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A STUDY OF THE ELECTRODYNAMIC SHAKER

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Abstract. *In order to fully understand the vibratory dynamics of engineering systems it is often necessary to perform laboratory tests on scaled-down components or structures. Data acquisition tests involve, at a basic level, vibrating a structure at a point with an actuator and measuring the vibration of the structure at a separate point with a sensor. One particular actuation device is that of an electrodynamic shaker.*

In a recent in-house vibration study an electrodynamic actuation device was identified as a potential source of problems. The application was to develop an active control test-rig capable of controlling the vibratory response of a steel structure due to the excitation forces produced by a reciprocating engine. The idea of merely manufacturing or purchasing an off the shelf device and integrating it into an Active Control System (ACS), whilst sounding simple, proved not to be so. There are several factors to be assessed before selecting the type of shaker (of which there are many) capable of producing the required results for any particular vibration application. Obvious factors e.g. force required and frequency range of interest, coupled with the not so obvious e.g. continual or intermittent usage, power supply, amplification availability and signal generation, these all contribute to determining which shaker type can accomplish what is required, all of the time, [1].

Due to the complexities in actuator selection and design, it is important that for an application that is so heavily dependent upon the actuator, time and efforts must be taken to truly understand the workings and operations of the electrodynamic shaker, [2]. Thus, the following paper attempts to assess, in detail, the electrodynamic shaker from first mathematical principals, through to design and manufacture and then failure modes and life expectancy. A description of the application and the test case is given and an introductory survey of shaker types and manufacturers is also provided.

1 INTRODUCTION

As a most basic description, an electrodynamic shaker is a transducer device that causes vibratory motion of a structure by converting electrical energy into mechanical motion. The physical structure of this type of actuator resembles a common loudspeaker. The shaker consists of a coil of wire attached to a moving armature, and a magnet structure with a small gap through which the coil moves. By passing a current through this coil a magnetic field, generating an axial force, is produced that is proportional to the current. This force can passed to the structure under test in a controlled manner. A cross section showing the basic components of this type of shaker is given in Figure 1.

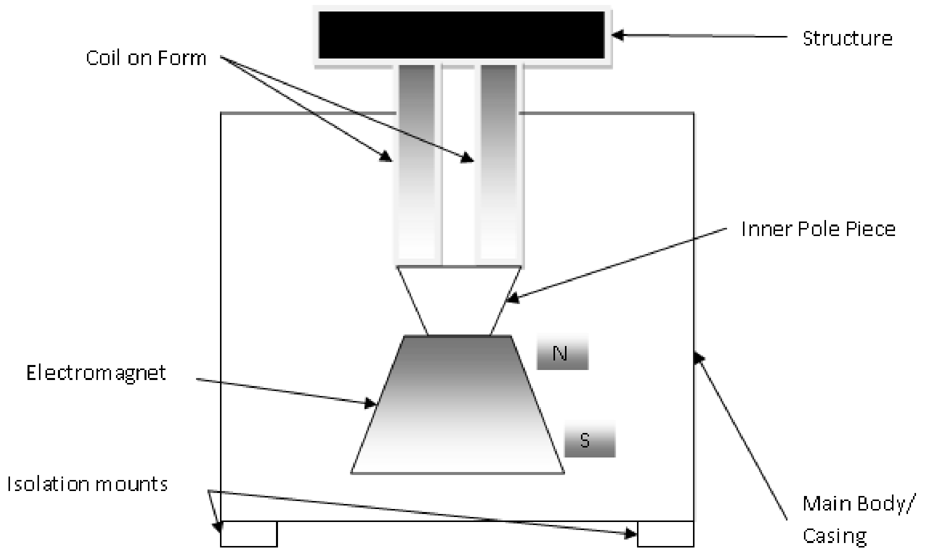

Figure 1: Soft iron pole pieces bend and concentrate almost all of the magnetic field into a very narrow gap. The armature coil is centered in this gap.

