Nonlinearity compensation of low-frequency loudspeaker response using internal model controller

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Abstract

This paper presents the nonlinearity compensation of low-frequency loudspeaker response. The loudspeaker is dedicated to measuring the response of Electret Condenser Microphone which operated in the arterial pulse region. The nonlinearity of loudspeaker has several problems which cause the nonlinearity behaviour consists of the back electromagnetic field, spring, mass of cone and inductance. Nonlinearity compensation is done using the Internal Model Controller with voltage feedback linearization. Several signal tests consist of step, impulse and sine wave signal are examined on different frequencies to validate the effectiveness of the design. The result showed that the Internal Mode Controller can achieve the high-speed response with a small error value.

Keywords*: electret condenser microphone, internal model controller, loudspeaker, nonlinearity*

1. Introduction

A loudspeaker can be used as an actuator in a frequency response test. Previous work utilized the loudspeaker to test the response of an Electret Condenser Microphone (ECM) intended as an arterial pulse sensor [1] working at the frequency range of 0-10 Hz [2-3]. The ECM senses the mechanical motion of the loudspeaker through a soft silicon rubber as a mechanical coupling. This loudspeaker imitated the arterial pulse signal and soft silicon rubber as a medium to deliver mechanical transfer ideally between the loudspeaker and ECM. The loudspeaker converts audio frequency signals into the sound waves by vibrating diaphragm. In an ideal condition, the vibrating diaphragm of the loudspeaker can correlate with the input signal. Unfortunately, the conversion has not perfect caused by the nonlinearity of loudspeaker components [4-8]. The nonlinearity of loudspeakers is produced by nonlinear component consisting back EMF (electromagnetic field), spring, the mass of cone and inductance. The loudspeaker output signal is different from the input so that it indicates a nonlinearity on the loudspeaker. So, the main challenge is to make a compensator to reduce the nonlinearity of the loudspeaker. In terms of eliminating the nonlinearity of loudspeakers and reducing distortion, new controllers are needed such as automatic compensation [9], Fractional Order [10-12], Internal Model Controller [13-16]. Internal Model Controller (IMC) is one of the compensators that can be used because it has advantages in terms of speed and accuracy of the controller.

This research contributes to the nonlinearity compensation of low-frequency loudspeaker using an Internal Model Controller dedicated to measuring the response of ECM which operated in the range of arterial pulse. At first, the loudspeaker response and the nonlinearity compensation was determined. From this fact of nonlinearity loudspeaker and novel controller were designed. The behaviour of this system was investigated using a simulation and modelling using Klippel® and Matlab®. Finally, the result of nonlinearity compensation on the low-frequency loudspeaker using the internal mode controller is presented.

2. Method

In this section, we describe the control system method for the nonlinearity compensation of loudspeaker based on the electromechanical parameter, acceleration, force

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factor, stiffness suspension and coil inductance. In addition, the internal model control is presented. The overall step of the method is described in Figure 1.

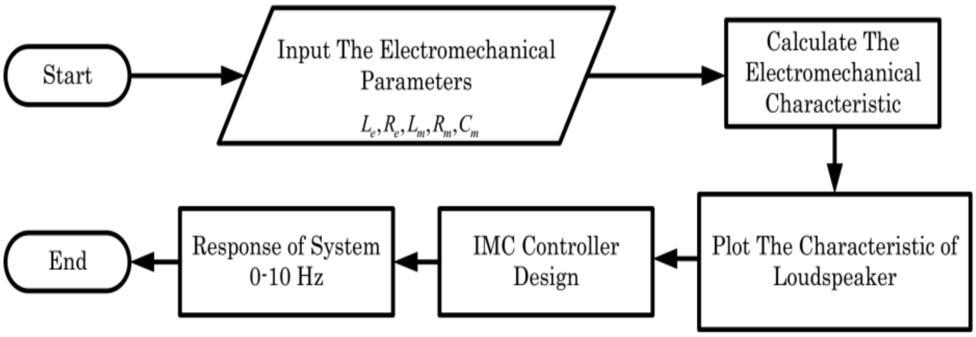

Figure 1. IMC design

The electromechanical parameters are given in subsection 2.1. In this subsection, the mathematical analysis of electromechanical also described in alongside with the plot of loudspeaker characteristic. The IMC controller design presents in subsection 2.2 and the response of system presents in result and discussion in section 4.

