Application of disturbance-observer-type velocity estimator to electroacoustic absorber for noise absorbing

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ABSTRACT

Direct impedance control (DIC) technique used for an electroacoustic absorber in this paper requires a pair of pressure and velocity sensor. However, it can be quite costly to develop array system of this electrostatic absorber for acoustically large space. To overcome this problem, in this paper instead of using velocity sensor, disturbance-observer-type velocity estimator is applied to DIC technique for the electroacoustic absorber. In order to verify the practicality of this technique, a robust velocity estimation performance of disturbance-observer-type velocity estimator to acoustic load change of the loudspeaker diaphragm is demonstrated experimentally. Next, its velocity estimation performance is verified after diaphragm velocity is induced both by external pressure and applied DIC voltage. Finally, the possibility of applying disturbance-observer-type velocity estimator to electroacoustic absorber is verified through the measurement of sound absorption coefficients. In this paper, the possibility for the real space acoustic control using array system of electroacoustic absorber using DIC technique is presented.

Keywords: Active noise control in ducts, Electroacoustic absorber, Disturbance-observer-type velocity estimation, Sensorless loudspeaker control

1. INTRODUCTION

Active noise cancellation technique is one of the most widely known active noise control method. Unlike this active noise cancellation technique, another active noise reduction control method so-called ‘electro sound absorber’ is introduced by Olson and May [1]. In this method, the incident noise is absorbed through the loudspeaker diaphragm by controlling its acoustic impedance to be matched with that of air (i.e., acoustic medium of noise). Thereafter, hybrid sound absorber concept using passive absorber and active absorber is introduced by Guicking [2]. Furstoss studied new concept of sound absorber using direct impedance control (DIC) technique [3]. Recently, H. Lissek implemented sound absorber using the DIC technique successfully and named it as electroacoustic absorber. Through his studies, one can confirm that low frequency noise reduction performance of the electroacoustic absorber can be obtained over a broadband frequency range [4-6].

On the other hand, in order to match the acoustic impedance of the loudspeaker with that of air, DIC technique requires a pair of pressure and velocity sensor for obtaining signals nearby loudspeaker diaphragm. In this case where electroacoustic absorber array system using this direct impedance feedback control technique is necessary for the acoustically large space, a lot of sensors are needed inevitably. This will increase the cost of the system. In order to solve this problem, diaphragm velocity estimator is applied to DIC technique instead of velocity sensor.

Estimation methods for diaphragm velocity can be mainly classified into two groups. One uses back-EMF in electrical circuit of the loudspeaker [7]. Even though there are several research cases using this estimation method, it has not been used due to the low performance and limitation of available velocity estimation frequency.

The other uses current signal circulating around voice-coil of loudspeaker. This estimation method

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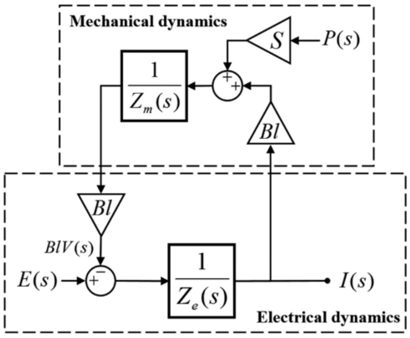

Figure 1 – Block diagram of a loudspeaker

is more cost-effective and reliable in terms of estimating velocity than the aforementioned method. Firstly, Lane and Clark facilitate this advantage to develop a new diaphragm velocity estimator based on Lorenz force induced by the current and mechanical impedance in a loudspeaker [11]. Since this velocity estimator is composed of several poles based on the mechanical impedance of the loudspeaker, accurate identification of the mechanical impedance is necessary for exact diaphragm velocity estimation. For this reason, this method has a limitation i.e. the velocity estimator should be redesigned inevitably whenever acoustic load of the loudspeaker is changed.

For compensating this limitation, Yaoyu Li developed disturbance-observer-type velocity estimator based on the blocked impedance rather than mechanical impedance of the loudspeaker. They also theoretically verified robust velocity estimation performance to acoustic load change of the loudspeaker diaphragm [12]. In this paper, thus, the corresponding experimental verification is conducted as a means to support simulation study in Yaoyu Li's paper. Note that disturbance-observer-type velocity estimator is originally studied for estimating diaphragm velocity induced by applied voltage to the loudspeaker. In this paper, however, the diaphragm velocity of loudspeaker is induced by both external pressure and DIC applied voltage. Therefore, we need to investigate whether the disturbance-observer-type velocity estimator works well or not under this case.

