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Automatic measurement of electro-mechanical parameters of low-frequency loudspeakers

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Abstract

This work is to present a system for automatic measurement of low-frequency loudspeaker electro-mechanical parameters. The proposed system is of virtual characteristics, consisting of a personal computer, dynamic data acquisition, displacement laser sensor, and voltage and current probes. A computer programming was coded to control sine-sweep generation that was fed to a loudspeaker and to process electrical signals from a displacement laser sensor and electric probes. The analysis was done in frequency domain to yield loudspeaker parameters, such as mechanical quality factor (Q_{MS}), total quality factor (Q_{TS}), electrical quality factor (Q_{ES}), force factor (*Bl*), voice coil's electrical resistance (R_E), and mechanical mass (M_{MS}), resistance (R_{MS}), compliance (C_{MS}) and stiffness (K_{MS}). The constructed system was tested for measuring the parameters of 8-inch and 12-inch loudspeakers, and results were compared to that utilizing a traditional mass-adding technique. It was found that the automated system was capable to complete the measurement in the frequency ranges of 20 Hz – 220 Hz within 3.34 minutes, much faster than that using the traditional approach that normally consumed time of 30 - 45 minutes. Most of the measured parameters from both the automated system and the traditional approach were similar, but some were quite different due to successive calculation and cumulative error. However, a further work could be done to reduce such the error.

Keywords: Loudspeaker parameters, Automatic measurement system, Displacement laser sensor, Diaphragm velocity, Sine sweep

1. Introduction

Measurement of loudspeaker parameters is importance since it has been used by manufacturers for controlling the sound quality of their loudspeakers. Loudspeaker parameters are also essential information for designing a suitable loudspeaker box so that it produces good quality sound. Loudspeaker parameters measurement could be done by using several methods in both time and frequency domains [1-5]. Since computer is now inexpensive, it has been used for loudspeaker parameter measurement, such as in [6] that utilized the traditional mass-adding technique that capable of yielding the loudspeaker parameter with high accuracy. However, such technique was time consuming, because the impedance curves were repeatedly obtained for different additional masses added to the diaphragm and also, the measurement process was not automatic. An approach as in [4], that employed a laser velocity transducer and a stand-alone analyzer, was possible for automatic measurement of the parameters. However, such the laser velocity transducer and the ready-to-use analyzer are quite costly.

This study was a research and development to construct a system of virtual characteristics for performing an automatically measurement of electro-mechanical parameters of low-frequency loudspeakers. The proposed system consisted of a personal computer, a dynamic data acquisition, a displacement laser sensor, and electrical current and voltage probes. A program was coded to control sine sweep generation, to read electrical signals from the displacement sensor and electric probes, and then to analyze the signals in frequency domain, as well as perform calculation of the loudspeaker parameters. The run-time tests for the parameter measurement would display rapidity of the developed system. Result comparison of 8-inch and 12-inch loudspeaker parameter measurement between that from the developed system and from using the traditional mass-adding approach would show efficiency.

2. Loudspeaker structure and equivalent circuit model

2.1 Loudspeaker structures

Structure of direct-radiator loudspeaker is displayed in Figure 1(a). It has three main components, 1) magnet and voice coil, 2) spider and surround, and 3) diaphragm and dust cap. Magnetic flux is always induced when there is electric ac current flowing in the voice coil. This magnetic flux interacts with the permanent magnet to create a driving force that causes the voice coil, dust cap and diaphragm to vibrate and then radiate acoustical energy into air medium. The

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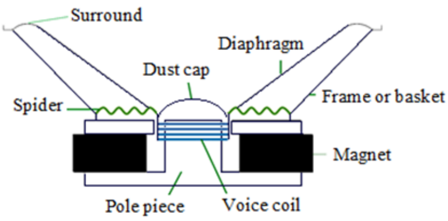
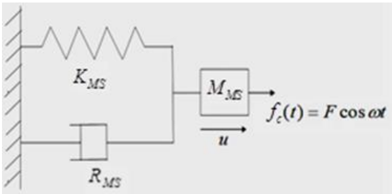
vibration is of harmonic motion and can be displayed as a spring-mass-damper system as shown in Figure 1(b) where f_c is driven force causing the vibration, K_{MS} is mechanical stiffness, R_{MS} is mechanical resistance, and M_{MS} is mechanical mass including air-loaded mass.