2.1. Determination of Response and Nonlinearity of Loudspeaker

The response and the nonlinearity of the loudspeaker were determined by analyzing its parameters in the datasheet. The data consists of the electromechanical parameters which are the electrical component and mechanical component. The loudspeaker has nonlinearity characteristic because of the nonlinear component of the loudspeaker. The component consists of spring, back EMF, the mass of cone and inductance. The response was modelled using Thiele & Small parameters describing the nonlinearity of the loudspeaker which the electrical and mechanical behaviour of the loudspeaker is represented by the RLC component [17-18]. The electrical components consist of coil inductance, coil resistance and force factor. The mechanical components consist of spring diaphragm of the loudspeaker, and suspension stiffness and damping of mechanical and drag force. The electromechanical components are shown in Figure 2 as follows:

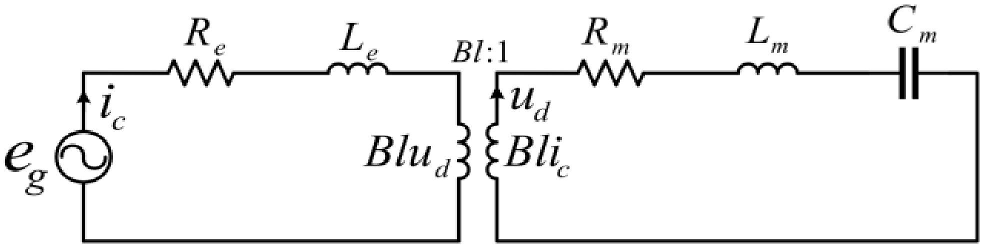

Figure 2. The electromechanical representation circuit [19]

e_g is the input voltage of the loudspeaker, i_c is the current through to the loudspeaker. When the i_c flows, a magnetic field Blu_d is induced to the mechanical side as Bli_c. This phenomenon is called back EMF which the Blu_d is in the electrical domain and the mechanical domain is Bli_c with one turn ratio between the both. The R_m, L_m and C_m confront the current of u_d which supplied by Bli_c. The analysis of the nonlinearity of loudspeaker was conducted with Matlab® by using a transfer function analysis. The plot of the electrical characteristic indicates the response of the loudspeaker. The mechanical characteristic also indicates the mechanical behaviouristic. The loudspeaker movement is represented by displacement χ. The mechanical behaviouristic deals by Klippel®.

2.2. Design of IMC Controller

The numerous types of techniques used to control loudspeaker such as nonlinear distortion active reduction [20] and nonlinear loudspeaker with direct feedback linearization [21]. The IMC is presented for compensating the nonlinearity of the loudspeaker. The controller is designed by employing the scheme shown in Figure 3.

