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Numerical Investigation on the Acceleration Vibration Response of Linear Actuator

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Abstract

This study is aimed to investigate the acceleration response of the non-commutated Direct Current (DC) linear actuator in a numerical approach. The linear actuator is often driven with the specified wave digital signal processing (DSP), which gets forced vibration. The acceleration response of the actuator matters because it is related to vibration intensity. As well, the experiments and technical datasheets report that after the resonance frequency, the acceleration decreased, and the vibration intensity also reduced. This work uses the vibration fundamental concepts and presents results via a numerical approach that significantly matches the available experiments.

Subject Areas

Numerical Mathematics

Keywords

Vibration, Linear Actuator, Acceleration Response, Numerical Approach

1. Introduction

The non-commutated Direct Current (DC) linear actuator is employed in many fields such as smartphones and tablets, gaming controllers, automotive, headsets, tactile toys, and wearables [1] [2] [3] [4] [5]. It is capable of making displacement in a specific length. The voice coil actuator includes a constant force over the stroke and can move bi-directionally [6]. It can be used for force application to make a vibration for a limited time and periodic [7]. A voice coil generates a force based on an interaction of a current-carrying conductor in a permanent magnetic field [8] [9]. This vibration has many applications, and in order to know how the force and vibration are created and apply it in the equipment, it is essential to understand the motion equation and vibration response in displacement, velocity, and acceleration.

Usually, the consumer asks for a datasheet for different products to find the appropriate voice coil related to the application. The manufacturer reports experiment data for the product with the curve, and it is possible to study the voice coil response and behavior with this datasheet.

This work aims to investigate the vibration motion and suggest a simple model to figure out the voice coil (DC linear) actuator response concerning the internal motor driver. The driver signal is assumed Sin, and data input from the L5 voice coil [1] has been used in the model. The result is compared to the experiment report from the manufacturer. Hence, this work is organized as follows. The applied theory and the methods are presented in Section 2. In Section 3, the results are provided, and the conclusions are represented in Section 4.

2. Theory

2.1. Free Vibration

In vibration, the system response depends upon the initial and boundary conditions. When the system has no external driving force, it has a free vibration, and it is an inherent behavior. The first-order equation for the free simple system is [10] [11]:

$$m\ddot{x} + kx = 0 \tag{1}$$

where m is a mass and k stiffness, they are both system properties. The vibration frequency for the free vibration is $\omega_n = \sqrt{k/m}$, and it is a function of the inherent system properties. Stiffness is related to system structure, material, and dimension. M is the mass, and sometimes possible to change it depending on the system structure. x is present displacement, and $\ddot{x}$ is acceleration.

From Equation (1), it is simple arithmetic to derive the displacement and acceleration of the system. We assume the free vibration response [10] [11] [12].

$$X_{\text{free}} = A_{\text{free}} \sin(\omega_n t) = A_{\text{free}} \sin\left(\sqrt{k/mt}\right) \tag{2}$$

$$a_{\text{free}} = -A_{\text{free}} \omega_n^2 \sin(\omega_n t) = -A_{\text{free}} \frac{k}{m} \sin\left(\sqrt{k/mt}\right) \tag{3}$$

Here X_{free} is displacement response, a_{free} is acceleration response of the system. A_{free} is the amplitude vibration of the system and t is the time.

2.2. Forced Vibration

The system with force vibration has a different response than free vibration. Because it is imposed driving motion, it causes the system reacts according to new boundary conditions. The first order notion equation for a system with the external driving force [10] [11] [12]:

$$m\ddot{x} + kx = F_d \tag{4}$$

where F_d is the external driving vibration force, the solution for this equation is combined from free vibration response (general) and force vibration response. Equations (2) and (3) are the public response to the system. We assume the forced vibration is a Sin wave, and then the specific response is:

$$X_{\text{force}} = A_{\text{force}} \sin(\omega_d t + \varphi) = A_{\text{force}} \sin(2\pi f t + \varphi) \tag{5}$$

$$a_{\text{force}} = -A_{\text{force}} \omega_d^2 \sin(\omega_d t + \varphi) = -4\pi f^2 A_{\text{force}} \sin(2\pi f t + \varphi) \tag{6}$$