The remainder of this paper is organized as follows. The concept and noise absorbing principle of the electroacoustic absorber using DIC technique is introduced. Additionally, sound absorption coefficients i.e. the performance evaluation index of the electroacoustic absorber is explained in section II. Then, the concept of disturbance-observer-type velocity estimator is presented along with the reason of choosing disturbance-observer-type velocity estimator over velocity sensor for DIC technique in section III. Next, design results of the disturbance-observer-type velocity estimator used in this paper and the corresponding experimental results are explained in section IV. Lastly, conclusion is discussed in section V.

2. ELECTROACOUSTIC ABSORBER

2.1 Dynamic Modeling of Loudspeaker

To begin with, the dynamic modeling of a general loudspeaker which is used as an actuator of electroacoustic absorber is presented. Note that the loudspeaker used in this paper is a moving-coil type loudspeaker including its enclosure. Moreover, certain assumptions are necessary for the loudspeaker's dynamic modeling which are as follow. Firstly, loudspeaker is modeled as a simple mass, damper, spring system, since the electroacoustic absorber in this paper considers only low frequency range noise, i.e. from 20Hz to 500Hz, therefore this assumption is valid. For the same reason, it can be assumed that the displacement of the loudspeaker diaphragm works as acoustic source of air nearby the diaphragm and determines its acoustic velocity. From this assumption, the acoustic velocity of air nearby the loudspeaker can be regarded to be equal with the diaphragm velocity itself.

The mechanical dynamics of the loudspeaker can be written as equation (1) based on Newton's second law.

$$SP(s) + BlI(s) = \left(Ms + R + \frac{K}{s} \right) V(s) \tag{1}$$

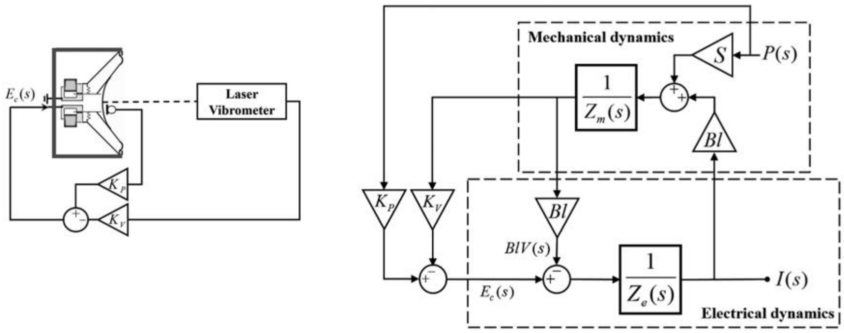

Figure 2 - Representation of an electroacoustic absorber; schematic (left) and block diagram (right)

Where, $s = jw$ is Laplace variable, S denotes the effective area of the loudspeaker, $P(s)$ represents acoustic pressure nearby the loudspeaker diaphragm, l is strength of the magnetic field, is length of the voice-coil in the loudspeaker, Bl is force factor, $I(s)$ is current circulating the voice-coil, $BlI(s)$ means Lorenz's force. Next, M, R, K represent effective mass, resistance, and stiffness including the effect of enclosure volume, respectively. Lastly, $V(s)$ denotes diaphragm velocity of the loudspeaker.

In the same way, the electrical dynamic of the loudspeaker can be written as equation (2).

$$E(s) - BlV(s) = \left(L_e s + R_e\right) I(s) \tag{2}$$

Where, $E(s)$ is the loudspeaker applied voltage, $BlV(s)$ is back-EMF, L_e and R_e are inductance and dc resistance of the voice-coil respectively. The above equations of mechanical and electrical dynamics can be rewritten as equation (3) using mechanical impedance $Z_m(s)$ and blocked impedance $Z_e(s)$ of the loudspeaker.

$$\begin{aligned} SP(s) + BlI(s) &= Z_m V(s) \\ E(s) - BlV(s) &= Z_e I(s) \end{aligned} \tag{3}$$

Fig. 1 shows the corresponding block diagram of equation (3). In general, since the external pressure can hardly affect the diaphragm velocity of the loudspeaker, therefore it is ignored in the loudspeaker dynamic modeling. In this paper, however, since the loudspeaker is largely effected by the external pressure due to the loudspeaker coupled with a duct, external pressure should be included in the dynamic modeling.

