Robust Control of a Sensorless Bass-enhanced Moving-Coil Loudspeaker System

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ABSTRACT

Moving-coil loudspeakers generally exhibit poor response in the low frequency range this study focuses on enhancing the low-frequency performance of loudspeakers by means of modern control techniques. A self-sensing velocity observer is utilized for producing the cone velocity signal required by the controller. Feedback H_∞ *robust control and feedforward* H_2 *model matching control are employed to simultaneously achieve robust stabilization and tracking performance.*

INTRODUCTION

In general, moving-coil loudspeakers exhibit poor response in the low frequency range because the speaker diaphragms are unable to produce sufficient volume velocity below the mechanical resonance frequency (Borwick, 1994). The approach is electronic compensation. Some audio systems are equipped with equalizers to boost the bass output. In doing so, only the magnitude of the low-frequency response is increased, while the phase is distorted even further (unless a linear phase FIR digital filter is used). In contrast to conventional equalizers, this study adopted a different approach of electronic compensation that seeks to increase the bass level without disturbing the phase response so that the waveform distortion is minimized. A very good collection of references on the loudspeaker development in last 30 years can be found in Borwick, 1994.

I. MOVING-COIL LOUDSPEAKER

A. Modeling

In this section, a brief review of the model of moving-coil loudspeakers which is also similar to the Thiele-Small's model (Small, 1972) is given. The following definitions are used (Beranek, 1954):

e_s, R_i: input voltage and input resistance of the power amplifier.
e_g, R_g: open-circuit voltage and internal resistance of the generator.
e'_g: output voltage of the power amplifier.
R_u: resistance for the velocity observer.
e_u: voltage drop across the resistor R_u.
L_E, R_E: inductance and resistance of the coil measured with the voice

coil blocked ($u_c = 0$).

Bl : the electromagnetic coupling factor (magnetic flux density × coil length).

e , i : back electromotive force (EMF) and the current of the coil.

u_c , f_c : coil velocity and Lorentz force.

M_M , C_M , r_M : equivalent mass, compliance, and responsiveness of the mechanical system.

z_{MR} : radiation mobility, $z_{MR} = \left(Z_{MR}\right)^{-1}$, Z_{MR} being radiation impedance.

z_{MOT} : motional mobility of mechanical and acoustical systems.

B. Implementation of the Velocity Observer

In the far-field, the sound pressure of a direct-radiator loudspeaker is related to the diaphragm velocity (Beranek, 1954). Hence, cone velocity is selected as the controlled variable in our design. However, direct access of cone velocity requires sensors such as accelerometers that may result in adverse effects of mass loading. A simpler solution is the *self-sensing velocity observer* (Okada et al., 1995). From the electrical side of Fig. 1(a),

$$e_g = \left(R_t + j\omega L_E\right)i + Blu_c . \tag{6}$$

Knowing that $i = e_u / R_u$, we can thus express the coil velocity u_c as

$$u_c = \frac{1}{Bl}\left[e_g - \left(\frac{R_t + j\omega L_E}{R_u}\right)e_u\right]. \tag{7}$$

Hence, a velocity observer can be constructed based on the idea of Eq. (7), provided the parameters R_u, R_t, L_E, and Bl have been measured. However, common calibration procedures (Beranek, 1954) that treat these parameters as ideal constants appeared insufficient for our purpose. We use a different approach to accommodate the frequency variation of the parameters. Rewrite Eq. (7) in terms of the output voltage of the power amplifier (e'_g)

II. ROBUST CONTROL DESIGN

The hybrid structure (Aström, 1990) composed of a feedforward controller and a feedback controller is adopted in the control design. The design strategy is first to find an H_∞ feedback controller that stabilizes the open-loop plant, where “plant” means “the controlled system.” The reason of using a feedback module is to increase robustness against plant uncertainties and perturbations (Morari and Zafirou, 1989). Next, a feedforward controller is introduced to achieve tracking performance without degrading the stability of the feedback-compensated system. It is noted that an optimally matched feedforward control is a step further than merely using a linear phase FIR digital filter that does not take into account the phase response of the plant.