(a)



(b)

Figure 1 (a) Loudspeaker structure and (b) mass-spring system

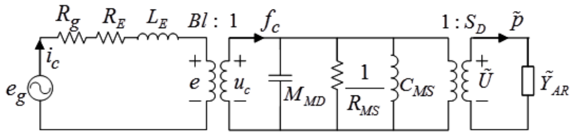
Analysis of harmonic motion can be done in frequency domain. With the definition of mechanical impedance that is the ratio of complex driven force $\tilde{f}_c$ () to the resulted complex velocity ($\tilde{u}_c$), mechanical impedance ($\tilde{Z}_m$) of the loudspeaker is as equation (1), where $C_{MS}=1/K_{MS}$ and $\omega = 2\pi f$. Resonance frequency (f_s) can be obtained as the frequency causing the imaginary part of impedance to be zero and it is as equation (2).

$$\tilde{Z}_m = \frac{\tilde{f}_c}{\tilde{u}} = R_{MS} + j\left(\omega M_{MS} - \frac{1}{\omega C_{MS}}\right) \tag{1}$$

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{C_{MS}M_{MS}}} = \frac{1}{2\pi}\sqrt{\frac{K_{MS}}{M_{MS}}} \tag{2}$$

2.2 Loudspeaker circuit model

With mobility analogous, a circuit model of a loudspeaker that displays coupling between electrical, mechanical, and acoustical system is shown in Figure 2(a), where R_g is source's inner electrical resistance, L_E is voice coil inductance, M_{MD} is mechanical mass of voice coil, dust cap and diaphragm, and $\tilde{Y}_{AR}$ is acoustical admittance. For convenience, all parts in acoustical and mechanical sides are reflected to the electrical side as displayed in Figure 2(b). When considered at low frequency range, reactance from the inductance L_E is small so that it can be neglected. Hence, a simplified circuit model for a low-frequency loudspeaker is allowed as in Figure 3, where e_g is a source voltage and i_c is electric current in the voice coil.



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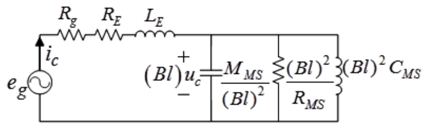


(b)

Figure 2 (a) A loudspeaker circuit model and (b) that when acoustical and mechanical parts were reflected to the electrical side

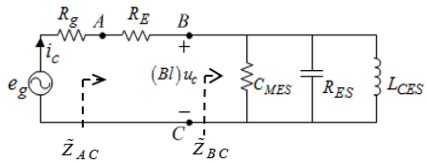


Figure 3 A simplified circuit model of low-frequency loudspeaker

2.3 Impedance and quality factor

With an assumption that R_g in simplified circuit is very small ($R_g \sim 0$), impedance $\tilde{Z}_{AC}$ can be derived as equation (3) and relations $\tilde{u}_c/\tilde{\imath}_c$ and $\tilde{u}_c/\tilde{e}_g$ can be obtained as equation (4) and (5), where $C_{MES} = M_{MS}/(Bl)^2$, $R_{ES} = (Bl)^2/R_{MS}$, and $L_{CES} = (Bl)^2/C_{MS}$.