2.2 Sound Absorbing using Electroacoustic Absorber with Direct Impedance Control

Electroacoustic absorber is composed of a loudspeaker and a pair of pressure and velocity sensor. Fig. 2 shows the corresponding schematic and block diagram. Direct impedance controller forms DIC voltage $E_c(s)$ using pressure and velocity signals measured nearby the loudspeaker diaphragm as shown in equation (4).

$$E_c(s) = K_P P(s) - K_V V(s) \tag{4}$$

Where, K_P and K_V denote feedforward gain with respect to pressure and feedback gain with respect to velocity, respectively. Acoustic admittance of the loudspeaker controlled by above DIC voltage $E_c(s)$ can be represented through simple arithmetic using equation (3) and (4) as shown below.

$$\frac{V(s)}{P(s)} = \frac{SZ_e + BlK_P}{Z_m Z_e + \left(Bl\right)^2 + BlK_V} \tag{5}$$

Fig.3. is the simulation result of normalized acoustic admittance for a general loudspeaker and a loudspeaker under DIC technique, i.e. electroacoustic absorber. Note that the magnitude of the result

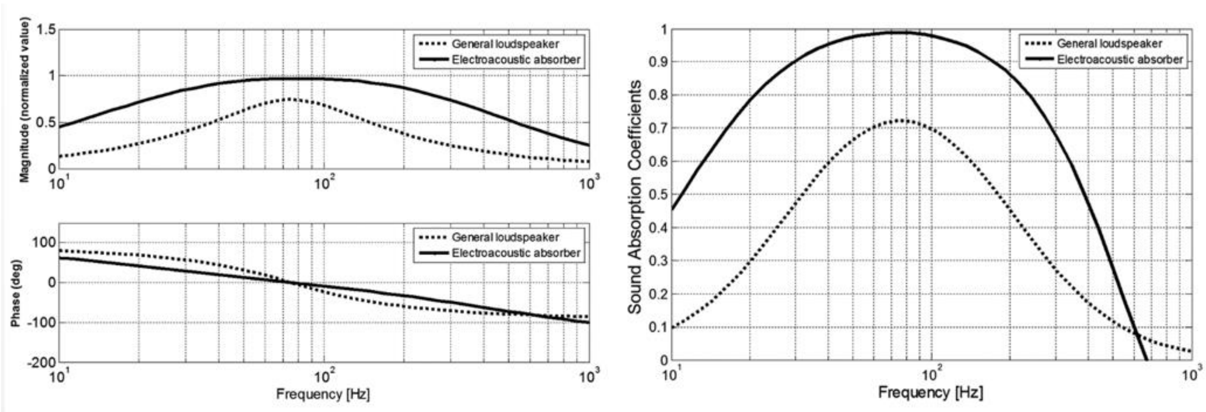

Figure 3 - Comparison of simulation results between a general loudspeaker and an electroacoustic absorber; Normalized acoustic admittance (left) and Sound absorption coefficient (right)

are normalized by air's characteristic impedance so that we can check how well acoustic impedance of the loudspeaker is matched up with that of air. This result shows that the acoustic admittance of electroacoustic absorber is affected by both pressure feedforward control and negative velocity feedback control compared with that of the general loudspeaker. Due to these effects, an electroacoustic absorber can meet acoustic impedance matching with air over a wider frequency range than a general loudspeaker. The corresponding sound absorption coefficient can be calculated and the result is shown in Fig. 3.

2.3 Performance Index of Electroacoustic Absorber: Sound Absorption Coefficient

Sound absorption coefficient i.e. the performance evaluation index of electroacoustic absorber is measured by the following method. Measurement of sound absorption coefficients follows ISO 10534-2 standard [13] and the corresponding schematic of the experimental setup is shown in Fig. 4. Note that the loudspeaker used for actuator is referred to as primary loudspeaker, whereas the loudspeaker used for noise source is referred to as secondary loudspeaker. Here, it is assumed that the noise propagates as plane wave from the secondary loudspeaker to the primary loudspeaker. Sound absorption coefficients can be calculated as equation (6).

$$\alpha = 1 - |\gamma|^2 \tag{6}$$

Where, γ is reflection coefficients obtained through equation (7).

$$\gamma = \frac{H_{12} - H_I}{H_R - H_{12}} \exp(2jkx_1) \tag{7}$$

Where, H_{12} is the transfer function between pressure data P_1, P_2 measured at distance x_1, x_2 far from the primary loudspeaker. Next, $H_I = \exp(-jk(x_1 - x_2))$, $H_R = \exp(jk(x_1 - x_2))$ and k means wave number.