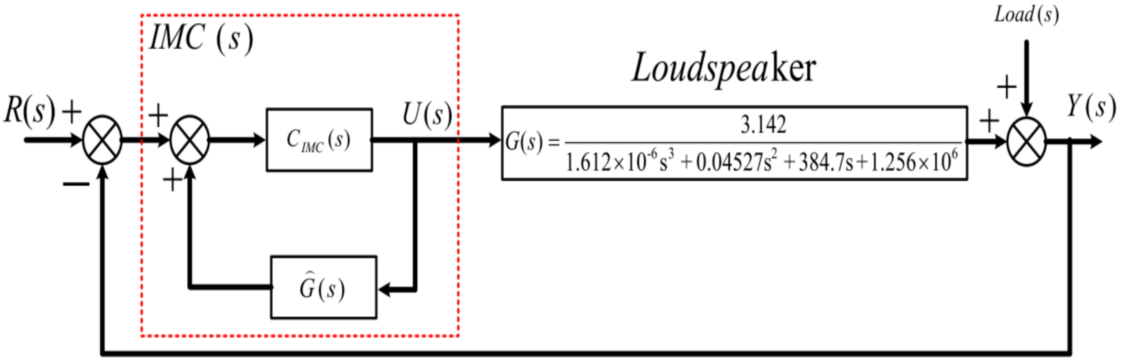

Figure 3. The Internal Model Controller scheme of loudspeaker

$R(s)$ is the reference and $Y(s)$ is the output of the system. The system has two feedback consist of negative feedback from the output $Y(s)$ and positive feedback in $IMC(s)$. The inverse value of the loudspeaker is denoted by $\hat{G}(s)$. The load of the system is denoted by $Load(s)$. Based on Figure 3, the positive feedback is obtained from the inverse value of $G(s)$. The $IMC(s)$ compensator is represented in (1) as follows:

$$IMC(s)=\frac{C_{IMC}(s)}{1-\hat{G}(s)C_{IMC}(s)} \tag{1}$$

C_{IMC} is the value of feedback compensator which is obtained from the inverse value of the loudspeaker $G(s)$. The input $R(s)$ is a reference voltage and $Load(s)$ is a load of the loudspeaker, $Y(s)$ is the output of the system. The closed loop of the complete system is represented in (2) as follows:

$$Y(s)=\frac{G(s)IMC(s)}{1+G(s)IMC(s)}R(s)+\frac{G(s)}{1+G(s)IMC(s)}Load(s) \tag{2}$$

In verifying the compensator model, Matlab® is used to obtain the IMC value from the transfer function of the loudspeaker. The transfer function value of the $IMC(s)$ is represented in (3) as follows:

$$IMC(s)=\frac{1.292\times10^{7}s^{3}+3.682\times10^{11}s^{2}+3.083\times10^{15}\mathrm{s}+1.007\times10^{19}}{\mathrm{s}^{3}+18.793\times10^{4}\mathrm{s}^{2}+2.577\times10^{9}\,\mathrm{s}+0.02736} \tag{3}$$

Finally, the complete system was verified by using a test signal consist of step and impulse signals. The system also tested by using a sine wave to represent arterial pulse. The investigation of the complete system will be presented in the result and discussion.

3. Results and Analysis

The results of this study indicate that the system is stable that shown by step response, impulse response and bode plot. The system is also validated using sine waves in the frequency range 0-10 Hz to identify the difference in magnitude and phase between the reference signal $R(s)$ and the output signal $Y(s)$. The complete analysis of the transfer function is described in (4-8).The electromechanical components are coupled by Bl. In the electrical domain, Bl is represented as Blu_d that called back electromotive force (EMF). In mechanical component, Bl is represented by Bli_c that called motion force. When both parameters are expected on linear condition, this coupling must be stated to the two linear differential formulas [19]. We can write to the differential equation in the time domain as follows:

$$-L_m\frac{d^2x_d(t)}{dt^2}-R_m\frac{dx_d(t)}{dt}-\frac{1}{C_m}x(t)+Bli_c(t)=0 \tag{4}$$

$$e_g(t)-R_e i_c(t)-Bl\frac{dx_d(t)}{dt}-L_e\frac{di_c(t)}{dt}=0 \tag{5}$$

$e_i(t)$ is input voltage of loudspeaker (Volt), $i_c(t)$ is current of the coil (Ampere), R_e is the loudspeaker coil resistance (Ohm), L_e is the loudspeaker coil inductance (Henry), Bl is the force factor of loudspeaker $(T.m)$, L_m is the spring diaphragm of loudspeaker (kg), R_m is the damping of mechanical and drag force $(N.s.m^{-1})$ and C_m is the suspension stiffness $(N.m^{-1})$ Rearranging from (4) and Equa (5), we can describe the frequency domain as follows:

$$-L_m s^2X_d(s)-R_m sX_d(s)-C_m X_d(s)+BlI_c(s)=0 \tag{6}$$

$$E_g(s)-R_e I_c(s)-BlsX_d(s)-L_e sI_c(s)=0 \tag{7}$$

From (3) and (4), we can calculate the numerator and the denumerator form to determine the X_d/E_g characteristic. So, the transfer function of X_d/E_g can be written in (8) as follows:

$$\frac{X_d(s)}{E_g(s)}=\frac{Bl}{(R_e+L_e s)(L_m s^2+R_m s+C_m)+(Bl)^2 s} \tag{8}$$

$E_g(s)$ is the input voltage and $X_d(s)$ is the displacement of the loudspeaker. The dynamics input and output can be observed in the transfer function where speed is represented by s and the acceleration is represented as s^2. The parameter of the loudspeaker is defining in Table 1 as follows:

Table 1. The Parameter of the Electromechanical of the Loudspeaker at ($x=0$)

Parameter	Value	Unit
R_e	6.28	Ω
L_e	0.403×10^{-3}	H
Bl	3.14	$T.m$
L_m	4×10^{-3}	kg
R_m	50	$N.s/m$
C_m	2×10^{5}	N/m

The characteristic of electromechanical is performing by Matlab® consists of a bode plot, impedance, step response and impulse response which represented in Figures 4-7 respectively. The behaviouristic of electromechanical of the loudspeaker is represented into displacement force. The electromechanical impact the acceleration level, force factor, stiffness suspension and inductance which exhibited in Figures 8-11 respectively.

