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VELOCITY FEEDBACK COMPENSATION OF ELECTROMECHANICAL SPEAKERS FOR ACOUSTIC APPLICATIONS

Clark. J. Radcliffe, Professor
Sachin D. Gogate, Ph.D.

Controls Research Laboratory
Department of Mechanical Engineering
Michigan State University
East Lansing, MI 48824
e-mail : radcliffe@me.msu.edu

Abstract: Electromechanical speakers are commonly used as actuators in acoustic control applications and have non-constant velocity frequency response making them poor actuators. Velocity feedback compensation designed to minimize magnitude and phase variations in speaker velocity response is developed in this work. A proportional feedback compensator acting on the error between desired velocity input and measured speaker velocity is used to drive the speaker. Speaker cone velocity is sensed using velocity induced voltage in a secondary speaker coil. Laboratory tests on a dual-wound coil subwoofer are presented to demonstrate the performance of sensor and feedback compensation. As the compensation gain is increased, the compensated speaker velocity response magnitude and phase variations are reduced. The compensated speaker velocity accurately follows any desired velocity input from 4 Hz to over 400 Hz and makes feedback compensated speakers effective acoustic control actuators.

Key words: Modeling, Active Noise Control, Closed-Loop Control, Electromagnetic Transducers, Velocity Control

INTRODUCTION

Electromechanical speakers are commonly used as control actuators in many acoustic control applications (Hull et al., 1990). The volumetric flow rate generated by the speaker is the appropriate input for most acoustic systems and is equal to speaker cone velocity times effective speaker cone area. Successful performance of acoustic control system requires control actuators to have a minimum bandwidth greater than the frequency range of the controller. Over this frequency range, actuators should have a velocity frequency response with constant magnitude and minimum phase shift. These response characteristics allow actuator velocity to accurately track the desired velocity output of the acoustic controller. Electromechanical speakers typically have a non-constant voltage-to-velocity frequency response due to the free-air resonance of the speaker (Fig. 1). The variation in speaker volumetric velocity frequency response prevents accurate tracking of controller output signals. This makes electromechanical speakers ineffective as control actuators unless a compensation is provided for their varying velocity response.

The idea of compensating speaker velocity response dates back to early 1920s. Articles on this subject (Harwood, 1974, Klaassen, et al., 1968, Holdaway, 1963, Werner, 1958, Holle, 1952, Tanner, 1951) mention the use of velocity feedback as the compensation technique. They,

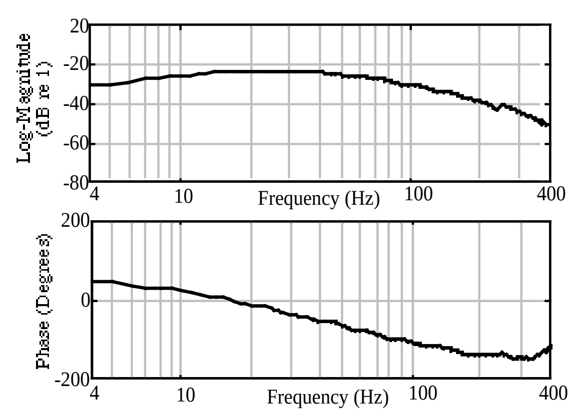

Fig. 1. Measured Velocity Response of a Typical Speaker

however, differ on the method used for sensing speaker cone velocity. The earliest mention of speaker compensation is found in a patent U.K. 231972) awarded to P. G. A. H. Voigt on Jan. 29th 1924. In his patent, Voigt used back emf induced in the speaker coil by its motion in the magnetic field as a measure of speaker cone velocity. The difficulties reported in his implementation (Harwood, 1974) were the needs to compensate for temperature induced changes in speaker coil resistance and frequency dependent variations in speaker coil inductance. Another speaker compensation is found in a patent U.K. 272622) by A. F. Sykes dated March 20th 1926. He used voltage introduced in an auxiliary coil to sense the speaker cone velocity. The method was not successful because the mutual inductance between auxiliary and speaker coil introduced errors in the speaker cone velocity sensing. In a third implementation, M. Trouton in his patent U.K. 320713, Aug. 10th 1928) used the voltage obtained from speaker cone displacement in a capacitive method to sense speaker cone velocity. The method though relatively simple, required a considerable spacing between capacitive elements for large amplitudes motions of speaker cone. Non-axial movement of the speaker coil also introduced error in this method. The use of accelerometers to measure speaker cone velocity has also been mentioned (Klaassen et al., 1968). In this method, the output of accelerometer attached to the speaker cone diaphragm is integrated to obtain voltage proportional to speaker cone velocity. The obvious disadvantages in this method are the inaccuracies in integrator due to noise and accelerometer mass loading of the speaker cone. The novel speaker cone velocity sensor developed in this work uses the mutual inductance effect compensated voltage introduced in an auxiliary speaker coil. The compensated auxiliary coil voltage provides an accurate velocity sensor and does not have the problems associated with sensors mentioned above.