Here X_{force} is displacement response; a_{force} is acceleration response of the system. A_{force} is the amplitude of the forced vibration. ω_d is the driving frequency and it is function of the frequency f (or period T). φ is a phase frequency and it is properties of the digital signal.

$$\omega_d = 2\pi f = 2\pi/T \tag{7}$$

2.3. Response of the Linear Actuator to Force Driving

The response acceleration for free and forced vibration are specified. The total acceleration response for the linear actuators (system) is a summation of both responses and is shown in Equation (8):

$$a_t = -A_{\text{free}} (k/m) \sin\left(\sqrt{k/mt}\right) - 4\pi^2 f^2 A_{\text{force}} \sin(2\pi f t + \varphi) \tag{8}$$

It must notice in these equations; we assumed the actuator (system) does not have damping. Indeed, it has damping because when the force driving removes, the system displacement will stop and reach zero acceleration. This study aims to consider the acceleration response, and the damping only changes the result value, but the response curve behaves in the same manner. Then, to avoid using second-order motion, we assumed damping zero in this study. As well, the phase frequency is assumed zero and without phase difference. Therefore, the equation considers in this form:

$$a_t = -A_{\text{free}} (k/m) \sin\left(\sqrt{k/mt}\right) - 4\pi^2 f^2 A_{\text{force}} \sin(2\pi f t) \tag{9}$$

2.4. Data Input

In this work, we use technical data from the L5 voice coil actuator [1], Lofelt GmbH product, to have a comparison with real product information. **Figure 1** illustrates a physical information from L5 datasheet. The input data used in this work is dictated in **Table 1**.