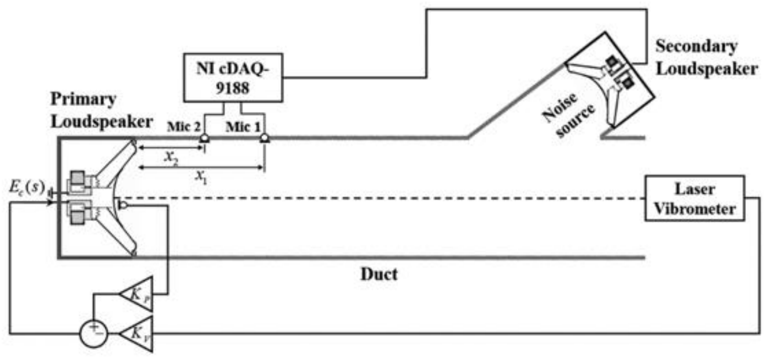

Figure 4 - Experimental setup for the measurement of the sound absorption coefficient

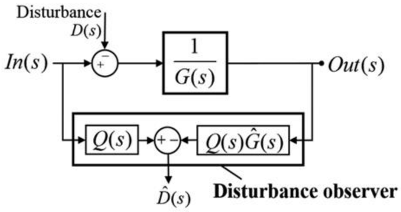

Figure 5 - Block diagram of disturbance observer

3. DISTURBANCE-OBSERVER-TYPE VELOCITY ESTIMATOR

3.1 Disturbance-Observer-Type Velocity Estimator

Originally, the disturbance observer is primarily applied to the actuator used for the motion control such as robot manipulator or motor as illustrated in Fig. 5. Its objective is to estimate disturbance occurring in the system such as external force or torque ripple.

Yaoyu Li extends this disturbance observer concept to the loudspeaker and introduces disturbance-observer-type velocity estimator for the first time [12]. The diaphragm velocity can be estimated through this velocity estimator, considering back-EMF signal containing actual diaphragm velocity signal as a disturbance occurring in the system. Since the disturbance-observer-type velocity estimator considers only a blocked impedance except mechanical impedance of the loudspeaker as a system, it can have a strength of robust diaphragm velocity estimation capability even though the acoustic load is changed.

3.2 Electroacoustic Absorber using Disturbance-Observer-Type Velocity Estimator

In the case when the diaphragm velocity is estimated by applying disturbance-observer-type velocity estimator to electroacoustic absorber, the estimated velocity $\hat{V}(s)$ of primary loudspeaker in Fig. 4 is estimated through equation (8). The corresponding block diagram is shown in Fig. 6.

$$\begin{aligned}\hat{V}(s) &= \frac{1}{Bl}\left\{E(s)Q(s)-\hat{Z}_e(s)I(s)Q(s)\right\} \\ &= \frac{1}{Bl}\left\{E(s)Q(s)-\hat{Z}_e(s)\left(\frac{E(s)-BlV(s)}{Z_e(s)}\right)Q(s)\right\} = V(s)Q(s)\end{aligned} \tag{8}$$

From above formula, the followings are noticed; firstly, it is possible to estimate the diaphragm velocity $\hat{V}(s)$ of primary loudspeaker because the actual velocity signal is contained in current signal $I(s)$ circulating in voice-coil as form of back-EMF signal. Secondly, precise identification of the blocked impedance $\hat{Z}_e(s)$ of the primary loudspeaker is necessary for the trustworthy velocity estimation. It is because the reciprocal form of the actual blocked impedance $Z_e(s)$ included in current

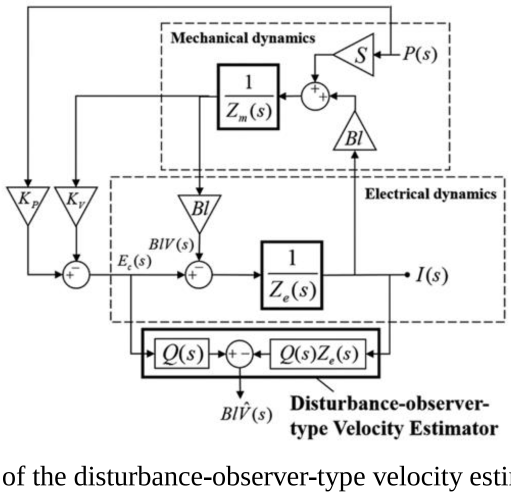

Figure 6 - Block diagram of the disturbance-observer-type velocity estimator used for the velocity estimation of the electroacoustic absorber's diaphragm velocity

signal should be nullified by the identified blocked impedance in disturbance-observer-type velocity estimator. Lastly, since the effect of Q-filter is still remained in the estimated velocity after disturbance-observer-type velocity estimator, Q-filter design is important factor for the velocity estimation performance as well.