Velocity feedback compensation (Fig. 2) for minimizing the magnitude and phase variations in speaker velocity response is developed and demonstrated in laboratory tests on a dual-wound coil subwoofer speaker. The feedback compensation uses proportional controller, K_p to generate drive voltage, $e(t)$ at the primary set of speaker coils. The speaker cone velocity is obtained through sensor transfer function, $H(s)$. The closed loop system transfer function, $T(s)$, from block diagram (2) is

$$T(s) = \frac{V_{spkr}(s)}{V_d(s)} = \frac{K_p G_{spkr}(s)}{1 + K_p G_{spkr}(s) H(s)} \qquad (1)$$

where, $V_d(s)$ is the Laplace transform of desired velocity input, $v_d(t)$. As the proportional compensator gain, K_p, is increased, the closed loop transfer function approaches $1/H(s)$. If the sensor transfer function is a real constant, k, over the controller bandwidth, ω_b,

$$H(j\omega) = k \qquad \omega \quad [0, \omega_b] \qquad (2)$$

the closed loop transfer function, $T(s)$, will approach a constant, $1/k$, with zero phase. This compensation forces speaker cone velocity to accurately follow the desired velocity input. The result is independent of the speaker dynamics provided the sensor has a constant transfer function (2) over the controller bandwidth. Proper selection and design of the velocity sensor is critical.

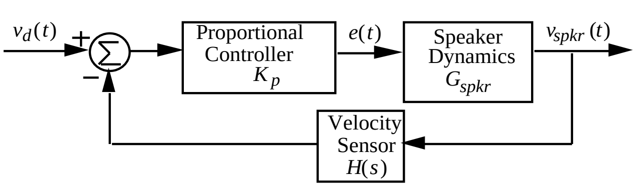

Fig. 2. Speaker Velocity Feedback Compensation Schematic

Speaker cone velocity was sensed using the mutual inductance compensated voltage induced in a secondary speaker coil by speaker cone velocity. The mutual inductance between speaker coils yields a complex, second-order transfer function between secondary speaker coil voltage and the cone velocity. The mutual inductance effect was predicted by a speaker dynamic model and a second order filter built to cancel this zero and compensate the secondary coil voltage. Mutual inductance compensated secondary coil voltage provided a viable velocity sensor for speaker feedback compensation.

The performance of speaker velocity feedback compensation was evaluated by measuring the closed loop transfer function from desired velocity input to the compensated speaker cone velocity measured with a laser velocimeter. As the gain of the speaker proportional compensator was increased, the closed loop speaker transfer function approached a real constant. The feedback compensation thus drove speaker cone velocity to track the desired velocity. This compensated response makes a feedback compensated speaker an effective actuator in acoustic control applications.

MODELING A DUAL-WOUND COIL SUBWOOFER SPEAKER

Dual-wound coil subwoofer (Fig. 3) is common in the audio industry. It is an electromechanical speaker (Fig. 4) consisting of electrical, mechanical and acoustic components. The dual-wound coil design consists of primary and secondary coils wound on a bobbin connected to the speaker cone. The 12 inch (30 cm) subwoofer used in this work (Radio Shack Realistic Model 40-1350) is driven through the primary coil of the speaker. As the drive voltage is applied to the primary coil, the varying electromagnetic field produced around the primary coil interacts with the magnetic field produced by a fixed permanent magnet. The interaction between the two magnetic fields produces a mechanical force in the primary coil attached to the speaker cone. The voltage in the speaker cone's secondary coil is induced by both the velocity of the coil in the speaker

Fig. 3. 12 inch, Dual-Wound, Subwoofer

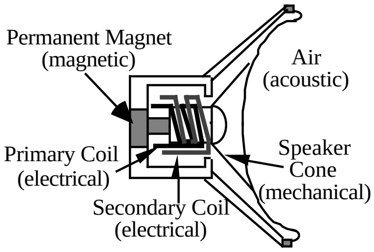

Fig. 4. Dual-Wound Coil Subwoofer Speaker Schematic

magnet's electromagnetic field and the mutual inductance between primary and secondary coils. This voltage was used to sense the speaker cone velocity.