Soft iron pole pieces bend and concentrate almost all of the magnetic field into a very narrow gap. The armature coil is centred in this gap using support flexures (for small shakers) or rollers (for large shakers). The magnet structure provides a strong magnetic field across the gap, when current flows through the coil a force is generated that is dependent on the strength of this current and the magnitude of the magnetic field. Small shakers tend to use high strength permanent magnets whereas larger skaters tend to use electromagnets. An alternating current in the coil causes the shaker to oscillate; the transfer of this motion to the armature will in turn cause the test structure to vibrate. Much research has been conducted into the magnet system component for these types of shaker; discovery of rare earth materials has enabled the production of higher strength magnetic fields, improving the power to weight ratio and power to size ratio of modern electrodynamic shakers.

The components pointed out in Figure 1 can be visualized by dissecting an electrodynamic shaker (Figure 2).

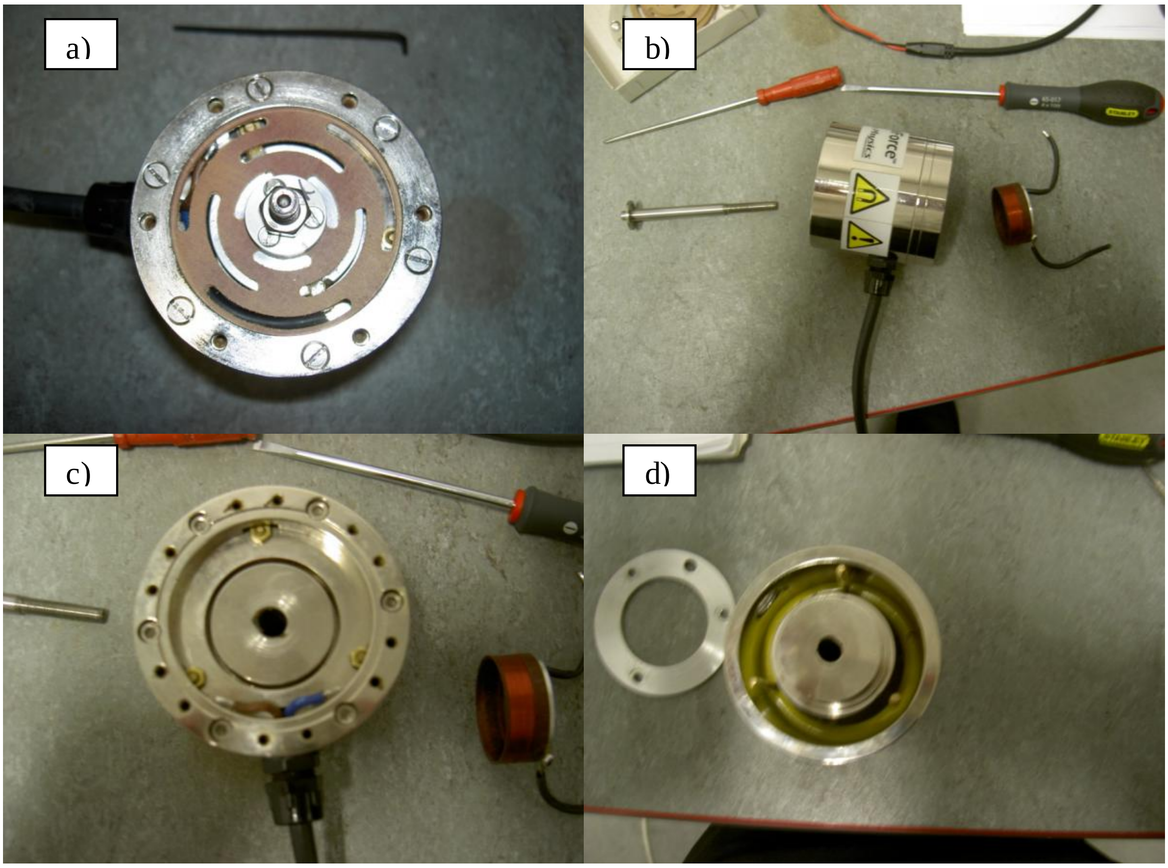

Figure 2: Pictures of a dismantled electrodynamic shaker.

