

INVESTIGATION INTO THE RESONANCES OF VIBRATION EXCITER

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Abstract: Vibration exciters can cause several problems of vibration calibration. The classical one comes from the exciter resonances, which are closed to some calibration frequencies. Although efforts have been made in the design stage to overcome the resonance problems, some of them still exist in particular calibration conditions. In this paper, the resonances of a Brüel & Kjær vibration exciter system (model 4805 with 4811) are studied theoretically and experimentally. A mass-spring model is used to describe the vibration characteristics of the exciter system. The measured resonances are extracted from the measured frequency response of the system. The influence of exciter resonance on the primary calibration of accelerometer is preliminarily investigated.

Keywords: Resonance, Vibration Exciter, Frequency Response Function, Accelerometer Calibration.

1. INTRODUCTION

Vibration exciters are widely used for calibration applications. However, it is often the case that the motions of the exciters affect the calibration results. Ripper *et al.* [1] has shown seven calibration issues due to vibration exciter. Those are the problems concerning low stiffness and heating of moving element, rocking and transverse motions, air bearing, harmonic distortion and resonance, which is of interest in this work. As the exciter resonance can significantly affect the calibration results when it lies closed to calibration frequency, the understanding of the exciter resonance characteristics is important to prevent this potential effect.

The characteristics including resonance of electrodynamic vibration exciter has been discussed in several studies. The fundamentals of electrodynamic exciter were presented in Lang [2]. The suspension characteristics of exciter were investigated by measuring exciter with bare table and with a known mass. The electrical impedance was measured in two circumstances, i.e. blocked and free tests, to exhibit the resonance characteristics. Lang and Snyder [3] studied performance of exciter physically. The model for exciter involving three vibration modes was proposed. Those are isolation, suspension and coil modes. The low-frequency performance of exciter was found to be controlled by exciter design stroke, while the high-frequency performance is limited by “coil mode” resonance. Varoto and Oliveira [4] investigated the interaction between the electrodynamic exciter and the structure under test. The effects of this interaction were explored by both theoretical model and experimental analysis. Peres *et al.* [5] reviewed

the basic design of electrodynamic exciters and common problems, which result in the measurement errors for modal testing. Also the guidelines to perform modal test effectively were presented.

The aim of this work is to investigate the resonance of electrodynamic exciter used at National Institute of Metrology (Thailand), NIMT. Also the effect of the resonance to the primary calibration of accelerometer is preliminarily explored.

Following this introduction, the exciter system characteristics are described theoretically. The experimental set-up to measure frequency response of exciter of interest and the measured results are presented in section 3. Section 4 discusses the influence of resonance on the calibration of accelerometer. Finally section 5 contains some conclusions

2. EXCITER SYSTEM CHARACTERISTICS

The characteristics of exciter bare table when operating in the voltage mode of power amplifier were studied. The conventional approach to investigate these characteristics concerns vibration analysis of exciter armature. For a simple analysis, it is assumed that the frequencies of study are less than one-half of the bare table coil resonance. As a result, the exciter system can be modelled as a single degree of freedom (SDOF) system, whose vibrations can be obtained by solving the equations of motion. The equations are derived and discussed in this section.

The exciter SDOF system is shown in figure 1. The differential equation of motion is given by [6]

$$m_a \ddot{x} + C_a \dot{x} + k_a x = F_c(t) = K_f I(t) \quad (1)$$

where x , m_a , C_a , k_a , $F_c(t)$, $I(t)$ and K_f are the armature motion, armature mass, armature damping, armature stiffness, coil excitation force, coil current and linear electromagnetic force current constant.

The electrical component of the exciter system is modelled as shown in figure 2. The differential equation relating the coil driving voltage is [6]

$$RI + L\dot{I} + K_v \dot{x} = E(t) \quad (2)$$

where

$$K_v \dot{x} = (Bl n) \dot{x} = E_{\text{bemf}} \quad (3)$$

Here R , L , I , E , E_{bemf} , K_v , B , l and n are the coil resistance, coil inductance, coil current, coil driving voltage, back electromotive force (emf) voltage, back emf voltage constant, magnetic field strength, coil length per turn, and number of turns respectively.

