Modeling and Characterizing of Electrodynamic Shaker ESE 211

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Abstract— **The Shaker actuator is a fundamental component in vibration testing and control systems, serving as a versatile tool for inducing controlled vibrations in mechanical structures. Knowing the characteristics performance is essential for selecting the right electrodynamic shaker for a specific testing application. This paper investigates performance parameters of electro-dynamic shaker type ESE211 from VEB Schwingungtechink und Akustik, WIB, Dresden, for which there is no available performance data online. Using system identification techniques by measuring dynamic response and various electrical and mechanical parameters, we create an integrated electro-mechanical mathematical model and simulation model in MATLAB/SIMULINK. Using this combined modeling technique, where part of the parameters are obtained with static measurements, and part with dynamic measurements, we create a model which gave an excellent result in comparison to the experimental results. The testing range of dynamical response of the shaker was from 1Hz to 100 Hz sinusoidal sweep input signal and payloads specimens from bare table to 975grams.**

Keywords - system identification, electrodynamic actuator shaker, MATLAB/Simulink, ES211 shaker

I. INTRODUCTION

In engineering and control systems, understanding the dynamic behavior of complex mechanisms is crucial for optimizing performance, enhancing reliability, and facilitating advancements in various applications. Shaker actuators are widely used to simulate the vibrations for academic research, play a pivotal role in experimental setups ranging from modal and structural analyses [1], aerospace applications [2,3], energy harvesting, automobile industry [4], vibration test products, vibration screening of small components, testing of electronic assemblies such as mobile phones. These actuators are designed to impart controlled forces and vibrations to test articles, allowing engineers to evaluate structural responses, study material behavior, and validate system designs. Understanding these characteristics is essential for selecting the right electrodynamic shaker for a specific testing application. The choice depends on factors such as the type of testing, frequency range, employ force, acceleration or velocity requirements, stroke limitations, payload considerations, weight, size, and etc. Electrodynamic shakers operate on the principle of electromagnetic induction. A coil of wire with the length L is placed within the radial magnetic field $\vec{B}$ of a permanent magnet, and when an electric current is passed through the coil, it experiences a force due to the interaction with the magnetic field. This force is known as Lorenz force.

$$\vec{F}_m = L \cdot \vec{I} \times \vec{B} \qquad (1)$$

The term BL is known as Electromechanical force factor. The electromagnetic force $\vec{F}_m$ is proportional to the current and force factor. Real-world shaker actuators exhibit nonlinearities [5,6]. The appearance of hysteresis, dependence in stiffness, inductance, uniformity of magnetic field vs position of shaker table, dependence of damping on frequency contributes to the appearance of non-linearities in the voltage, current and displacement, acceleration relationships. A comprehensive mathematical model is crucial for understanding and predicting the dynamic behavior of shaker actuators. Understanding the relationship between the electrical and mechanical responses of an electrodynamic shaker system can provide test engineers with valuable information on the performance limitations of the system. The process of modeling can be in different approaches. Lumped parameter modelling [7] can be done by measuring its various electrical and mechanical parameters. A method for modeling a vibration shaker test system using the transmission simulator method (TSM) is shown in [8]. System Identification is a discipline within control theory, empowers researchers and engineers to unravel the inherent complexities of engineers to unravel the inherent complexities of Shanker systems by extracting valuable insights from experimental data [9]. This paper embarks on a comprehensive exploration of the system identification techniques employed static and dynamic measurement to unveil the dynamic parameters governing Shanker systems. By measuring the relation of force-displacement of flexure support, stiffness of flexure support can be determinate. Measuring current-force relation vs different positions of stroke, the characteristic of force factor can be determinate in the whole range of stroke limitations movement. The dynamic responses and natural frequency are obtained by using an input sweep signal and measuring displacement and acceleration. Using this relationship and measuring electrical parameters like resistance (R) and inductance (L) of the coil, an analytical mathematical model is

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developed. Two models are created, one is created using MATLAB/Simulink electro-mechanical modeling, and the other is by using the System Identification toolbox. At the end a comparations in made between real experimental data and simulation data of both transfer function model of System identification toolbox and Simulink model.

I. MATHEMATICAL MODELING

A. Electro-mechanical model of the shaker system

Accurate mathematical modeling of shaker actuators is essential for designing robust control strategies, optimizing performance, and ensuring the reliability of various engineering applications. An electrodynamic shaker is an electro-mechanical system which can be seen on (fig.1).