The picture in Figure 2a) shows an aerial shot of the shaker with its top plate removed revealing a Tufenol disk. This purpose of this disk is to prevent flux lines from escaping the casing. Figures b) and c) show side and aerial shots of the removed coil and the armature and finally d) reveals the permanent magnet.

2 DESIGN OF ELECTRODYNAMIC SHAKER SYSTEMS

When in the actuator design phase for a particular application it is important to consider a number of initial factors. These factors range from identifying the force levels and resonant frequencies involved to determination of the impedance of the structure. It is also useful to know the amount of actuator - structure interaction. Indeed these are structure or system dependant and some *a-priori* knowledge or some initial testing of the system can provide the answers to these questions. As is the case in many applications a good what to begin is by modeling the system and analyzing the results.

2.1 Modelling of electrodynamic shaker systems

Mathematically, the electro-dynamic shaker is modeled as a fully coupled four degree-of-freedom system. Accounting for the mechanical and the electrical components separately the shaker can be modeled, for simplicity, as two separate, but fully coupled in the damping parameters, free body diagrams. The fully coupled nature of the system ensures that the application is multi-physical. Figure 3 represents theme mechanical free body diagram, where M_B is the mass of the body, M_C is the mass of the coil, M_D is the mass of the structure and M_T is the mass of the inner pole pieces. K and C are the stiffness and damping coefficients associated with the body, coil, structure, pole pieces. Finally X is the response of the masses to an electrodynamic excitation force given by F.

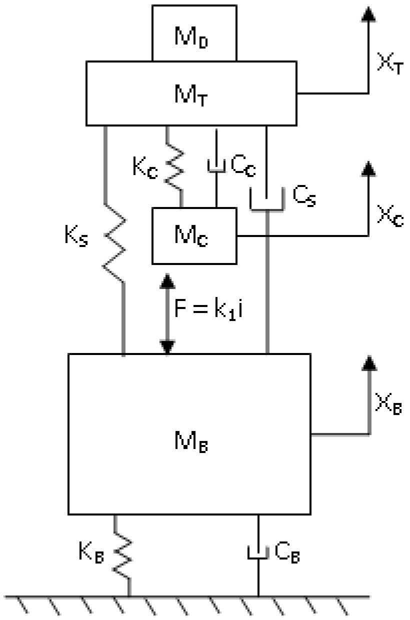

Figure 3: Free Body Diagram of an electrodynamic shaker, based on the simplified representation given in Figure 1.

The electrodynamic excitation force can be examined further by looking at the free body diagram of the electrical components involved, Figure 4.

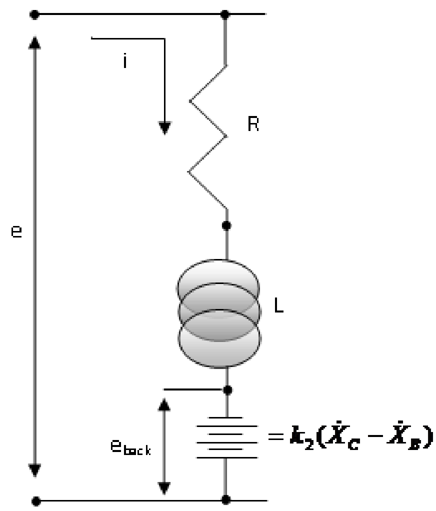

Figure 4: Free body diagram of the electrical force producing components within the electrodynamic shaker.

