 1.- the active material principle

The electroacoustic transduction can be expressed with a transduction matrix correlating the acoustic parameters ($\underline{p}_d$,$\underline{v}_d$) at the diaphragm and the electric parameters ($\underline{V}_{LS}$,$\underline{I}_{LS}$) at the loudspeaker's inputs (see Figure 3). In the specific case of electrodynamic transduction, the terms of the transduction matrix are simple functions of the electric and mechanical impedances $\underline{Z}_e(\omega) = R_e + j\omega L_e$ and $\underline{Z}_{ms}(\omega) = R_{ms} + j\omega M_{ms} + 1/j\omega C_{ms}$, of the transducer's force factor Bl, and of the diaphragm's surface S.

The equation system, composed with the feedback control equation and the electroacoustic transducer's system equations (mesh equation and Newton's law) lead to, assuming the whole diaphragm surface vibrates with the moving coil velocity (radiating piston hypothesis):

$$\underline{V}_g = \underline{V}_{FB} = \Gamma_v \underline{V}_v + \Gamma_p \underline{V}_p = \Gamma_v \sigma_v \underline{v}_d + \Gamma_p \sigma_p \underline{p}_d \quad \text{(Eq. 1)}$$

$$\underline{V}_g = (\underline{Z}_{g+}\underline{Z}_e)\underline{I}_{LS} - (Bl)\underline{v}_d \approx \underline{Z}_e \underline{I}_{LS} - (Bl)\underline{v}_d \quad \text{(Eq. 2)}$$

$$\underline{Z}_{ms}\underline{v}_d = (Bl)\underline{I}_{LS} - \underline{p}_d S \quad \text{(Eq. 3)}$$

Then this system leads to the following acoustic admittance $\underline{Y}_a(\omega)$ at the transducer's diaphragm:

$$\underline{Y}_a(\omega) = \frac{\underline{v}_d}{\underline{p}_d}(\omega) = -\frac{S - \Gamma_p \sigma_p(\omega)(Bl)/\underline{Z}_e(\omega)}{\underline{Z}_{ms}(\omega) - \left[\Gamma_v \sigma_v(\omega) + (Bl)\right](Bl)/\underline{Z}_e(\omega)} \quad \text{(Eq. 4)}$$

Around the resonance frequency of the transducer's moving body (ω=ω_s=$(M_{ms}C_{ms})^{-1/2}$), we can neglect the reactive part in $\underline{Z}_e$ and $\underline{Z}_{ms}$, which leads to the desired acoustic admittance of the material, assuming $|\Gamma_v\sigma_v| >> (Bl)$ and $R_e R_{ms}/(Bl)$, and $|\Gamma_p\sigma_p| >> SR_e/(Bl)$ (feedback gains much greater than unity):

$$Y_{ad} = \underline{Y}_a(\omega_s) = -\frac{\Gamma_p \sigma_p(\omega_s)}{\Gamma_v \sigma_v(\omega_s)} \propto \frac{1}{\rho c} = \frac{1}{Z_c} \quad \text{(Eq. 5)},$$

where ρ and c are the density of the medium and the celerity of sound in the medium, Z_c being the characteristic impedance of the medium. One can see that the setting of desired acoustic admittance at the diaphragm is feasible by simply adjusting two feedback gains, the ratio of which gives the target admittance. Moreover, under the assumption that the self inductance of the moving coil can be neglected along the frequency bandwidth of interest ($\omega < R_e/L_e$), the expression of $\underline{Y}_a(\omega)$ highlights the following behaviour:

$$\underline{Y}_a(\omega) = Y_{ad} \frac{R'_{md}}{\underline{Z}'_{ms}(\omega)}, \text{ where } \begin{cases} R'_{md} = S/Y_{ad} - Bl\Gamma_v\sigma_v/R_e \\ \underline{Z}'_{ms}(\omega) = (R_{ms} - Bl\Gamma_v\sigma_v/R_e) + j\omega M_{ms} + \dfrac{1}{j\omega C_{ms}} \end{cases} \quad \text{(Eq. 6)},$$