An analytical model of the dual-wound coil subwoofer speaker can be developed (Fig. 5) by using the power summation and energy conservation principles of the Bond Graph methodology (Rosenberg and Karnopp, 1983). The Bond Graph arrows represent power flow from the electrical voltage, S_e, applied at primary coil through the model's elements. Dual-wound coils are represented here as a multiport $\mathbf{I}_{\text{coil}}$ field in the bond graph model. The electrical power is either dissipated, transformed or stored in the model elements. Power is dissipated in resistive elements R_{coil} and R_{spkr}, and transformed both from electrical to mechanical power in the 'GY' element and from mechanical to acoustic power in the 'TF' element. Power is stored as kinetic energy in the 'I' elements and as potential energy in the 'C' elements. The open circuit on secondary coil is represented by secondary coil current, $i_s = 0$ imposed by the source of flow, S_f.

The energy variables in the bond graph model include coil flux linkages, λ_p and λ_s, speaker cone displacement, x_{spkr} and speaker cone velocity, v_{spkr}. A linear approximation is used to relate the flux linkages, λ_p and λ_s, of multiport $\mathbf{I}_{\text{coil}}$ field to the port currents i_p and i_s in primary and secondary coils.

$$\lambda = \mathbf{I}\boldsymbol{i} \tag{3}$$

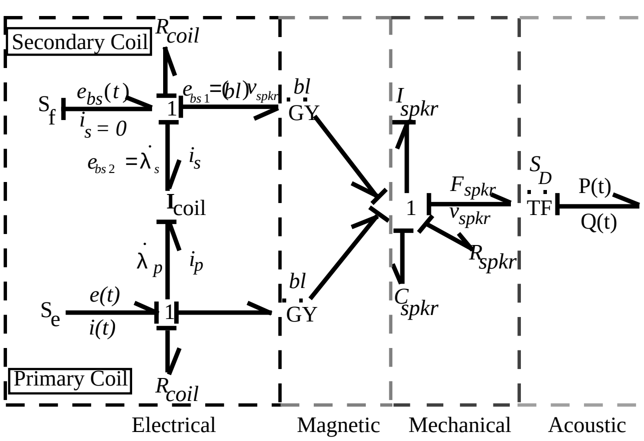

Fig. 5. Bond Graph Model of a Dual-Wound Coil Subwoofer Speaker without Enclosure

where, $\mathbf{I} = \begin{bmatrix} I_{coil,p} & M_{coil,p} \\ M_{coil,s} & I_{coil,s} \end{bmatrix}$ is the inductance matrix, $\boldsymbol{i} = \begin{pmatrix} i_p \\ i_s \end{pmatrix}$ is the vector of port currents and $\lambda = \begin{pmatrix} \lambda_p \\ \lambda_s \end{pmatrix}$ is the vector of coil flux linkages. $I_{coil,p}$ and $I_{coil,s}$ in the inductance matrix are the self inductances of primary and secondary coils, whereas, $M_{coil,p}$ and $M_{coil,s}$ are the mutual inductances between primary and secondary coils. The self and mutual inductance terms in the inductance matrix are equal for audio dual-wound speakers because the coils are designed to be identical in construction.

$$M_{coil,p} = M_{coil,s} = M_{coil} \tag{4}$$

$$I_{coil,p} = I_{coil,s} = I_{coil} \tag{5}$$

The speaker equations can be written from the bond graph in state space form by choosing energy variables as state variables and appropriate input and output variables. The input variables are speaker drive voltage, $e(t)$, and acoustic pressure, $P(t)$. The output variables are speaker volumetric flow rate, $Q(t)$ and speaker drive current in the primary coil, $i_p(t)$.