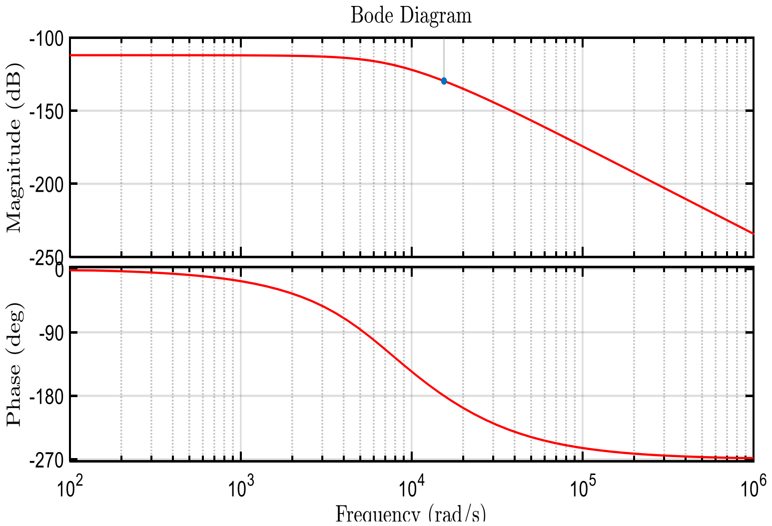

Figure 4. Bode plot of the loudspeaker before controlling

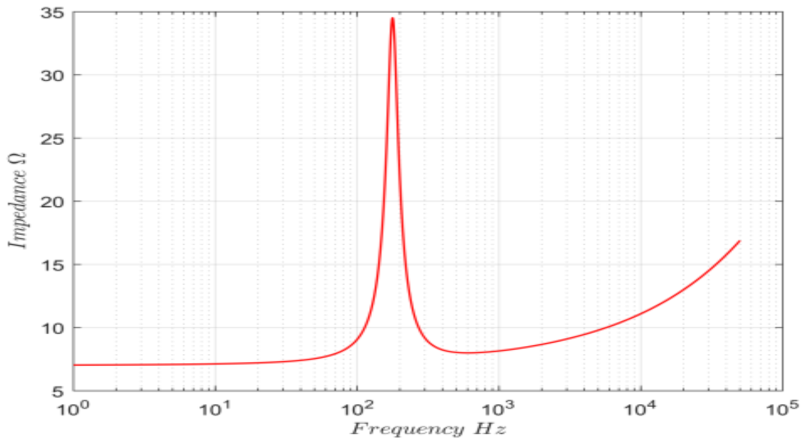

Figure 5. The impedance of the loudspeaker

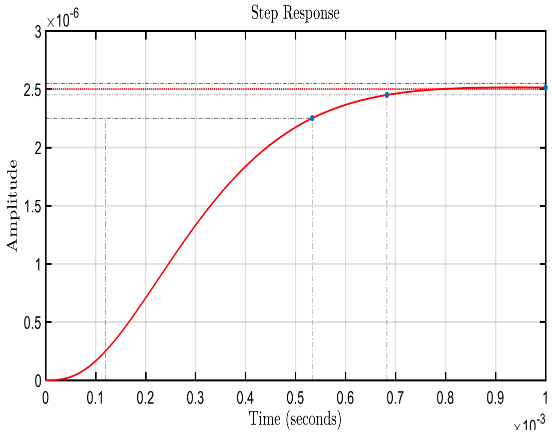

Figure 6. The step response of the loudspeaker

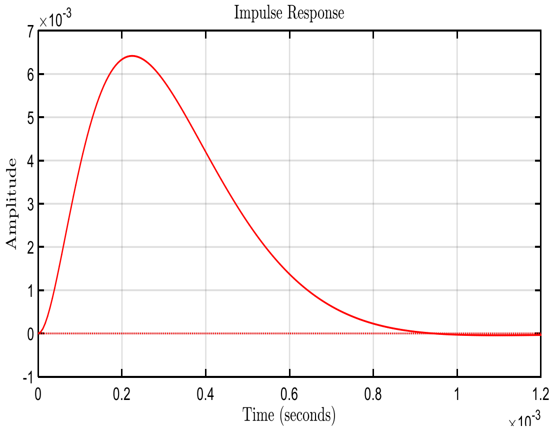

Figure 7. The impulse response of the loudspeaker

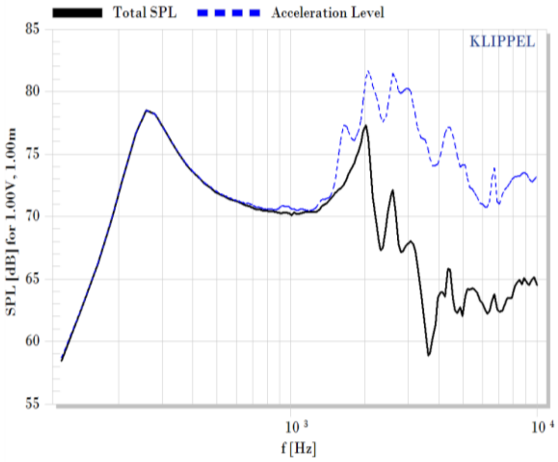

Figure 8. The acceleration level against total Sound Pressure Level (SPL)