Finally this free body representation can be used to obtain the equations of motion for the system, Eq. (1):

$$\begin{bmatrix} M_C & 0 & 0 & 0 \\ 0 & M_T + M_D & 0 & 0 \\ 0 & 0 & M_B & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \ddot{X}_C \\ \ddot{X}_T \\ \ddot{X}_B \\ 0 \end{Bmatrix} + \begin{bmatrix} C_C & -C_C & 0 & 0 \\ -C_C & C_C + C_S & -C_S & 0 \\ 0 & -C_S & C_B + C_S & 0 \\ k_2 & 0 & -k_2 & L \end{bmatrix} \begin{Bmatrix} \dot{X}_C \\ \dot{X}_T \\ \dot{X}_B \\ di/dt \end{Bmatrix} + \dots$$

$$\dots + \begin{bmatrix} K_C & -K_C & 0 & -k_1 \\ -K_C & K_S + K_C & -K_S & 0 \\ 0 & -K_S & K_B + K_S & k_1 \\ 0 & 0 & 0 & R \end{bmatrix} \begin{Bmatrix} X_C \\ X_T \\ X_B \\ i \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ e \end{Bmatrix} \tag{1}$$

3 RESULTS

Responses for the four-degree-of-freedom system of ordinary differential equations (ODE's) were obtained numerically using a fourth-order Runga-Kutta integration scheme, to produce the following displacement and velocity time domain plots.

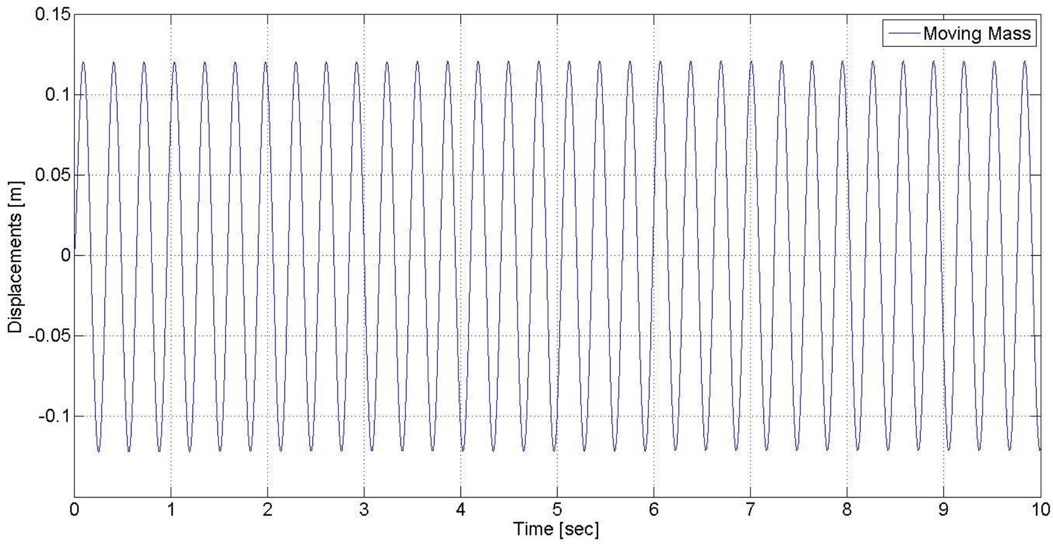

Figure 5: Time domain analysis of the movable mass and structure, M_D+M_T.

The analysis of the structure and the shaker movable mass reveals a sinusoid at the same frequency as that of the forcing signal, Figure 5, this is to be expected. Other interesting features appear in the plots for the internal masses.