4. EXPERIMENTAL RESULTS

4.1 Experimental Setup

Peerless 830860 5-1/4" PPB Cone HDS Woofer is used as a loudspeaker actuator of electrostatic absorber. The length and diameter of the duct are 1.93[m] and 0.13[m], respectively.

The schematic of the experiment setup is already shown in Fig. 4. In this paper, the loudspeaker used as an electroacoustic absorber is referred to as primary loudspeaker, while the other loudspeaker located at the opposite end of the duct is referred to as secondary loudspeaker which functions as a noise source. For checking acoustic admittance of the loudspeaker, pressure and velocity signals are measured by B&K type 4192 1/2'' pressure-field microphone in the duct and ESV-200 laser vibrometer installed outside of the duct, respectively. Note that the ESV-200 is commercial laser vibrometer, which was developed in collaboration with the EM4SYS Inc. Its detailed description is included in appendix. The measured velocity signal using the laser vibrometer is considered as reference signal to estimated velocity signal $\hat{V}(s)$ using disturbance-observer-type velocity estimator. NI cDAQ-9188 module and LabVIEW are used for data acquisition. The Disturbance-observer-type velocity estimator is realized in LabVIEW software with NI PCI-6215 DAQ board. Two pressure measuring locations for sound absorption coefficient, are determined as x1= 0.64[m] and x2 =0.39[m]. These pressure data are measured by B&K type 4935 1/4'' array microphone.

4.2 Design of the Disturbance-observer-type Velocity Estimator

As mentioned in the previous section, estimated blocked impedance $Z_e(s)$ and Q-filter of disturbance-observer-type velocity estimator are very important factors in determining the velocity estimation performance. The design process and results of these factors are as follows.

Blocked impedance of the loudspeaker can be obtained through transfer function measurement using current signal $I(s)$ and total applied voltage, i.e., $E(s)-BlV(s)$ in electrical part. In this way, the blocked impedance $\hat{Z}_e(s)$ is identified and Q-filter is designed.

4.3 Robust Velocity Estimation Performance of Disturbance-Observer -Type Velocity Estimator to acoustic load change of the Primary Loudspeaker

A robust velocity estimation performance to acoustic load change of disturbance-observer-type velocity estimator as previous designed is confirmed experimentally. That is, we compared the velocity frequency response versus applied voltage to the loudspeaker of an open-air loudspeaker with that of a loudspeaker coupled with a duct as shown in Fig. 7. Note that impedance tube has the role of

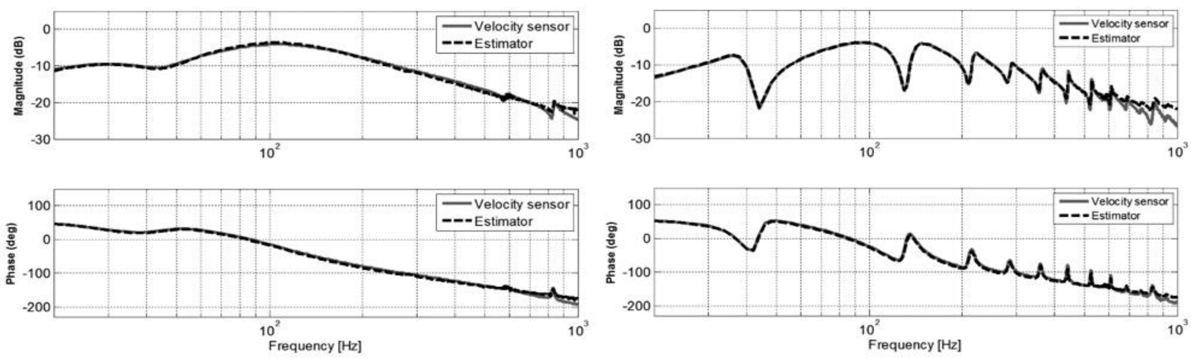

Figure 7 - Diaphragm velocity frequency response versus applied voltage to the primary loudspeaker; an open-air loudspeaker (left) and a loudspeaker coupled with a duct (right)