Figure 2 illustrates the behaviour of this theoretical active material (based on an Audax HT210F0 bass midrange loudspeaker, see Table I for relative specifications), with ideal flat pressure and velocity sensing ($\sigma_v(\omega)$=1V/m.s^{-1} and $\sigma_p(\omega)$=1V/Pa on the whole bandwidth of interest), for the case $Y_{ad}=1/Z_c$ and different values of Γ_v, in regards with the passive behaviour (Γ_v=0).

Table I.- Thiele-Small parameters of the Audax HT210F0

Parameter	Symbol	Value	Units
DC resistance	R_e	6,3	Ω
Voice-coil inductance	L_e	0,6.10^{-3}	H
Suspension compliance	C_{ms}	0,8.10^{-3}	m.N^{-1}
Mechanical resistance	R_{ms}	2,91	kg.s^{-1}
Moving mass	M_{ms}	27,9.10^{-3}	kg
Force factor	Bl	9,24	N.A^{-1}
Effective piston area	S	2,21.10^{-2}	m^2

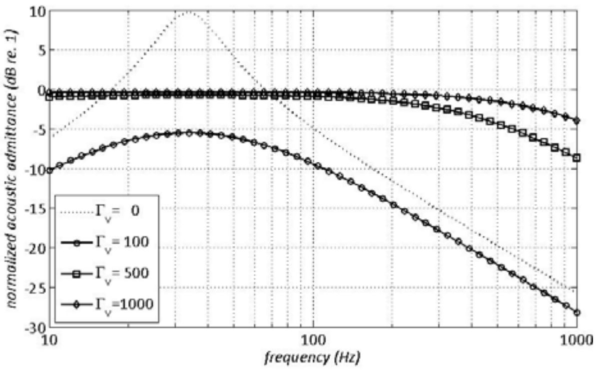

Figure 2.- normalized acoustic admittance of an active material set to $Y_{ad}=1/Z_c$, computed for various velocity feedback gains (Γ_v=[0; 100; 500; 1000])

Note that the former model remains valid under the cut-off frequency $f_c = R_e / 2\pi L_e = 1671\text{ Hz}$.

The described active material concept is a very simple way of varying acoustic properties of the diaphragm of any loudspeaker, with broadband effect under certain assumptions on the values of electroacoustic components of the transducer. Moreover it is obvious in Eq. 6 that the transfer function of the control is a simple function of constant parameters for a specific transducer, and that, whatever the sensing sensitivities values, there is always one combination of the signs of the two feedback voltage that provide stability for a desired acoustic admittance.

Up to now, acoustic quantities sensings were performed by way of external sensors (microphone, accelerometers or double moving coils). The aim of the following sections is to prove that an all-electric sensing of the acoustic quantities is feasible.

III THE LOUDSPEAKER ELECTRIC ANALOGUE

The design of electroacoustic transducers is made much easier by way of a Kirchhoff network representation, for example the electric analogue of the transducer, representing the whole physical equations within a single formalism ([3]). If we consider an electrodynamic loudspeaker, with electrical inputs ($\underline{V}_{LS}$, $\underline{I}_{LS}$) (voltage and current intensity) and acoustical inputs ($\underline{p}_d$, $\underline{v}_d$) (acoustic pressure and velocity at the diaphragm), the electric analogue of the transducer can be represented by the following scheme:

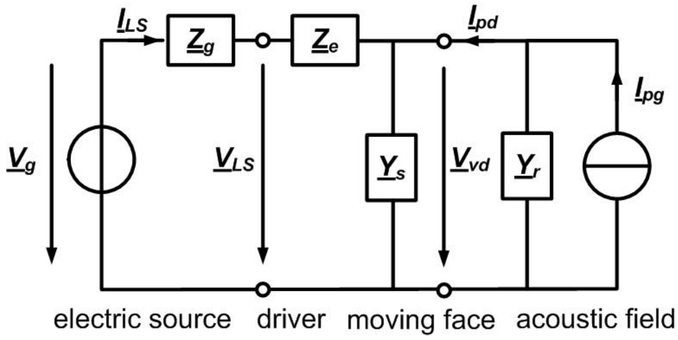

Figure 3.- the electric analogue of an electrodynamic loudspeaker

In this representation, each of the following mechanical parameter (diaphragm velocity $\underline{v}_d$, mechanical impedance of the diaphragm $\underline{Z}_{ms}(\omega)$ and the mechanical radiation impedance $\underline{Z}_{mr}(\omega)$) and acoustical quantity (acoustic pressure $\underline{p}_d$ at the diaphragm, acoustic pressure of the ideal sound source $\underline{p}_g$) is represented by an equivalent electrical component:

$$\underline{V}_{v_d}(\omega) = -(Bl)\underline{v}_d$$

$$\underline{Y}_s(\omega) = \frac{\underline{Z}_{ms}(\omega)}{(Bl)^2} \text{ and } \underline{Y}_r(\omega) = \frac{\underline{Z}_{mr}(\omega)}{(Bl)^2}$$

$$\underline{I}_{p_d}(\omega) = -\frac{S}{(Bl)}\underline{p}_d(\omega) \text{ and } \underline{I}_{p_g}(\omega) = -\frac{S}{(Bl)}\underline{p}_g(\omega)$$

Using this representation, it seems obvious that any of the acoustic metrics related to the voicing face of the loudspeaker ($\underline{p}_d$, $\underline{v}_d$) can be sensed by way of a dedicated electric filtering of the electric inputs of the loudspeaker (and by reciprocity electric metrics can be sensed by way of acoustic sensing).

IV ELECTROACOUSTIC SENSING

Diaphragm velocity sensing

After De Boer theory on motional feedback ([4]), formerly applied to improve the over-all response characteristic and to reduce the total distortion within electrodynamic loudspeakers dedicated to audio applications, a velocity sensing disposal has been designed to fit the requirements of the active impedance control ([5]). Assuming the electrical impedance of the loudspeaker is made of a purely electric impedance of the static coil (*blocked impedance*, denoted $\underline{Z}_e$) plus an additional *motional impedance* highlighting the electromotive force applied on the diaphragm (resulting of Lenz' law), and proportional to velocity $\underline{v}_d$, it can be easily shown that a dedicated differentiating circuit with, on one hand the loudspeaker's electric voltage, and on the other hand the voltage at the inputs of an electric impedance mimicking the loudspeaker's blocked impedance, will result to broadband sensing of the moving coil velocity.

The motional feedback voltage is then:

$$\underline{V}_v = -(Bl)\underline{v}_d = \underline{V}_{LS} - \underline{Z}_e \underline{I}_{LS} \qquad \text{(Eq. 7)}$$

In this case, σ_v=$-Bl$ (order of magnitude 10 V/m.s^{-1} for an Audax HT210F0) along the whole bandwidth of interest.

Acoustic pressure sensing

After Eq. 3 and the motional feedback expression (Eq. 7), it comes:

$$\underline{V}_p = \frac{S(Bl)}{R_{ms}}\underline{p}_d = \frac{(Bl)^2}{R_{ms}}\underline{I}_{LS} + \frac{\underline{Z}_{ms}}{R_{ms}}\underline{V}_v \qquad \text{(Eq. 8)}$$

In this case, σ_v=SBl/R_{ms} (order of magnitude 10^{-1} V/Pa for Audax HT210F0). It is obvious that the acoustic pressure sensing can be performed by a quite simple electric disposal (pressure feedback), combining the voltage at an electric resistance in series with the loudspeaker, and the motional feedback voltage filtered by way of a voltage divider disposal, comprising a series (R,L,C) branch and an electric resistance R_0 such as $R_0>>R$.