$$\begin{pmatrix} \dot{x}_{spkr} \\ \dot{v}_{spkr} \\ \dot{\lambda}_p \end{pmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \dfrac{-1}{C_{spkr} I_{spkr}} & \dfrac{-R_{spkr}}{I_{spkr}} & \dfrac{bl}{(I_{spkr} I_{coil})} \\ 0 & -bl & \dfrac{-R_{coil}}{I_{coil}} \end{bmatrix} \begin{pmatrix} x_{spkr} \\ v_{spkr} \\ \lambda_p \end{pmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{-S_D}{I_{spkr}} \\ 1 & 0 \end{bmatrix} \begin{pmatrix} e(t) \\ P(t) \end{pmatrix} \tag{6a}$$

$$\begin{pmatrix} Q(t) \\ i_p(t) \end{pmatrix} = \begin{bmatrix} 0 & S_D & 0 \\ 0 & 0 & \dfrac{1}{I_{coil}} \end{bmatrix} \begin{pmatrix} x_{spkr} \\ v_{spkr} \\ \lambda_p \end{pmatrix} \tag{6b}$$

The voltage, $e_{bs}(t)$, introduced in the secondary speaker coil is obtained from the bond graph model (Fig. 5) by summing the voltages across 1-junction on secondary coil side. These voltages include the voltage, $e_{bs1}(t)$, due to the mechanical motion of speaker cone and the voltage, $e_{bs2}(t)$ due to the mutual inductance, M_{coil}, between the coils.

$$e_{bs}(t) = e_{bs1}(t) + e_{bs2}(t) \tag{7}$$

The voltage, $e_{bs1}(t)$, introduced due to mechanical motion of the speaker cone is linearly proportional to the speaker cone velocity, v_{spkr} through electromagnetic coupling factor, (bl).

$$e_{bs1}(t) = (bl)v_{spkr}(t) \tag{8}$$

The voltage, $e_{bs2}(t)$, in the secondary speaker coil can be written from the constitutive relation (3) of the coils by noting that the secondary coil current, $i_s = 0$ due to the open circuit on secondary coil.

$$e_{bs2}(t) = \dot{\lambda}_s = M_{coil}\frac{di_p(t)}{dt} \tag{9}$$

Hence, the voltage, $e_{bs}(t)$, introduced in secondary speaker coil is

$$e_{bs}(t) = (bl)v_{spkr} + M_{coil}\frac{di_p}{dt} \tag{10}$$

Equations (6) and (10) define the model of a dual-wound coil subwoofer speaker. The speaker parameters necessary to define the model are: mechanical inertia of speaker, I_{spkr}, mechanical compliance of speaker, C_{spkr}, viscous friction of speaker, R_{spkr}, electromagnetic coupling factor, (bl), speaker coil resistance, R_{coil}, speaker coil inductance, I_{coil}, mutual inductance, M_{coil}, and the equivalent speaker area, S_D. With the exception of mutual inductance, M_{coil}, these electrical and mechanical parameters are defined in IEEE standard 219-1975 for loudspeaker measurements.

SYSTEM TRANSFER FUNCTIONS

The transfer functions of the subwoofer speaker system describe the dynamics between mechanical and electrical subsystems of the speaker. One of these transfer functions is the plant transfer function, $G_{spkr}(s)$, from the primary coil drive voltage, $e(t)$, to the speaker cone velocity, v_{spkr}. The other transfer function describes the dynamics between speaker cone velocity, v_{spkr}, and the voltage, $e_{bs}(t)$, introduced in the secondary speaker coil. Denoted $H_1(s)$, this transfer function was the basis for speaker cone velocity sensor design. The knowledge of both transfer functions is important to speaker velocity feedback compensator design.