$$\tilde{Z}_{AC} = R_E + R_{ES}\left(\frac{L_{CES}/R_{ES}}{L_{CES}/R_{ES} + j\omega C_{MES}L_{CES} + \frac{1}{j\omega}}\right) \tag{3}$$

$$\frac{\tilde{u}_c}{\tilde{i}_c} = \frac{\tilde{Z}_{BC}}{Bl} \tag{4}$$

$$\frac{\tilde{u}_c}{\tilde{e}_g} = \frac{1}{Bl}\frac{\tilde{Z}_{BC}}{\tilde{Z}_{AC}} \tag{5}$$

Mechanical quality factor (Q_{MS}) is obtained from a plot of impedance curve. The Q_{MS} can also be derived as equation (6) and then as equation (7), where $\omega_s = 2\pi f_s$ is a resonant frequency in radian unit.

$$Q_{MS} = \omega_s/(\omega_u - \omega_l) = \omega_s M_{MS}/R_{MS} \tag{6}$$

$$Q_{MS} = \omega_s\left(\frac{M_{MS}}{(Bl)^2}\right)\left(\frac{(Bl)^2}{R_{MS}}\right) = \omega_s C_{MES}R_{ES} \tag{7}$$

In addition, the impedance function $\tilde{Z}_{AC}$ as equation (3) can be rewritten in term of Q_{MS} and ω_s as equation (8). Similarly, the impedance $\tilde{Z}_{BC}$ is rewritten as equation (9).

$$\tilde{Z}_{AC}(j\omega) = R_E + R_{ES}\left(\frac{j\omega_s\omega / Q_{MS}}{-\omega^2 + j\omega_s\omega / Q_{MS} + \omega_s^2}\right) \quad (8)$$

$$\tilde{Z}_{BC}(j\omega) = R_{ES}\left(\frac{j\omega_s\omega / Q_{MS}}{-\omega^2 + j\omega_s\omega / Q_{MS} + \omega_s^2}\right) \quad (9)$$

Hence, at the resonant frequency ω_s, it yields the following relation.

$$\left|\frac{\tilde{Z}_{AC}(j\omega)}{\tilde{Z}_{BC}(j\omega)}\right|_{\omega=\omega_s} = \frac{R_E + R_{ES}}{R_{ES}} \quad (10)$$

Let Q_{ES} is the quality factor that only resistant of electrical parts is considered. Then Q_{ES} can be defined as equation (11) and the ratio between Q_{MS} and Q_{ES} is as equation (15).

$$Q_{ES} = \omega_s C_{MES} R_E \quad (11)$$

$$\frac{Q_{MS}}{Q_{ES}} = \frac{R_{ES}}{R_E} \quad (12)$$

Total quality factor (Q_{TS}) is the quality factor that all circuit resistances in Figure 3 are considered. It can be derived as equation (13).

$$Q_{TS} = \omega_s C_{MES} \frac{R_{ES} R_E}{\left|\tilde{Z}_{AB}\right|_{\omega_s}} \quad (13)$$

From equation (11) and (12), the Q_{TS} can be rearranged as equation (14).

$$Q_{ES} = \frac{Q_{MS} Q_{TS}}{Q_{MS} - Q_{TS}} \quad (14)$$

3. Calculation of electro-mechanical parameters of loudspeakers

3.1 Bl and R_E

Calculation for *Bl* can be derived from equation (5) by considering at the resonant frequency ω_s and from equation (10), (12) and (14). It yields *Bl* as equation (15). Similarly from equation (7) and (13), R_E is obtained as equation (16).

$$Bl = \left(\left|\frac{\tilde{u}_c}{\tilde{e}_g}\right|^{-1}\left|\frac{\tilde{Z}_{BC}}{\tilde{Z}_{AC}}\right|\right)_{\omega_s} = \left(\left|\frac{\tilde{u}_c}{\tilde{e}_g}\right|_{\omega_s}\right)^{-1}\left(\frac{R_{ES}}{R_E + R_{ES}}\right)$$

$$Bl = \left(\left|\frac{\tilde{u}_c}{\tilde{e}_g}\right|_{\omega_s}\right)^{-1}\left(1 - \frac{Q_{TS}}{Q_{MS}}\right) \quad (15)$$

$$R_E = \frac{\left|\tilde{u}_c / \tilde{i}_c\right|_{\omega_s}}{\left|\tilde{u}_c / \tilde{e}_g\right|_{\omega_s}} \frac{Q_{TS}}{Q_{MS}} = \left|\frac{\tilde{e}_g}{\tilde{i}_c}\right|_{\omega_s} \frac{Q_{TS}}{Q_{MS}} \quad (16)$$