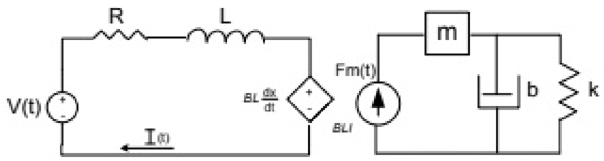

Figure 1. Equivalent model of electro-mechanical model

At the heart of the shaker is a coil of wire, suspended in a fixed radial magnetic field. When a current is passed through this coil, an axial force is produced in proportion to the current and transmitted to a table structure to which the test article is affixed. This compliant connection between the armature assembly and the shaker body forms an obvious spring/mass/damper vibration system with one degree-of-freedom. On its electrical side, it has an armature coil with resistance R and inductance L, and the voltage source which is dependent of the BL factor and the relative speed of the armature coil.

The electromagnetic force is proportional to BL factor and the magnitude of the current in the armature wire. The electrical and mechanical relationship can be expressed with the following equations (2) and (3).

$$V_{(t)} = RI_{(t)} + L\frac{dI}{dt} + Bl\frac{dx}{dt} \tag{2}$$

$$m \cdot \ddot{x} = Bl \cdot I - k \cdot x - b \cdot \dot{x} \tag{3}$$

Transfer function of the shaker can be calculated through a Laplace transformation of equations (2) and (3) where the final form is given in equation (4)

$$\frac{X_{(s)}}{V_{(s)}} = \frac{Bl/_{mL}}{s^3 + s^2 \cdot \left(\frac{mR + cL}{mL}\right) + s \cdot \left(\frac{cR + kL + Bl^2}{mL}\right) + \frac{KR}{mL}} \tag{4}$$

This equation shows the linear dependence between the control voltage input and position of the armature coil or table of the shaker. However, real-world shaker actuators demonstrate nonlinearities.

II. EXPERIMENTAL DETERMINATION OF PARAMETERS

A. Parameters determined by static measurement.

The relation force-displacement of flexure support was determined by experimental measuring on a universal tensile testing machine "Shimadzu" (fig.2). The testing measuring was made by the maximum stroke limitation ±3mm.

Figure 2. Experimental measuring on universal tensile testing machine

The appearance of hysteresis was noticed when changing the movement direction. Depending on the shaker table position the residual distribution goes up to ± 2N. Using the linear fitting curve (5) an approximation of the behavior has been made (fig. 3).

$$F_k = 25.29x + 0.13 \tag{5}$$

Estimate lump parameter of stiffness flexure can be adopted:

$$K = 25.29 \ N/mm \tag{6}$$

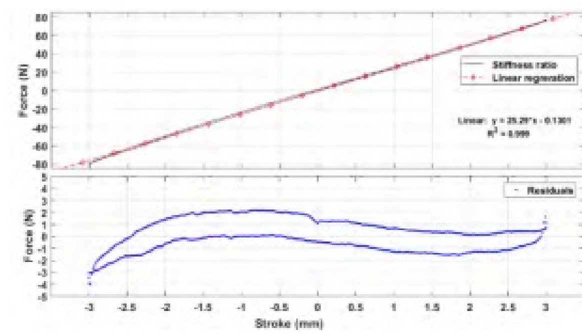

Figure 3. Flexure Stiffness and residual distribution

The relationship between the force factor $BL_{(x)}$ and the stroke is experimentally determined by measuring the generated force while applying different currents to the shaker up to 4.5A. These measurements are repeated for different positions of the shaker table, mainly for fixed strokes of 0mm, ±1mm, ±2mm, ±3mm. At the end the mean values of $BL_{(x)}$ are taken into consideration and shown on figure 4.

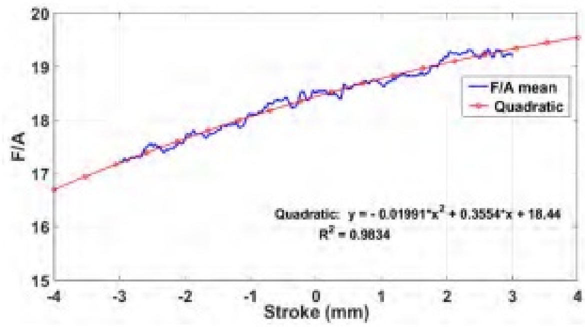

Figure 4. Force factor *BL(x)* vs stroke position.