The plant transfer function, $G_{spkr}(s)$, between drive voltage and speaker cone velocity can be written from (6) by noting that volumetric flow rate, $Q(t)$ is equal to speaker cone velocity, v_{spkr}, times its effective area, S_D.

$$G_{spkr}(s) = \frac{(bl)\ s}{as^3 + bs^2 + cs + d} \tag{11}$$

where: $a = I_{coil}I_{spkr}$, $b = I_{coil}R_{spkr} + R_{coil}I_{spkr}$,
$c = (I_{coil}/C_{spkr}) + R_{coil}R_{spkr} + (bl)^2$ and $d = R_{coil}/C_{spkr}$

The transfer function, $H_1(s)$, between speaker cone velocity, v_{spkr}, and secondary coil voltage, e_{bs}, is obtained by taking the Laplace transform of (10)

$$H_1(s) = \frac{E_{bs}(s)}{V_{spkr}(s)} = (bl) + s\frac{M_{coil}I_p(s)}{V_{spkr}(s)} \tag{12}$$

The transfer function between primary coil current, i_p, and speaker cone velocity, v_{spkr}, can be written from (6) as

$$\frac{I_p(s)}{V_{spkr}(s)} = \frac{I_{spkr}s^2 + R_{spkr}s + 1/C_{spkr}}{(bl)s} \tag{13}$$

From (12) and (13)

$$H_1(s) = \frac{M}{(bl)}\left[I_{spkr}s^2 + R_{spkr}s + \left(\frac{1}{C_{spkr}} + \frac{(bl)^2}{M}\right)\right] \tag{14}$$

Transfer functions (11) and (14) are the speaker transfer functions required for sensor and speaker compensation.

SPEAKER PARAMETER IDENTIFICATION

The parameters necessary to define the plant transfer function (11) of a dual-wound coil subwoofer speaker were identified using a laboratory based methodology (Radcliffe and Gogate, 1992). The analytical model (11) of the subwoofer was constructed and simulated in MatLab® using the speaker parameters tabulated in Table 1. A speaker coil inductance of 2.8 mH was used to obtain a good fit between the model and measured velocity frequency response. The measured frequency response of the transfer function from speaker drive voltage to speaker cone velocity was obtained using a Hewlett Packard Dynamic Signal Analyzer. A Brüel & Kjaer Laser Doppler Velocimeter was used to generate a calibrated voltage output proportional to the speaker cone velocity.

The measured and modeled velocity frequency responses are shown in Fig. 6 and have the same fundamental natural frequency, $f_n = 21$ Hz, indicated by phase response zero crossings. At 400 Hz, the measured velocity response magnitude is 30 dB below its value at 21 Hz resonance. This makes the effect of noise dominant above 400 Hz and accordingly measurements above 400 Hz were found unreliable due to poor signal-to-noise ratio. This fact was also verified by the poor measured coherence. The limited low frequency bandwidth of the Brüel & Kjaer Laser

Table 1 Dual-Wound Subwoofer Speaker Parameters

Parameter	Value
Mechanical Inertia, I_{spkr}	55.5 gm
Mechanical Compliance, C_{spkr}	1.03 mm/N
Viscous Friction, R_{spkr}	10.2 N-sec/m
Electromagnetic Coupling Factor, (bl)	5.4 N/A
Coil Resistance, R_{coil}	3.5 Ohms
Coil Inductance, I_{coil}	2.8 mH
Equivalent Speaker Area, S_D	531 cm^2

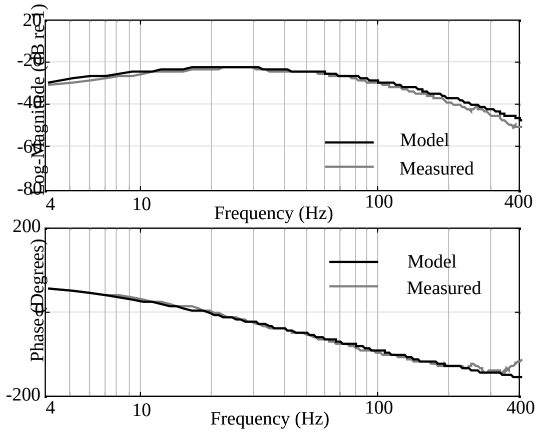

Fig. 6. Model vs. Measured Speaker Velocity Response

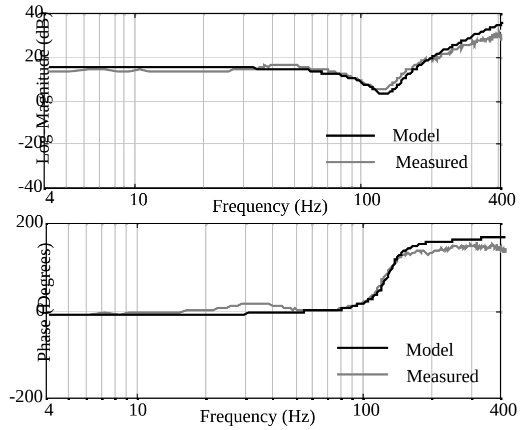

Fig. 7. Secondary Coil Voltage/Speaker Cone Velocity Model vs. Measured Responses