3.2 Q_{ES}, M_{MS}, R_{MS}, and C_{MS}

Parameters Q_{ES}, M_{MS} and R_{MS} can be calculated from equation (14), (11) and (6), as following:

$$Q_{ES} = \frac{Q_{MS} Q_{TS}}{Q_{MS} - Q_{TS}}, \quad M_{MS} = (Bl)^2 \frac{Q_{ES}}{\omega_s R_E}, \quad R_{MS} = \frac{\omega_s M_{MS}}{Q_{MS}}$$

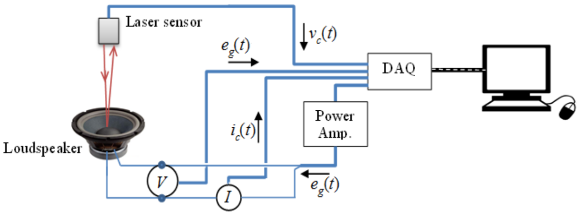
Parameter C_{MS} is obtained from the relation

$\omega_s^2 = 1/(M_{MS} C_{MS})$, then $C_{MS} = \dfrac{1}{\omega_s^2 M_{MS}}$.

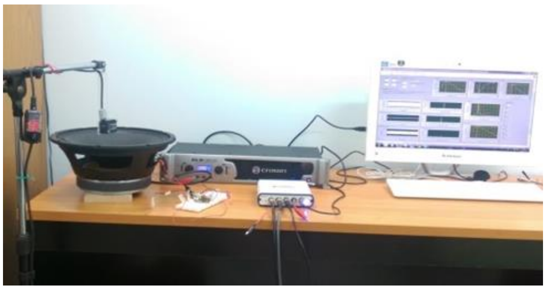
4. Proposed system for automatic loudspeaker parameter measurement

As one might already noticed, the calculations of electro-mechanical parameters of loudspeaker were originated from three parameters; the resonant frequency ω_s, mechanical quality factor Q_{MS}, and the total quality factor Q_{TS}. These three parameters had to be obtained via an experiment. The ω_s and Q_{MS} could be analyzed from frequency response of mechanical impedance, which was directly proportional to the $|\tilde{u}_c(f)/\tilde{\imath}_c(f)|$, and the Q_{TS} could be obtained from the frequency response of $|\tilde{u}_c(f)/\tilde{e}_g(f)|$. Hence, a function of the proposed system was to probe the loudspeaker diaphragm velocity $\tilde{u}_c$, and electrical current $\tilde{\imath}_c$ and voltage $\tilde{e}_g$ driven to the loudspeaker as functions of frequency (*f*). Other functions were to control measurement process and perform signal processing.

The proposed system was of virtual characteristics, consisting of a personal computer, dynamic data acquisition (DAQ), displacement laser sensor, and voltage and current probes. The schematic diagram and instrument setup of the proposed system is displayed in Figure 4. A LabVIEW programming was coded to control sine-sweep generation in a low frequency range of 20 Hz – 220 Hz that was fed to a tested loudspeaker via an amplifier, and to collect and analyze electrical signals from the displacement laser sensor and voltage and current probes. The analysis was done in frequency domain by applying Fourier transform to the measured signals to yield the complex diaphragm velocity $\tilde{u}_c$, complex driven voltage $\tilde{e}_g$, and complex driven current $\tilde{\imath}_c$ as functions of frequency (*f*). Remarked that the displacement laser sensor measured only the displacement, therefore amplitude of the complex diaphragm velocity was indirectly obtained via multiplication between the frequency and the displacement amplitude in the frequency domain, $|\tilde{u}_c(f)| = 2\pi f|\tilde{x}_c(f)$, where $\tilde{x}_c(f)$ = Fourier transform of $x_c(t)$, $x_c(t) = S \cdot v_c(t)$, and *S* = sensitivity of displacement laser sensor. A flowchart of the program developed for controlling, processing, and performing computation in the automated system is displayed in Figure 5.