It is also noticed that there is a non-linearity and non-symmetry in force factor when the stroke is moving in positive direction and negative direction. By applying a quadratic fitting curve, a polynomial relationship between force factor and stroke position is made (7).

$$BL_{(x)} = -0.0199 \cdot x^2 + 0.3554 \cdot x + 18.44 \tag{7}$$

B. System identification process

System identification refers to the process of characterizing and modeling the dynamic behavior of the actuator system by collecting experimental data. The experiment was conducted measuring the frequency response of the system with different payloads from a Bare system up to 975grams payload. The frequency response on different payload specimens is given in figure 5.

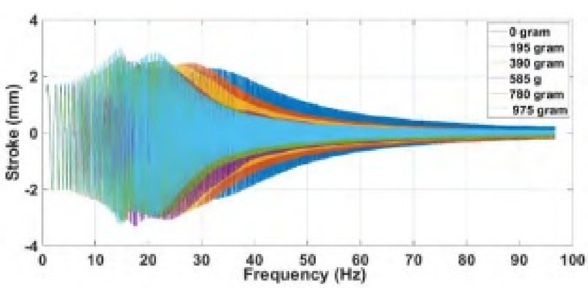

Figure 5. Experimental results of frequency response vs different payload specimens.

The data acquisition was done with National Instruments LabVIEW program and using Ni-cDAQ 9174 chassis with c-modules NI9234, NI9207. The generation of the test signal was done by signal generator type Agilent 33521A which was used to generate a sweep voltage signal range ± 10Vpp, with a stop frequency of 100Hz and a sweep time of 30s. The voltage signal was amplifier by a Linear amplifier with a factor of amplification 1:1, with power of 50VA and a Shunt resistor of 1Ω/20W connected in serial with the coil of the shaker. Measuring the voltage drop on shut resistor allowed for precise measurement of the current flowing in the actuator with ratio of 1:1. The stroke of the shaker table was measured with a laser micro-epsilon type optoNCDT1302. Utilizing the System Identification Toolbox within MATLAB facilitates the estimation and validation of transfer function models. Specifically, employing the 'tfest' function requires defining the order of the transfer function model and recording input/output data. By employing algorithms such as the least squares method, MATLAB can accurately estimate the optimal parameters of the model. The validation process entails comparing the model's response to new data that was not utilized during the estimation phase. In our study, the estimated transfer function demonstrated a correlation of 92%, indicating a robust estimation. The estimate transfer function is given by the equation (8) while figure 6 shows the correlation between the simulation results and the experimental results for bare table.

$$\frac{X_{(s)}}{V_{(s)}} = \frac{-5.489s + 2896}{s^3 + 446.9s^2 + 1.007e05s + 1.483e07} \tag{8}$$

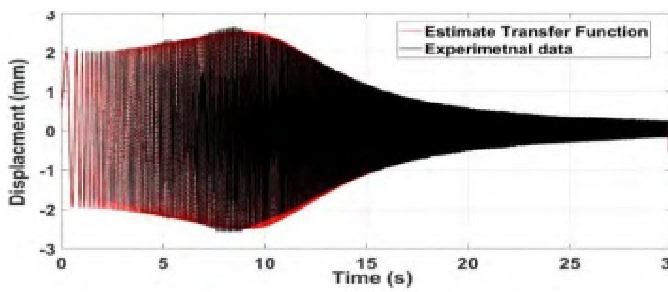

Figure 6. Bare table frequency response comparation between experimental data and transfer function simulation.

Analyzing experimental data and transfer function frequency response it can be noted that the pick value of displacement occurs on the value of 31.23Hz for a bare shaker table. Using a relationship formula for natural frequency, the flexure stiffness can be approximated, and the effective moving mass can be calculated using the following formula.

$$m_{eff} = \frac{K}{\omega^2} = \frac{25290}{(2\pi \cdot 31.23)^2} = 0.65\ Kg \tag{9}$$

C. Simulink model

Using the parameters given in Table 1, and relations in (2) and (3) an electro-mechanical model of the system was created in Simulink shown in figure 7.

TABLE I ESTIMATE PARAMETERS.