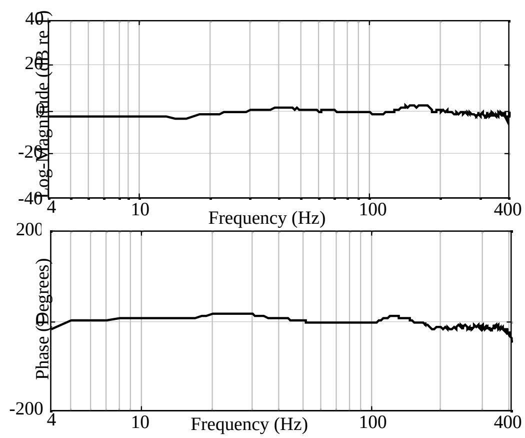

Figure 8: Compensated Secondary Speaker Coil Voltage/Laser Velocity Response

Doppler Velocimeter restricted the low frequency limit to 4 Hz. The velocity responses shown in Fig. 6 have limited bandwidth and large phase shifts that prevents speaker cone velocity tracking of desired velocity input. These bandwidth limited speakers are unsuitable acoustic control actuators unless compensation is provided for their varying velocity response. Successful speaker compensation, however, requires an accurate speaker cone velocity sensor.

SPEAKER CONE VELOCITY SENSOR DESIGN

An accurate speaker cone velocity sensor is necessary for the successful performance of closed loop speaker velocity feedback system. A novel cone velocity sensor design for a dual-wound coil subwoofer speaker is discussed here. It uses speaker cone velocity induced voltage in a secondary speaker coil obtained by compensating the mutual inductance effect between dual-wound coils.

The transfer function from speaker cone velocity to secondary speaker coil voltage is a second order zero (14). The measured and analytical frequency responses of this transfer function for a dual-wound coil subwoofer speaker (Table 1) placed in an enclosure of volume 0.0505 m^3 are shown in Fig. 7. The enclosure reacts as a compliant acoustic impedance and decreases the effective speaker compliance from 1.03mm/N to 0.12mm/N (Radcliffe and Gogate, 1992). Enclosure air leakage also adds the effect of a low frequency pole and changes the low frequency phase asymptote to zero degrees. The analytical frequency response is obtained by simulating the transfer function (15) of the enclosed speaker with mechanical speaker compliance of 0.12mm/N while other speaker parameters are obtained from Table 1. The mutual inductance, M_{coil}, was not supplied by the speaker manufacturer and a value of 1.2 mH provided a good fit between model and measured responses. A Hewlett Packard Dynamic Signal Analyzer 35660A was used to measure the frequency response between speaker cone velocity and secondary speaker coil voltage. Both model and measured frequency responses show damped second order zero ($\zeta = 0.24$) at 122 Hz indicated by 90^o phase crossing.

The secondary speaker coil voltage due to the mechanical motion of the speaker cone is linearly proportional (8) to the speaker cone velocity through the electromagnetic coupling factor, (bl). The coupling factor provides a good measure of speaker cone velocity below 70 Hz as seen from Fig. 7. Over this frequency range, the phase is nearly 0^o and the magnitude varies from 13.5 dB to 14.8 dB, the amplitude of the electromagnetic coupling factor, (bl). At frequencies above 70 Hz, the second order zero at 122 Hz due to mutual inductance between the dual-wound coils causes large magnitude and phase changes. The secondary speaker coil voltage becomes an inaccurate velocity sensor above 70 Hz unless the sensor is compensated for the second order zero at 122 Hz. A second order filter, $H_c(s)$, with an undamped natural frequency of 122 Hz and a damping ratio of $\zeta = 0.24$ was built to compensate for this mutual inductance zero.