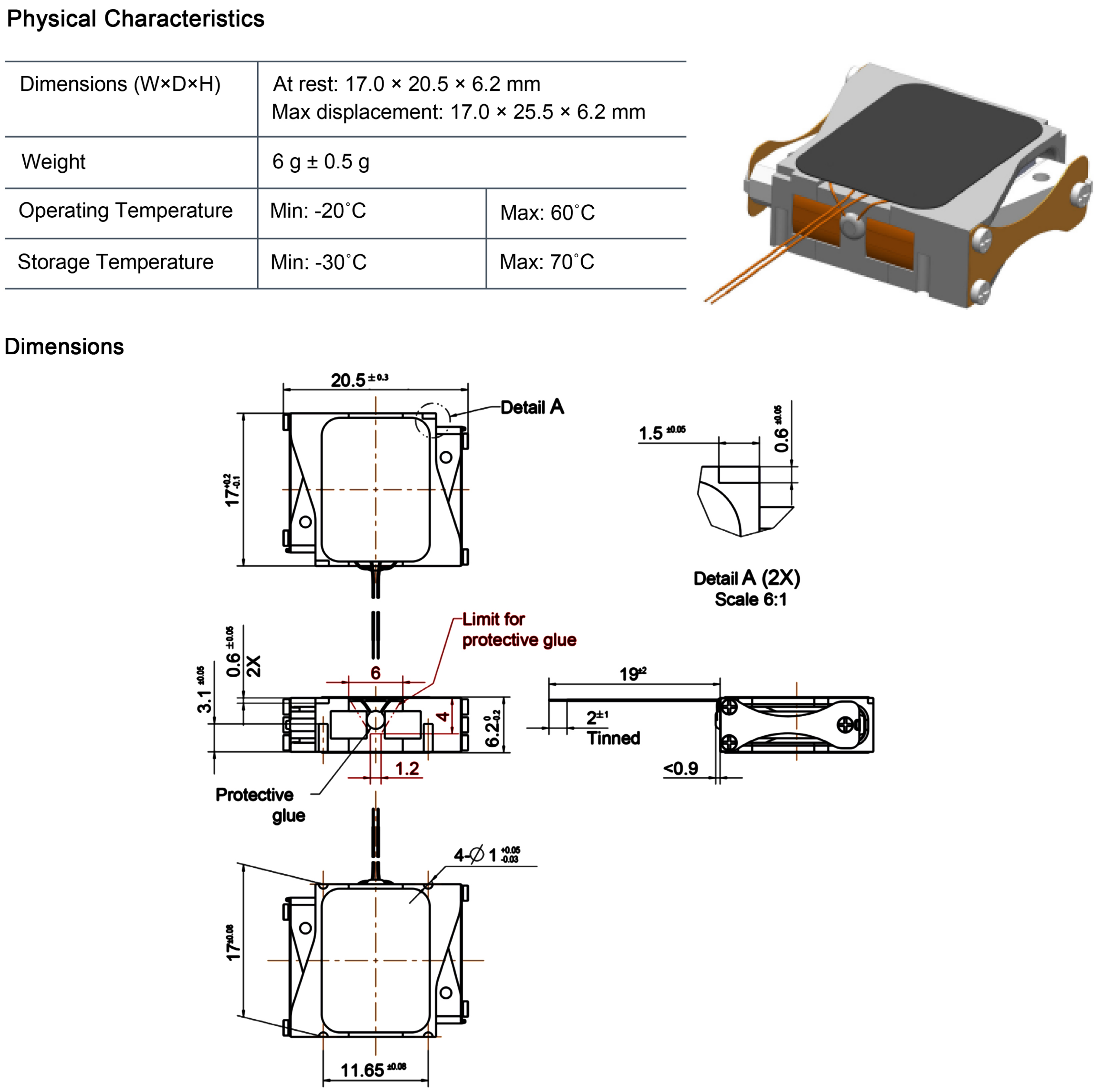
3. Result

For solving Equation (9) with input data from the L5 linear actuator datasheet, the results are represented in **Figure 2**. In order to illustrate the effect of the forced vibration, in **Figure 2**, the curve for free vibration response and forced vibration are plotted individually. Then the cumulative curve from these curves mentions the actuator response after the forced vibration.

As shown in **Figure 2**, the force vibration made more acceleration, and it is

Table 1. The data is used from the L5 voice coil [1] as input in Equations (9).

L5 voice coil technical data		
Description	Unit	Value
A_{Free}	mm	0.125
k	N/m	1000
m	gr	6
f	Hz	20 - 260
A_{Force}	mm	6



Physical Characteristics

Dimensions (W×D×H)	At rest: 17.0 × 20.5 × 6.2 mm Max displacement: 17.0 × 25.5 × 6.2 mm	
Weight	6 g ± 0.5 g	
Operating Temperature	Min: -20˚C	Max: 60˚C
Storage Temperature	Min: -30˚C	Max: 70˚C

Dimensions

Figure 1. Presentation of the technical and dimensional information for L5 voice coil from datasheet [1].

added to the inherent vibration response.

In **Figure 3**, the acceleration curve response from the experiment reported by Lofelt GmbH [1] is represented. **Figure 3** illustrates that the experiment curve is analogous to the curve from the numerical solution.

In the experiment actual L5 voice coil actuator, there is damping and phase-frequency for the digital signal. These parameters could affect the curve, and they are the reasons for the difference between the curves from experiment to numerical result in the response acceleration before the resonance frequency. According to the L5 datasheet, the resonance frequency is 65 Hz with an acceleration response of about 4.3 g (g is gravity acceleration). It can be seen that **Figure 2** shows resonance frequency in a similar location.