A. H_∞ Robust Feedback Controller

The feedback structure of Fig. 4 is considered. To find an H_∞ controller, we weight the sensitivity function $\widetilde{S}(z)$ by $W_1(z)$, the control input $u(k)$ by $W_2(z)$, and the complementary sensitivity function $\tilde{T}(z)$ with $W_3(z)$, where

$$\tilde{S}(z) = \frac{1}{1 + P(z)C(z)} \tag{12}$$

and

$$\tilde{T}(z) = \frac{P(z)C(z)}{1 + P(z)C(z)}. \tag{13}$$

B. H_2 Feedforward Model Matching Controller

Having stabilized the plant $G(z)$ by the feedback controller, the design effort can then be focused on finding a feedforward controller $C(z)$ that makes the plant output track the desired output of a reference model $M(z)$. In our study, $M(z)$ is chosen as the following function:

$$M(z) = \frac{z^{-10}\left(1.4695 - 0.0609z^{-1}\right)}{1 - 0.5305z^{-1}}. \tag{20}$$

Note that the above function contains a pure delay term z^{-10} and a first-order low-pass function. The low-pass function is to attenuate the excessive gain outside the control bandwidth. The pure delay that will not introduce waveform distortion is essential in calculating the controller using the model matching principle, as detailed as follows.

IV. CONCLUSIONS

Modern control techniques are exploited to enhance the low-frequency performance of moving-coil loudspeakers, under the electromagnetic properties and acoustical constraints. A self-sensing velocity observer is developed for cone velocity estimation without additional motional or acoustical sensors. H_∞ feedback control is employed for robust stabilization, while H_2 feedforward model matching control for tracking performance. The results obtained in experiments indicate that the proposed system yields improved performance over the uncompensated one. However, as a limitation of the proposed methodology, the success of this method relies on adequate design of the original mechanical system and acoustical system (such as a sufficiently large diameter of the speaker). That is, one can never adequately control a poorly designed mechanical system. Overemphasis on the proposed electronic compensation will likely result in undesirable nonlinearity in the system.

Although this paper focuses mainly on audio loudspeakers, the same rationale can be extended to the other applications, e.g., control speakers for active noise cancellation, linear electromagnetic actuators for active vibration control and isolation, where efficient low-frequency response is crucial. Since the research was originally targeted at the subwoofer, only one driver was tested. However, the feasibility of the proposed technique applied to the systems of multiple drivers should be examined. Future research is planned in these areas.

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REFERENCES

Aström, J., and Wittenmark, B., 1990, *Computer-controlled Systems*, Prentice-Hall, Englewood Cliffs, NJ.

Bai, M. R., and Lin, H. H., 1997, "Comparison of Active Noise Control Structures in the Presence of Acoustical Feedback by Using the H_∞ Synthesis Technique," *Journal of Sound and Vibration*, Vol. 206, pp. 453-471.

Beranek, L. L., 1954, *Acoustics*, McGraw-Hill, New York.

Borwick, J., 1994, *Loudspeaker and Headphone Handbook*, Butterworth-Heinemann, Oxford.

Colloms, M., 1991, *High Performance Loudspeakers*, John-Wiley and Sons, New York.

Doyle, J. C., Francis, B. A., and Tannenbaum, A. R., 1992, *Feedback Control Theory*, Macmillan Publishing Company, New York.

Juang, J, N., 1994, *Applied System Identification*, Prentice-Hall, Englewood Cliffs, NJ.

Kinsler, L. E., Frey, A. R., Coppens, A. B., and Sanders, J. V., 1982, *Fundamentals of Acoustics*, John-Wiley, New York.

Kuriyama, J., and Furukawa, Y., 1989, "Adaptive Loudspeaker System," *J. Audio Eng. Soc.,* Vol. 37, No. 11, pp. 919-926.

Okada, Y., Matsuda, K., and Hashitani, H., 1995, "Self-Sensing Active Vibration Control Using the Moving-Coil-Type Actuator," ASME *J. of Vibration and Acoustics*, Vol. 117, pp. 411-415.

Morari, M. and Zafirou, E., 1989, *Robust Process Control*, Prentice-Hall, Englewood Cliffs, NJ.

Radcliffe, J., and Gogate, S. D., 1992, "Identification and Modeling of Speaker Dynamics for Acoustic Control Application," ASME *Active Control of Noise and Vibration*, Vol. 38, pp. 295-300.

Schaumann, R., Ghausi, M. S., and Laker, K. R., 1989, *Design of Analog Filters: Passive Active RC, and Switched Capacitor*, Prentice-Hall, Englewood Cliffs, NJ.

Small, R. H., 1972, "Closed-box Loudspeaker Systems, Part I: Analysis," *J. Audio Eng. Soc.,* Vol. 20, No. 10, pp. 798-808.