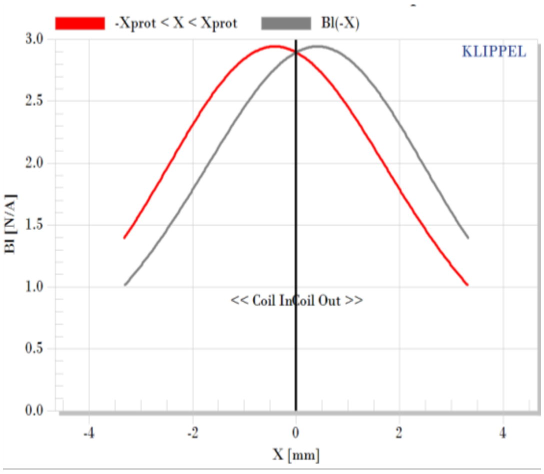

Figure 9. The force factor Bl versus displacement

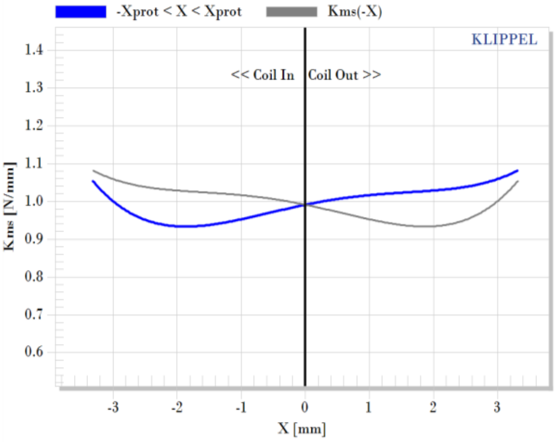

Figure 10. The stiffness suspension against the displacement

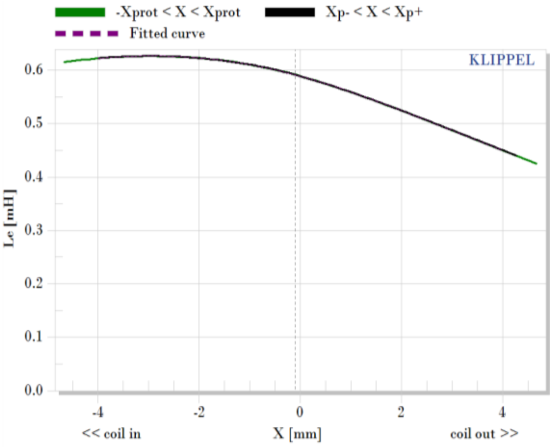

Figure 11. The inductance Lm against the displacement

Figures 12-14 showing the step response, impulse response and Bode plot of the complete system after controlled using IMC. The complete system using IMC can follow the reference signal with a settling time at $3.5\text{x}10^{-4}$ seconds in the step response and $4\text{x}10^{-4}$ seconds in the impulse response. Bode plot after controlling in Figure 14 shows that the system is stable. Figure 15 shows the investigated control scheme. The system has a gain margin -17.8 dB at the frequency of $5.01\text{x}10^{4}$ rad/sec which illustrated in Figure 16 as follows.