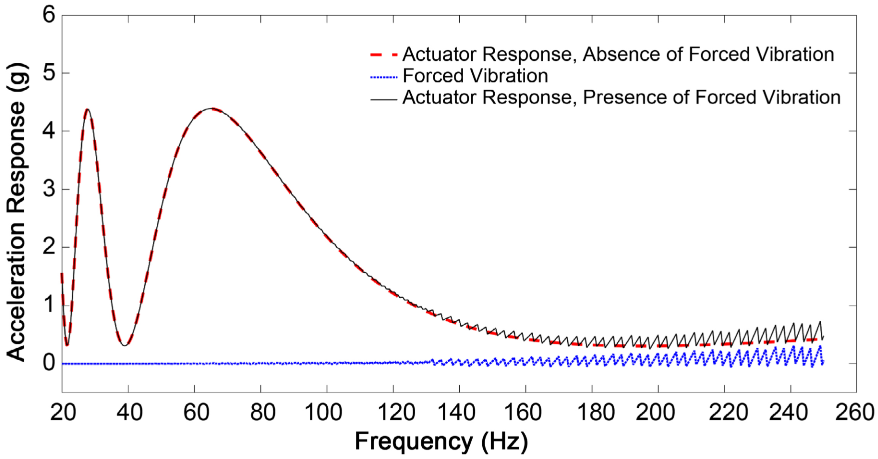


Figure 2. Presents the actuator acceleration responses (g is gravity acceleration is 9.81 m/s^2) to the force vibration from the internal driver motor. It shows the response is combined of free and forced vibration. The maximum point in the curve is related to the resonance frequency. The black line curve is the acceleration response, and the blue dashed line curve is the acceleration added by the forced vibration.

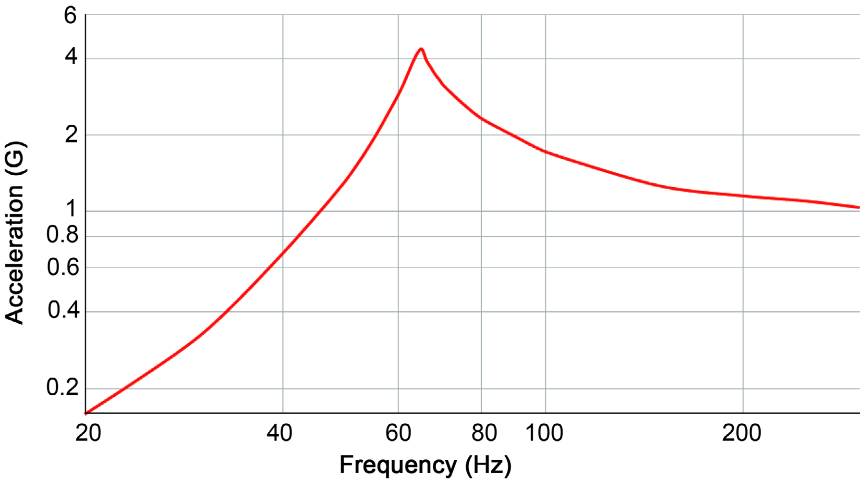


Figure 3. The acceleration response (times of g, gravity acceleration is 9.81 m/s^2) curve for the L5 voice actuator from the Lofelt GmbH datasheet [1]. The curve represents the maximum response is happening at the resonance frequency.

4. Conclusion

The goal of this study is to use vibration fundamentals and derive a simple model to investigate the acceleration response for Linear (voice coil) actuator driving with forced vibration by an internal motor. The obtained result from this study presents behavior that matches the experiment reported in the technical datasheet. The results demonstrate:

- The acceleration response curve for the voice coil actuator has a maximum value in resonance frequency analogous to datasheet experiment report in this case 65 Hz.
- After the resonance frequency, the acceleration response on this voice coil decays. So, forced vibration with higher frequency and same amplitude has lower response acceleration and so less vibration intensity.
- Forced vibration is adding acceleration to the main response acceleration if it has no different phase-frequency from the free vibration.
- The response curve depends on the driving forced signal function.

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Conflicts of Interest

The authors declare no conflict of interest.

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