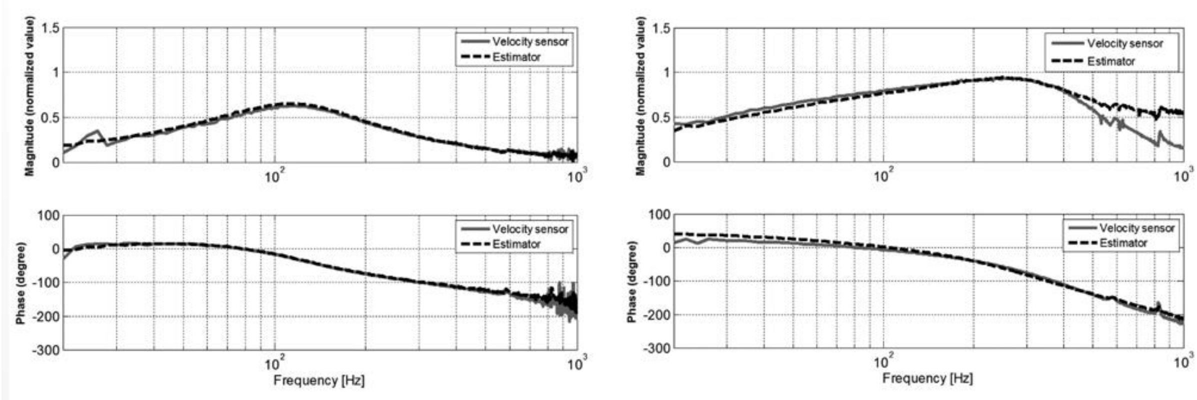

Figure 8 – Normalized acoustic admittance of the primary loudspeaker; Primary loudspeaker's diaphragm velocity induced by only external pressure (left) and Primary loudspeaker's diaphragm velocity induced by both external pressure and an applied DIC voltage (right)

changing acoustic load of the loudspeaker.

Comparing these experiment results, both cases have shown satisfactory velocity estimation performance below 600Hz frequency range. In particular, despite the case that acoustic load of the loudspeaker is changed by the impedance tube, disturbance-observer-type velocity estimator has still good velocity estimation performance. This result can be experimental demonstration of its robust velocity estimation performance to acoustic load change.

4.4 Normalized Acoustic Admittance Measurement of the Cases Examined

Here, we want to verify the velocity estimation performance of the previous designed disturbance-observer-type velocity estimator on following two case; in the first case, the diaphragm velocity of the primary loudspeaker is induced by only external pressure from secondary loudspeaker. While, in the second case, the same diaphragm velocity is induced by not only external pressure from secondary loudspeaker but also DIC voltage $E_c(s)$ applied to the primary loudspeaker. For these two verifications, we measure normalized acoustic admittance corresponding each case and represent the former case's result in Fig. 8 (left) and the latter case's result in Fig. 8 (right). By representing normalized acoustic admittance as the result, not only diaphragm velocity estimation performance but also how well the acoustic impedance of the loudspeaker is matched up with that of air can be more clearly figured out. From Fig. 8, one can notice the following findings.

Firstly, unlike in Fig. 8 (left), acoustic impedance matching phenomenon of the primary loudspeaker with air is discovered around its resonance frequency range due to DIC voltage $E_c(s)$ in the case of Fig. 8 (right). Secondly, both cases have good velocity estimation performance at the frequency below 400Hz frequency range. Since the interested frequency of the electroacoustic absorber in this paper is below 500Hz, this performance can be considered good enough to use. Thirdly, velocity estimation performance of Fig. 8 (left) is better than that of Fig. 8 (right) at above 400Hz frequency range. The reason for this behavior can be explained as follow. In equation (8) in section III, since DIC voltage $E_c(s)=0$ for the case of Fig. 8 (left), current signal $I(s)$ contains only back-EMF signal. Accordingly, velocity estimation error generated in disturbance-observer-type velocity estimator is hardly occurred. As a result, a satisfactory velocity estimation performance can be obtained over all measured frequencies. Lastly, from Fig. 8 (right), if we use disturbance-observer-type velocity estimator designed in this paper rather than velocity sensor for DIC technique, the better performance in terms of impedance matching with air is obtained above 400Hz frequency range. This result can also be explained using equation (8). In Fig. 8 (right), current signal $I(s)$ contains not only back-EMF signal but also DIC voltage $E_c(s)$. Therefore, the velocity estimation error is occurred in the process of nullifying the DIC voltage $E_c(s)$ in the disturbance-observer-type velocity estimator. This error worsen diaphragm velocity estimation performance of the primary loudspeaker, but it has a positive effect in terms of acoustic impedance matching of the primary loudspeaker.