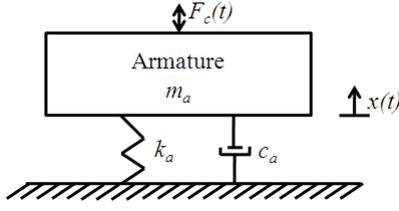


Figure 1: Single DOF model of exciter system [6].

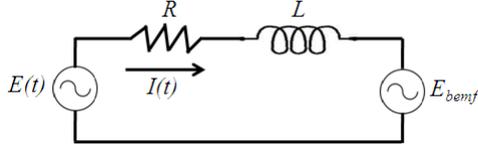


Figure 2: Coil electrical circuit of exciter system [6].

Assuming harmonic motion, i.e. $x = X e^{j\omega t}$, $I = I_0 e^{j\omega t}$, and $E = E_0 e^{j\omega t}$, the differential equations shown in equations (1-2) can be written as

$$(k_a - m_a \omega^2 + j c_a \omega) X = K_f I_0 \quad (4)$$

$$(R + j L \omega) I_0 + j K_v \omega X = E_0 \quad (5)$$

If the armature damping is structural and power amplifier works in voltage mode, the dimensionless accelerance (A_s) can be written by solving for I_0 from equation (5) and substituting it into equation (4). This gives [6]

$$A_s(\omega) = \frac{m_a (-\omega^2 X)}{K_f (E_0/R)} = \frac{-r^2}{1 - (1 + M_L) r^2 + j [\eta_a + 2\zeta_e r + \beta_L (1 - r^2)] r} \quad (6)$$

where η_a is the armature's structural damping

$$\zeta_e = K_v K_f / R (2\omega_a m_a), \text{ which is the electromagnetic damping ratio.}$$

$$M_L = \frac{L C_a / R}{m_a}$$

$$\beta_L = \frac{\omega_a}{R/L}$$

$$r = \omega / \omega_a, \text{ which is dimensionless frequency ratio}$$

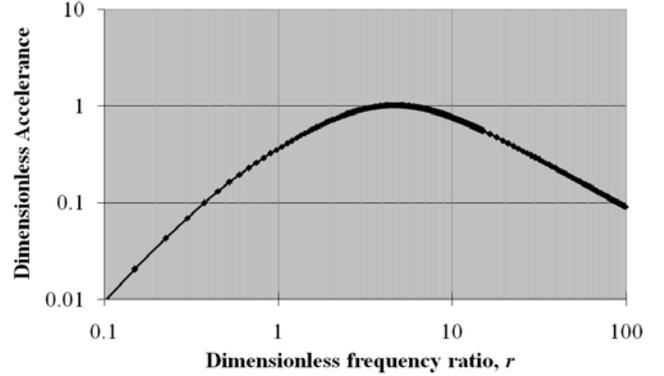
$$\omega_a = \sqrt{k_a / m_a}, \text{ which is the natural frequency of armature}$$

In case of undamped system, i.e. $\zeta_e = \eta_a = c_a = 0$, the accelerance shown in equation (6) tends to infinity at frequency $\omega = \omega_a$, the natural frequency of armature. This frequency can be varied by changing either the mass or the stiffness of the armature. Also around resonance of the undamped system, the phase of the system changes rapidly.

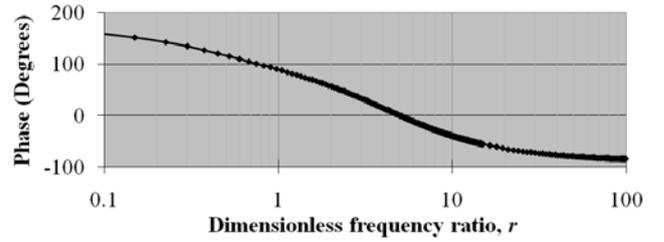
Figure 3 shows the dimensionless accelerance calculated from equation (6). They are simulated using parameters shown in Table 1.

η_a	0.2	M_L	0.022
ζ_e	0.1	R	1.5 ohms
ω_a	418 rad/second	L	0.4×10^{-3} henrys

Table 1: Properties of exciter used for simulation [6].