(a)



(b)

Figure 4 (a) Schematic diagram and (b) equipment setup of automated system for measuring loudspeaker electro-mechanical parameters

As shown in Figure 5, after spectrum curves of $|\tilde{u}_c/\tilde{\imath}_c|$and $|\tilde{u}_c/\tilde{e}_g|$ were created, the resonant frequency (f_s) was estimated as the frequency that yielded the maximum value of $|\tilde{u}_c/\tilde{\imath}_c|$. The Q_{MS} and Q_{TS} were obtained, as the relation in equation (6) or $Q = f_s/\Delta f$ and $\Delta f = (f_u - f_1)$, from the curve of $|\tilde{u}_c/\tilde{\imath}_c|$ and $|\tilde{u}_c/\tilde{e}_g|$, respectively. After that, the parameters Bl, R_E , Q_{ES} , M_{MS} and C_{MS} were computed by using the equations previously mentioned. Figure 6 displays the system monitor for controlling the frequency range and values in the measurement and displaying the result of the measured electro-mechanical parameters.

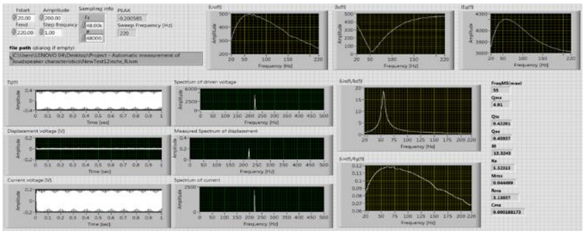


Figure 6 System monitor for controlling the range and values of frequency sweep and displaying the obtained frequency responses and the measured electro-mechanical parameters