IV RESULTS

In a first part, the motional feedback disposal has been assessed on an Audax HT210F0 bass midrange loudspeaker, and the feedback voltage has been compared to the moving coil velocity sensed by a Polytec PSV505 laser vibrometer at the diaphragm central ring (fixed at the moving coil). Figure 4 illustrates the electric voltages with the two different sensings, when a random noise (1 Vrms on [10 Hz 810 Hz]) feeds the loudspeaker in series with an electric impedance mimicking its blocked impedance, the motional feedback providing the voltage according to Eq. 7.

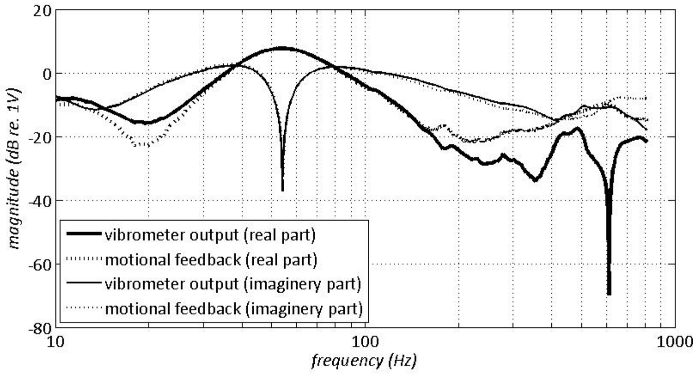

Figure 4.- comparison between velocity sensing and motional feedback (real part and imaginary part)

We can see that the motional feedback provides good results inside a wide bandwidth around the resonance frequency, but that differences occur for upper frequencies.

Then a pressure feedback disposal has been assessed in regards with the pressure sensed with a Norsonic Type 1225 microphone close to the diaphragm. Figure 5 illustrates the electric voltages with the two different sensings under the same condition as for motional feedback assessment. The dedicated filtering for the velocity sensing has been adjusted so as to obtain the best fitting frequency response around the resonance frequency of the actuator.

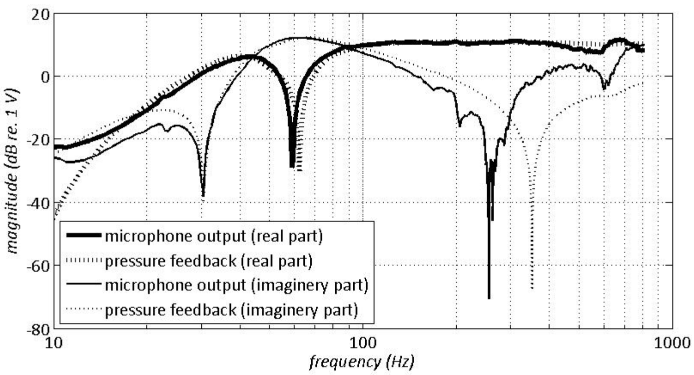

Figure 5.- comparison between pressure sensing and pressure feedback (real part and imaginary part)

One can observe the very good results obtained with such disposal. The different filters designed for those sensings are composed of discrete analogical components. Better results should be obtained by way of a dedicated digital filtering, in order to enhance the bandwidth of the sensing and, by way of consequence, the performances of the control.

CONCLUSIONS

It has been shown that all the relevant acoustic quantities requested as inputs for an active acoustic control disposal can be directly assessed on the actuator's own electrical inputs. This sensing might provide adequate sensitivity all along the bandwidth as soon as electroacoustic specifications of the actuator are well known. A dedicated digital filtering should provide more accurate sensing, allowing the flatness and adequate phase behaviour of the two transfer functions. The resulting active acoustic admittance would then follow an ideal behaviour as computed with the ideal active material described in section II.

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