The mutual inductance compensated frequency response between speaker cone velocity and secondary speaker coil voltage has less than 5 dB gain variation over 4-400 Hz (Fig. 8) frequency range compared to 30 dB variation for uncompensated secondary coil voltage (Fig. 7). Over the same range of frequencies, phase varies less than 20^o for filtered secondary coil voltage compared to a variation of 160^o for uncompensated secondary coil voltage. Although some magnitude and phase variations remain, the filtered secondary speaker coil voltage provides a more accurate measure of speaker cone velocity.

This velocity sensor does not have the drawbacks of previously mentioned sensors. There is no need to account for the temperature induced variations in speaker coil resistance and frequency dependent variations in speaker coil inductance as in Voigt's method. The sensor does not have the mass load on the speaker cone of accelerometer-based velocity sensors. There are no geometric inaccuracies associated with using capacitive pick-up elements. This unique velocity sensing mechanism requires only the filter and does not need any changes in the physical parameters of the subwoofer speaker. It yields a viable velocity sensor for the feedback compensation of the speaker system.

PERFORMANCE EVALUATION OF VELOCITY FEEDBACK COMPENSATOR

The performance of the speaker velocity feedback compensator was evaluated by measuring the closed loop transfer function, $T(s)$, of the speaker velocity feedback loop (Fig. 2) for different proportional compensator gains (Fig. 9). The speaker cone velocity was independently measured using the laser velocimeter. As the proportional compensator gain is increased, the magnitude of the closed loop speaker velocity response becomes more constant and phase change is minimized. At a compensator gain of $K_p = 200$, the magnitude varies less than 5 dB from 4 Hz to 400 Hz as compared to an open loop magnitude change of 20 dB. Over this range of frequencies, the phase angle changes less than 20 degrees as compared to an open loop change of 160 degrees. At high proportional gains, the closed loop transfer function (Fig. 9) approaches the inverse (2) of the sensor transfer function, $H(s)$ as expected (1). When compared to the uncompensated speaker, the feedback compensated subwoofer speaker has much lower magnitude and phase variations in velocity response.

The feedback compensation uses simple control technology, is easy to implement and the results are especially significant because no changes in speaker physical design are required. Compensation of speaker response allows speaker cone velocity to accurately track desired velocity inputs such as the output of an acoustic controller. Feedback compensation makes limited bandwidth subwoofer speakers effective acoustic control actuators.

CONCLUSION

Velocity feedback compensation for minimizing the magnitude and phase variations in the velocity frequency response of a dual-wound coil subwoofer speaker is presented in this work. The feedback compensation uses a proportional controller to drive the subwoofer through primary speaker coils. The speaker cone velocity sensing is done by a novel velocity sensor designed using a bond graph model of subwoofer dynamics. The control implementation uses speaker cone motion induced secondary coil voltage obtained by compensating the mutual inductance effect between the dual-wound speaker coils.

Speaker velocity feedback compensation is demonstrated experimentally to reduce speaker velocity magnitude and phase variations. The compensated speaker has variations less than 5 dB in gain and 20 degrees in phase over 4-400 Hz

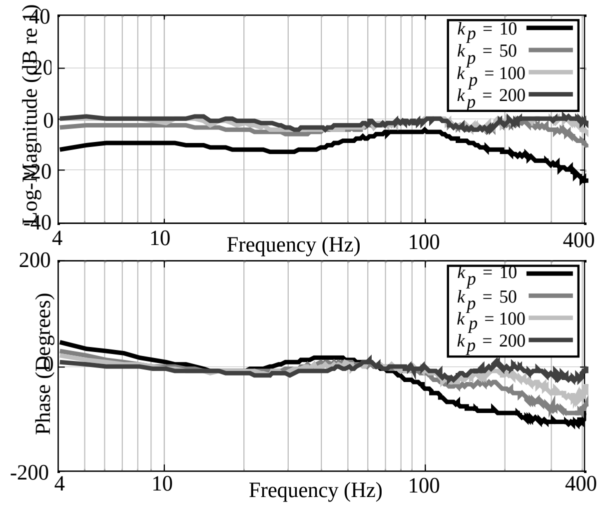

Fig. 9. Measured Closed-Loop Compensated Speaker Velocity Response vs. Proportional Gain

bandwidth compared to 20 dB and 160 degrees variations for the uncompensated speaker. This allows compensated subwoofer speakers to accurately follow any desired velocity input and makes them effective acoustic control actuators in applications.

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