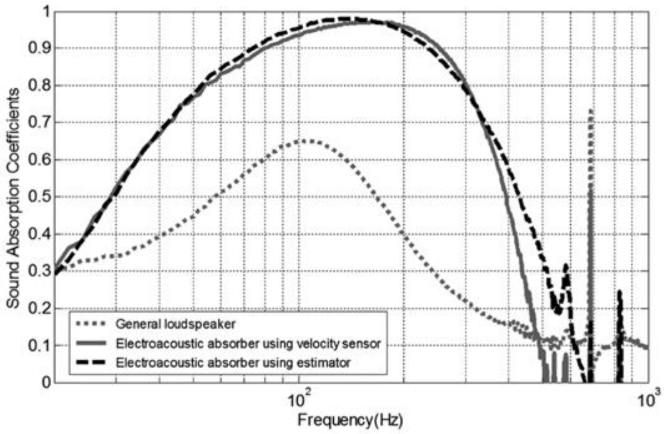

Figure 9 – Measured sound absorption coefficients of the three cases examined

4.5 Sound Absorption Coefficient of Electroacoustic Absorber using Disturbance -Observer-Type Velocity Estimator

Based on the previous experimental results, we verified the applicability of a disturbance-observer-type velocity estimator to an electroacoustic absorber through measuring sound absorption coefficient. The measurement of sound absorption coefficients is conducted according to the content previously mentioned in section II. Fig. 9 shows measured sound absorption coefficients for a general loudspeaker and an electroacoustic absorber using velocity sensor or disturbance-observer-type velocity estimator. From this figure, three following observations can be concluded.

Firstly, electroacoustic absorber has more improved sound absorbing performance than a general loudspeaker. This is followed by the fact that how well acoustic impedance of the primary loudspeaker is matched with that of air as mentioned previously. This result is in accordance with the first finding that was noticed from Fig. 8. Secondly, sound absorption coefficients measurement result obtained using disturbance-observer-type velocity estimator is almost same to the one obtained using velocity sensor at the frequency below 350Hz frequency range. This is in accordance with the second finding that was noticed from Fig. 8.

Lastly, when using a disturbance-observer-type velocity estimator, the sound absorbing performance is slightly improved than using velocity sensor within the frequency from about 350Hz to 700Hz. This phenomena is already mentioned in the last finding that was noticed from Fig. 8.

5. CONCLUSION

In this paper, electroacoustic absorber using disturbance-observer-type velocity estimator that is originally studied to estimate the diaphragm velocity of the moving-coil loudspeaker is proposed. In the process of verifying proposed contents in this paper, the following four contributions are summarized. Firstly, the verification for a robust velocity estimation performance of disturbance-observer-type velocity estimator to acoustic loud change of the loudspeaker is demonstrated experimentally. Secondly, a satisfactory velocity estimation performance of disturbance-observer-type velocity estimator is investigated even in the case where the diaphragm velocity is induced simultaneously by each or both DIC voltage $E_c(s)$ and external pressure. Thirdly we confirmed the applicability of a disturbance-observer-type velocity estimator to electroacoustic absorber. Lastly, an electroacoustic absorber using the disturbance-observer-type velocity estimator designed in this paper has an improved sound absorbing performance as compared with that using velocity sensor within the frequency from about 350Hz-700Hz.

Through this paper, we showed the possibility of applying disturbance-observer-type velocity estimator to an electroacoustic absorber and, by extension a solution for the cost and construction problem of electroacoustic absorber array system is presented. We have a plan for future work relevant to noise control for real acoustically large space using array systems of electroacoustic absorbers studied in this paper.

6. APPENDIX

ESV-200 is commercial laser vibrometer developed in collaboration with the EM4SYS Inc. and this laboratory. ESV-200 having features as a noncontact vibration sensor can be used for not only modal analysis but ODS analysis. Excepting this study, currently it is used in various research fields. The corresponding technical description is contained in paper [14].

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