(a)



(b)

Figure 3: Dimensionless Accelerance of bare table exciter calculated from equation (6): (a) Magnitude; (b) Phase.

Due to the large electrodynamic damping term [6], the amplitude around resonance, i.e. $r=1$, is heavily damped as shown in figures 3(a). This damping also has the effect on the phase change of the system, i.e. damping decreases the rate of phase change around resonance as shown in figure 3(b).

3. EXPERIMENTAL STUDIES

In this section, the resonance characteristics of exciter are investigated experimentally. The exciter under test is a B&K 4811 head with 4805 body. The experimental set-up is shown in figure 4.

In the experiments, an Agilent 35670A dynamic signal analyzer, which also acted as a signal generator, generated a random input signal to drive the exciter through a B&K 2707 power amplifier. Hence, the vibration exciter was driven in the horizontal direction. The applied voltage (E_0) to the exciter was measured by the analyzer.

The power amplifier was operated in "Low" Impedance mode or constant drive voltage mode, which keeps constant voltage applied to the exciter. This results in heavily damped of lower resonance frequency [7].

The Polytec laser vibrometer head OFV-505 with controller OFV-5000 were used to measure the vibration of the exciter bare table. The laser spot was pointed to about the center of exciter table. The measured velocity (V) from vibrometer controller was input to the analyzer.

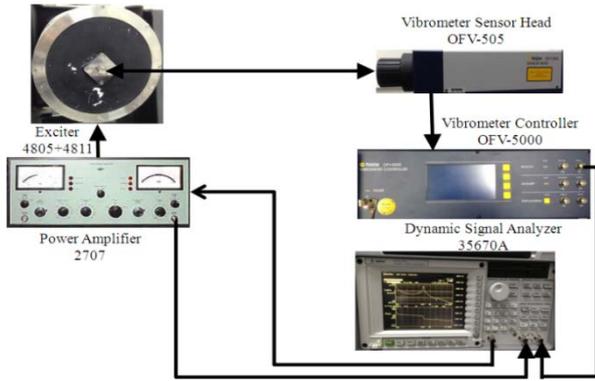


Figure 4: Experimental set-up to measure the resonance characteristics of the vibration exciter.

The measurements of bare table frequency response function (FRF) were conducted over the frequency of 0-10 kHz. The magnitude and phase of FRF are shown in figures 5(a) and 5(b) respectively. The vertical value shown in figure 5(a) is velocity per unit voltage applied, which is given in ms^{-1}/V .

Figure 5 shows two modes of vibrations. The first mode is suspension mode, while the second one is coil mode. It can be seen from both modes that around resonance frequencies, the magnitude of FRF is high and the phase of FRF changes rapidly as shown in figures 5(a) and 5(b) respectively.

Figure 6 (solid line) illustrates the measured FRF in the suspension mode. The exciter in this mode can be modeled as a SDOF system as described in section 2. It can be seen from the figure that the measured magnitude and phase show similar trend as the theory presented in figure 3. The resonance peak, which is the resonance of armature suspension system, occurs around 63 Hz approximately. As expected, it is largely damped because the voltage mode of amplifier was employed.

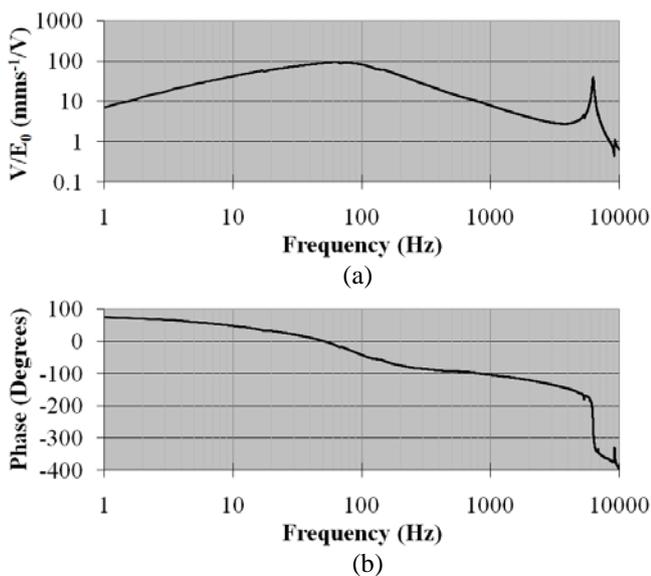


Figure 5: Measured FRF of the vibration exciter head 4811 with exciter body 4805: (a) Magnitude; (b) Phase.