	Lump parameters	*Value*
1	R –Resistance of coil	2.8 Ω
2	L – inductance of coil	12.7 mH
3	K -Stiffness flexure	24.29 N/mm
4	m_{ekv} – moving mass	0.65 Kg
5	C_{ekv} - damping factor	9.75 Ns/m
6	Stroke max position	±3mm

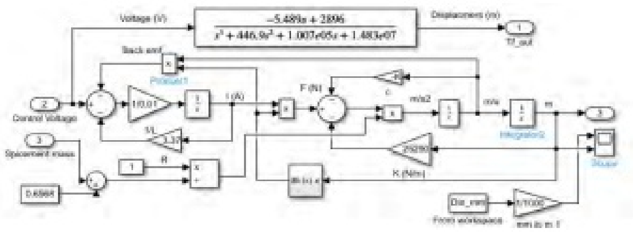

Figure 7. Electro-mechanical Simulink model of Shaker

Equations 2 gives Voltage/Current relation, where Voltage source was used from experimental data. The output signal of current is multiplied with the polynomial given in equation 7. This polynomial is used to model a compensation of non-linearity of the force factor. The output of the Simulink model is threefold, having the real system data, the transfer function data, and the modeled electromechanical data. For better visibility the comparison between the real model and the transfer function model are given in figure 6 while the comparison between the modeled electromechanical system and the real system are given in figure 8.

III. Results the Discussion

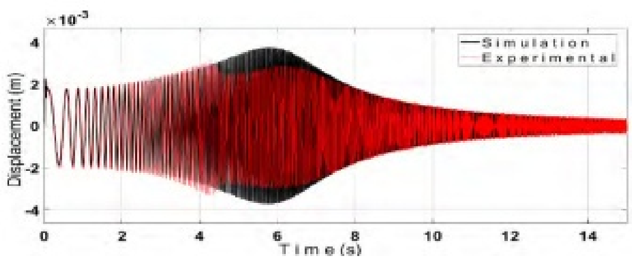

Figure 8. Frequency response comparation between experimental and Simulation results whit 975gram payload.

It can be seen from figure 8 that the simulation and experimental results have a good overlay which confirms the system model for the shaker, but it should be noted that on experimental model shows 2 peak values for the displacement. The first pick represents the natural frequency of armature weight and moving mass which goes in range from 31Hz for bare table down to 20Hz for 975gram Payload. The second lower pick is also mass payload dependent but is noted when payloads are more weights on and goes from range 17Hz for bare table down to 14Hz for 975gram Payload.

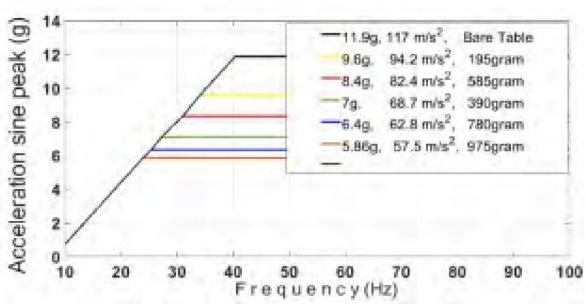

Figure 9. Characteristics performance of the shaker vs different payload

The characteristic performance of acceleration vs frequency range of 100Hz and different payload is shown in figure 9. It can be noticed that the maximum acceleration sine pick value of bare table is almost 12g down to 5.5g for 975grams payload. The relationship between Payloads and acceleration is approximately linear.

IV. Conclusion

The estimated model, using a combined modeling technique, where part of the parameters are obtained with static measurements, and part with dynamic measurements, gave an excellent result in comparison to the experimental and simulation results. A disadvantage is that the system can behave as a multi-degree-of-freedom system, depending on the support stiffness and overall mass. In our case, a second peak appears supporting the hypothesis of a two degree of freedom system however this peak is barely visible when actuating a bare shaker table, but it appears when experimenting with larger payload. Apart from the displacement of the natural frequency due to the additional mass loading, a second peak at a lower frequency is increasingly observed. The model with transfer function from system identification gave excellent results for a bare table system however it is difficult to add payloads for testing. On the other hand, in the Simulink model, it is very easy to change the payload and simulate different masses. The results obtained show good similarity. Another important note to take into consideration is heat energy dissipation because of the RI^2 factor. The experiments in this paper were conducted without any cooling of the actuator, this is intended as future work for the authors. It is hypothesized that cooling of the actuator will lead to an increase of the results in figure 9 by 50%.

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