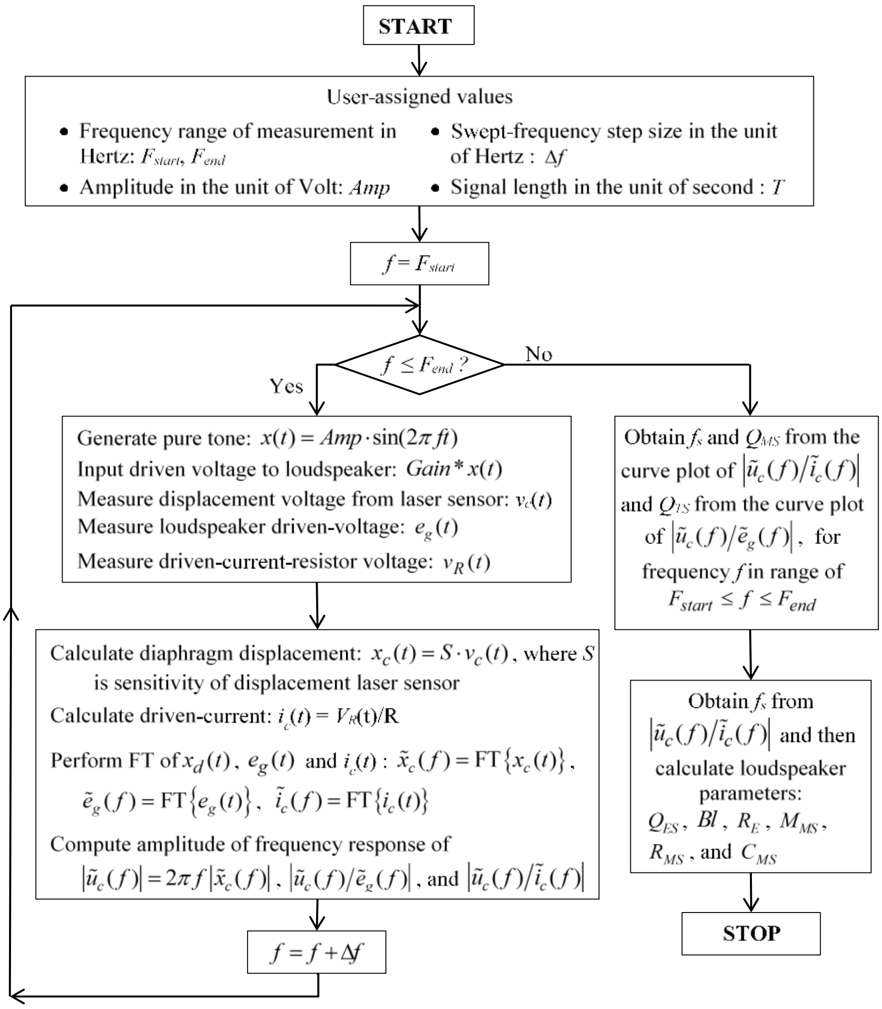


Figure 5 Flowchart of control, measurement and calculation process in the automated system

Table 1 Electro-mechanical parameters of tested 8-inch and 12-inch loudspeakers

Loudspeaker parameters	8-inch. Loudspeaker		12-inch. Loudspeaker	
	Measured with mass-adding technique	Measured with automated system	Measured with mass-adding technique	Measured with automated system
f_s	67.49 Hz	67	54.73 Hz	55 Hz
Q_{MS}	4.34	5.02	3.96	4.9
Q_{TS}	0.27	0.29	0.42	0.42
Bl	13.61 N/A	11.11 N/A	15.36 N/A	13.32 N/A
R_E	5.0 Ω	4.6 Ω	5.6 Ω	5.3 Ω
Q_{ES}	0.28	0.31	0.47	0.46
M_{MS}	24.8 g	19.6 g	57.07 g	44.50 g
R_{MS}	2.42 N.s/m	1.65 N.s/m	4.85 N.s/m	3.14 N.s/m
C_{MS}	2.24 x 10^{-4} m/N	2.88 x 10^{-4} m/N	1.48 x 10^{-4} m/N	1.88 x 10^{-4} m/N
Run time	45 minutes	3.34 minutes	45 minutes	3.34 minutes

5. Experiment, result and discussion

The proposed system was tested to measure electro-mechanical parameters of 8-inch and 12-inch loudspeakers. The results were compared to that using a traditional mass-adding technique and were shown in Table 1. It was seen that the automated system was capable to complete the measurement in the frequency ranges of 20 Hz – 220 Hz within 3.34 minutes, much faster than that using the traditional approach that normally consumed time of 30-45 minutes [5]. Most parameters were similar, but some were much of difference. This is due to successive calculation causing cumulative error. This error could possibly be reduced, if further works, such as calibration for exact sensitivity of displacement laser sensor, would be done.

6. Conclusions

A system for automatically measuring electro-mechanical parameters of a low-frequency loudspeaker was developed. By applying displacement laser sensor to measure the diaphragm velocity, using electric probes to measure driven voltage and current, and coding a program to control the system, process signals in frequency domain, and perform computation, the electro-mechanical parameters such as f_s, Q_{MS} , Q_{TS} , Bl, R_E , Q_{ES} , M_{MS} and M_{MS} were obtained. The system was tested for measuring the parameters of 8-inch and 12-inch loudspeakers. The results compared to that using a traditional approach were very satisfied, since most parameter values were similar and accomplished in much less time.

7. References

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