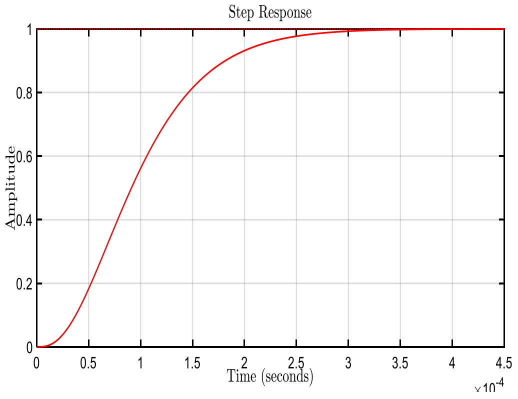

Figure 12. Step response after controlling

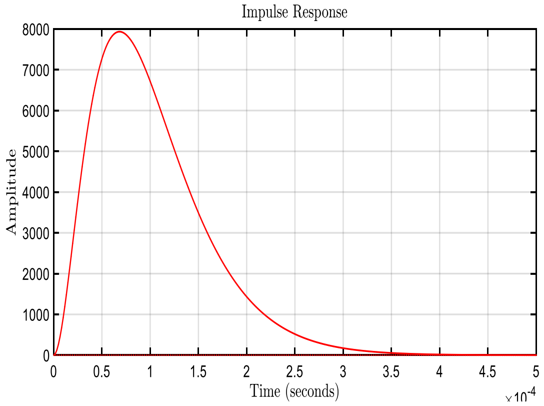

Figure 13. Impulse response after controlling

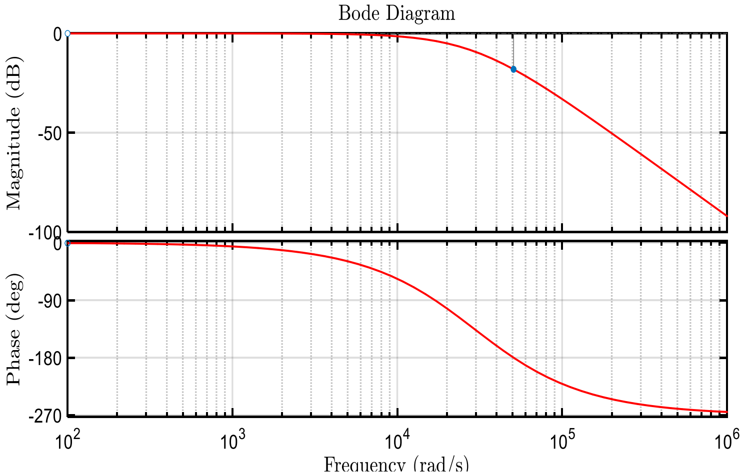

Figure 14. The Bode plot after controlling

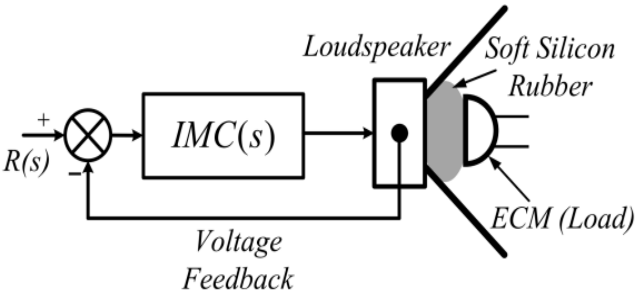

Figure 15. The investigated control scheme

Then, such as step and impulse response, the complete system is also verified using a 0-10 Hz test signal. This is done to compare the reference signal $R(s)$ and the output signal $Y(s)$. Figure 16 shows the response of a complete system with a 0-10 Hz reference signal. The black line is the reference signal and the red line is the output signal. Figure 16. Time response using test signal 0-10 Hz with 10 seconds duration. Figures 17-20 are expanded test signal response of Figure 16 as follows:

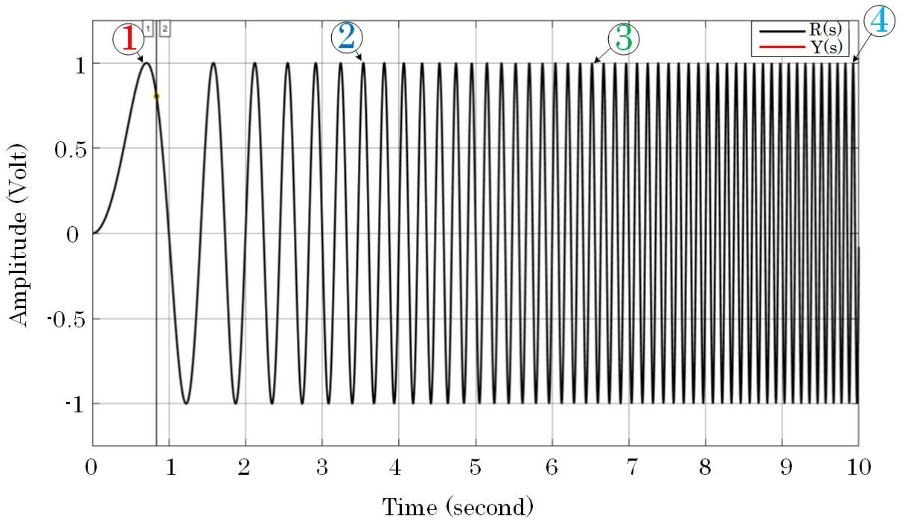

Figure 16. Time response using test signal 0-10 Hz with 10 seconds duration

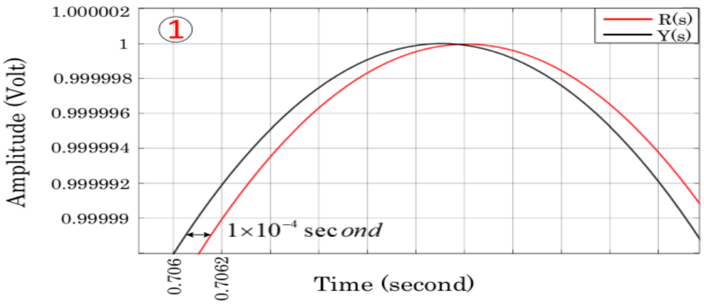

Figure 17. Test signal expanded 1

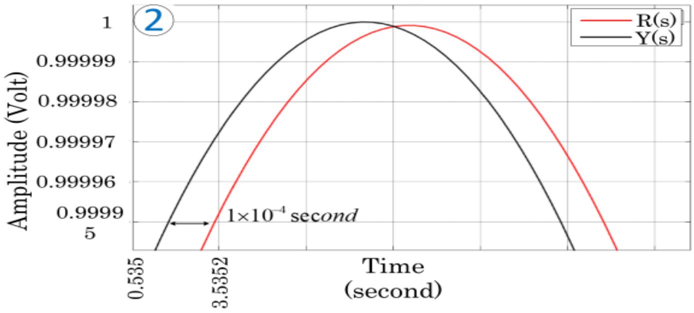

Figure 18. Test signal expanded 2

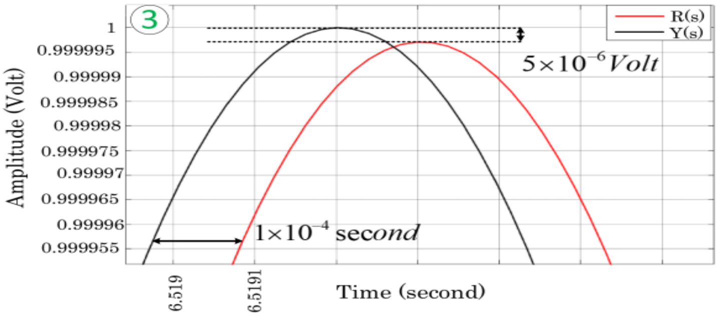

Figure 19. Test signal expanded 3

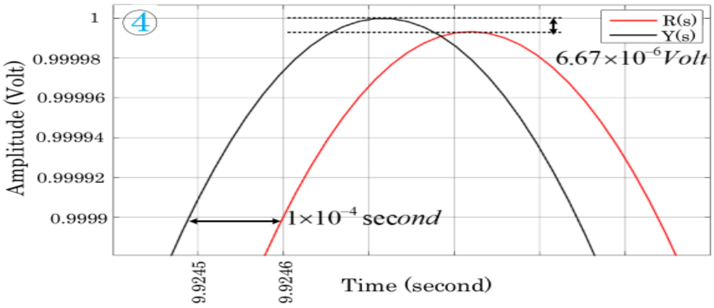

Figure 20. Test signal expanded 4

Based on Figures 17-20, the complete system can identify the differences in the amplitude and phase between the input reference $R(s)$ and the output $Y(s)$. The delay of the output $Y(s)$ is 1×10^{-4} seconds from the input reference $R(s)$. The voltage difference between the $R(s)$ and $Y(s)$ is 5×10^{-6} Volt in Figure 19 and 6.67×10^{-6} Volt in Figure 20.

4. Conclusion

Nonlinearity Compensation of Low-Frequency Loudspeaker Response Using Internal Model Controller has been conducted. The results show that the complete system using IMC can follow the reference signal. The IMC can be an option to compensate for the nonlinearity of the loudspeaker at low frequencies with a small error value and high-speed response. The further research of this study is how to implement in the real case of ECM test response using the loudspeaker which the IMC is implemented in the arterial pulse sensor.

Acknowledgements

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