Figure 7 presents the coil mode resonance closely. In this mode, the coil moves out-of-phase with the table [3]. The resonance peak occurs at 6.3 kHz approximately. This axial resonance is about 26 % lower than that given by manufacture data [8].

As the resonance frequency depends on mass and stiffness of the system. When using this exciter in the calibration application, the mass of transducer under test might have the effect on exciter resonance. Figure 6 also shows the comparison of measured FRFs between exciter bare table (solid line) and exciter with attached mass of 229 grams (dashed line). It can be seen from the figure that adding mass to the exciter system decreases the resonance frequency of the system.

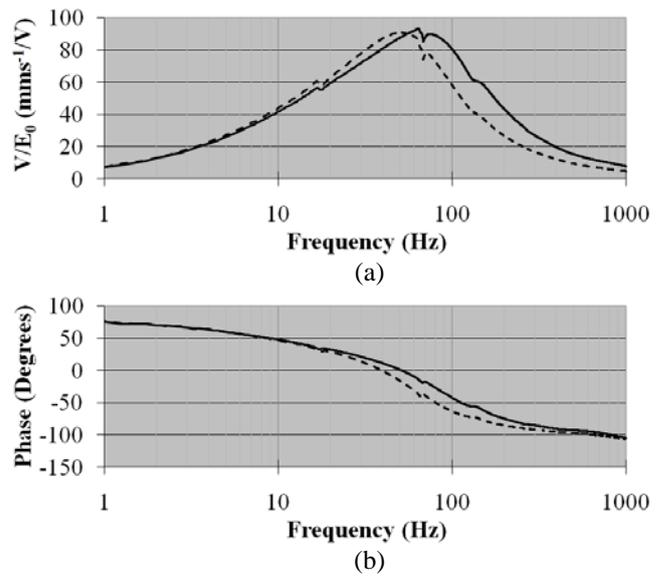


Figure 6: Measured FRF: - bare table; --- exciter with mass. (a) Magnitude. (b) Phase.

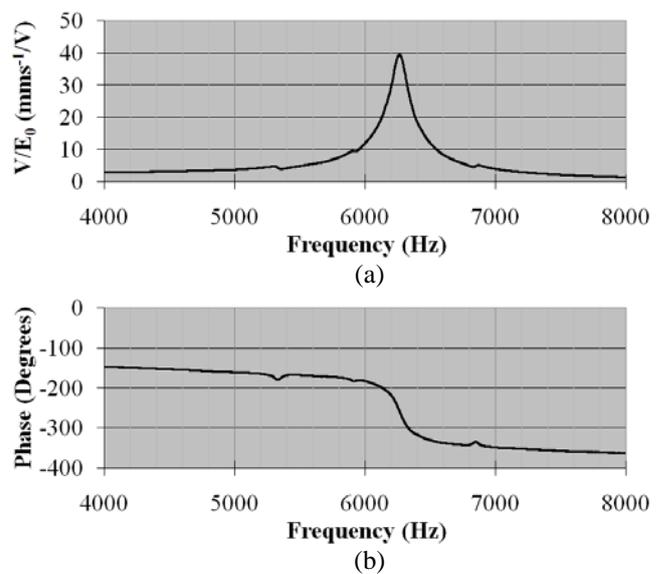


Figure 7: Measured FRF of the vibration exciter head 4811 with exciter body 4805 in the coil mode: (a) Magnitude; (b) Phase.

4. EFFECTS ON CALIBRATION RESULTS

As vibration exciter is an important part in the primary calibration of accelerometer, the effect of exciter resonance on the calibration results of accelerometer is preliminarily studied here. To investigate this effect, three sets of calibrations were performed. The accelerometer under calibration used was a B&K accelerometer model 8305, serial no. 2312063. The system shown in figure 8 was used for the calibration. An under test with a reflecting mass was connected to the top of a B&K exciter head model 4811. A B&K sine generator model 1051 generated an input signal to drive a B&K exciter model 4805 through a B&K power amplifier model 2707. Michelson interferometer, consisting of a beamsplitter, a reference mirror, a photodetector and a Helium-Neon laser with wavelength of 632.8 nm, was used to measure reference displacement amplitude. The output signal from accelerometer under test was measured by an Agilent digital multimeter (DMM) model 3458A through a B&K charge amplifier model 2650. The outputs from the DMM and the universal counter were sent to PC for the calculation of sensitivity.

Figure 9 shows the results of three calibration sets. The vertical axis is charge sensitivity of accelerometer. The dotted line presents the results of calibration set no. 1. The measurements were taken at ten frequencies, which are between 40-500 Hz. The result shown at each frequency was the average of ten measured data. The solid line and dashed line are the results of set no. 2 and 3 respectively, which were obtained by using the same process as data set no. 1.

It can be seen from figure 9 that the behaviour of sensitivity can be divided into two regions. The results from three sets of calibrations show good agreement for frequency from 100 to 500 Hz. However, the sensitivity at frequency lower than 100 Hz has some repeatability problem. This problem might be caused by the suspension mode of exciter shown in section 3. However, more measurements need to be performed to deeply investigate the problem and to propose the solution effectively.

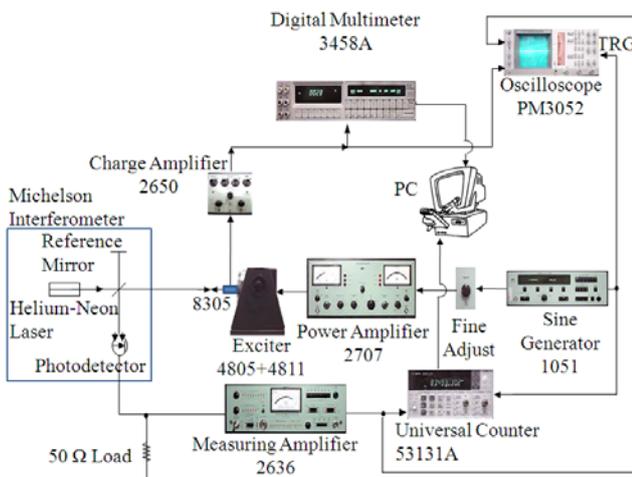


Figure 8: Experimental set-up to calibrate accelerometer using fringe counting method.

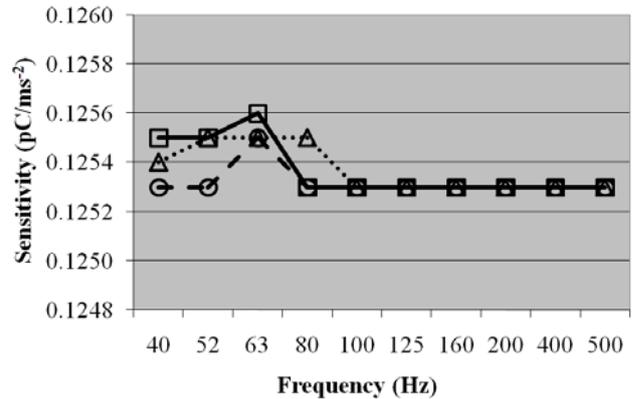


Figure 9: Sensitivity of accelerometer: Δ - calibration set no. 1; \blacksquare - calibration set no. 2; \circ - calibration set no. 3.

5. CONCLUSIONS

The resonance characteristics of vibration exciter model 4805 body with 4811 head were studied theoretically and experimentally. Expression for the frequency response of exciter system has been derived using a SDOF model. It was seen that the voltage mode of power amplifier resulted in large electrodynamic damping in the exciter system.

The frequency response function of exciter was measured experimentally using a dynamic signal analyzer. The measurements were taken over the frequency of 0-10 kHz. The measurement results show two modes of vibration. Those are suspension and coil modes. The first resonance peak occurs around 63 Hz, while the second one happens at 6.3 kHz approximately. It was also found that the measured magnitude and phase for the first mode show similar trend as those predicted by the theory.

6. REFERENCES

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