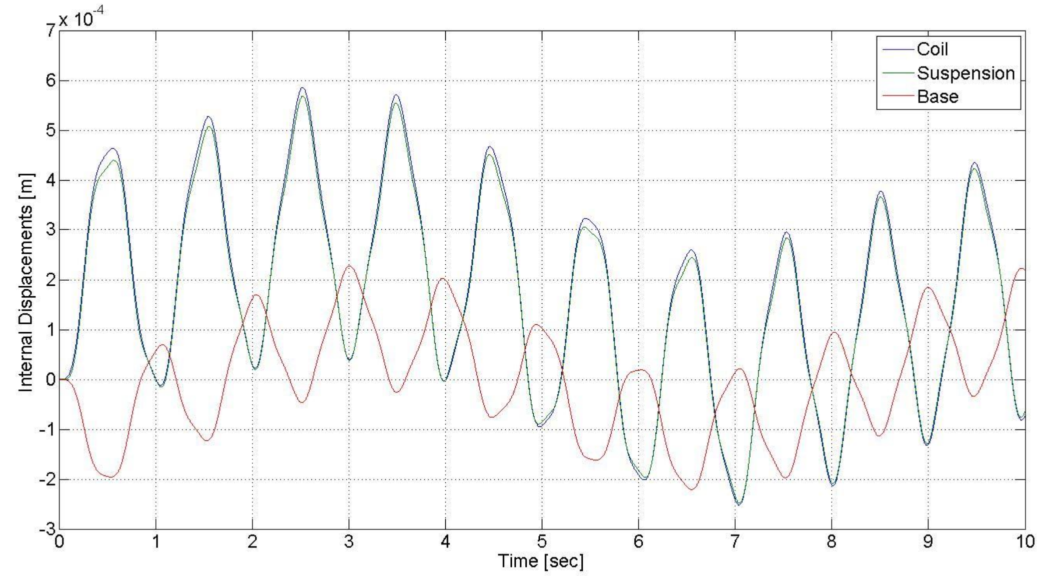

Figure 6: Time domain analysis for the displacements of the internal mass structure.

Looking at the displacements of the internal masses of the shaker reveals that the response pattern, Figure 6, is not as perfectly sinusoidal as that of Figure 5.

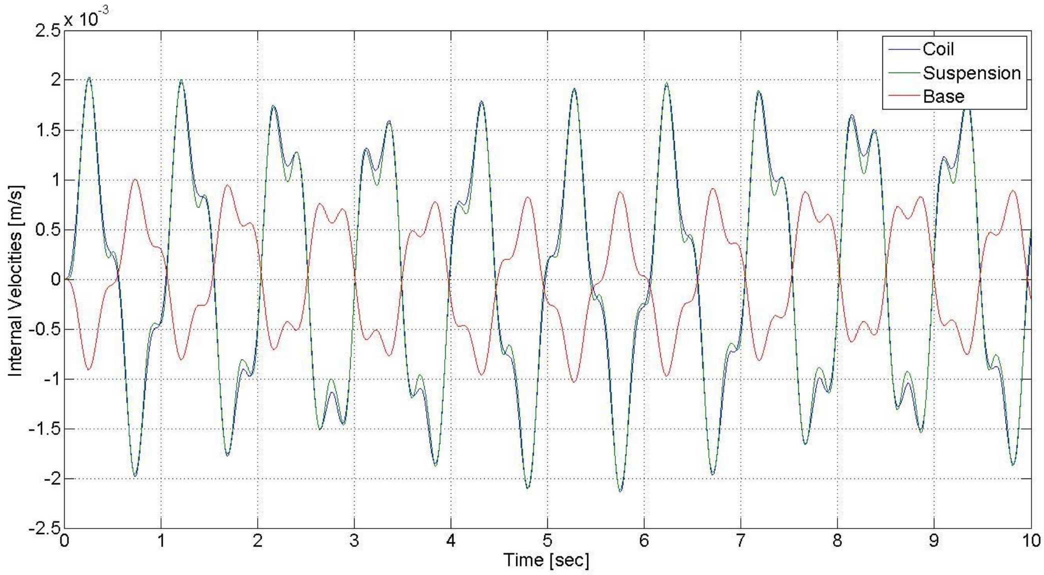

Figure 7: Time domain analysis for the displacements of the internal mass structure.

This behaviour is equally evident in the velocity pattern shown in Figure 7. It is clear that the signal is a concatenation of more than one frequency. This is probably due to the coupling between degrees-of-freedom.

Analysing the Ordinary Differential Equations (ODEs) in the frequency domain produces a series of transfer functions that describe the energy transfer between structural and electrical physics, Figure 8. The time data was transformed to the frequency domain by making use of a 512 point FFT and the transfer function between mechanical and electrical signals was analysed. This analysis reveals that the performance of the shaker is dominated by three modes of vibration represented by the three peaks in Figure 8. These frequencies are important design considerations in the manufacture of the shaker system and as such the characterisation of these is of paramount importance.

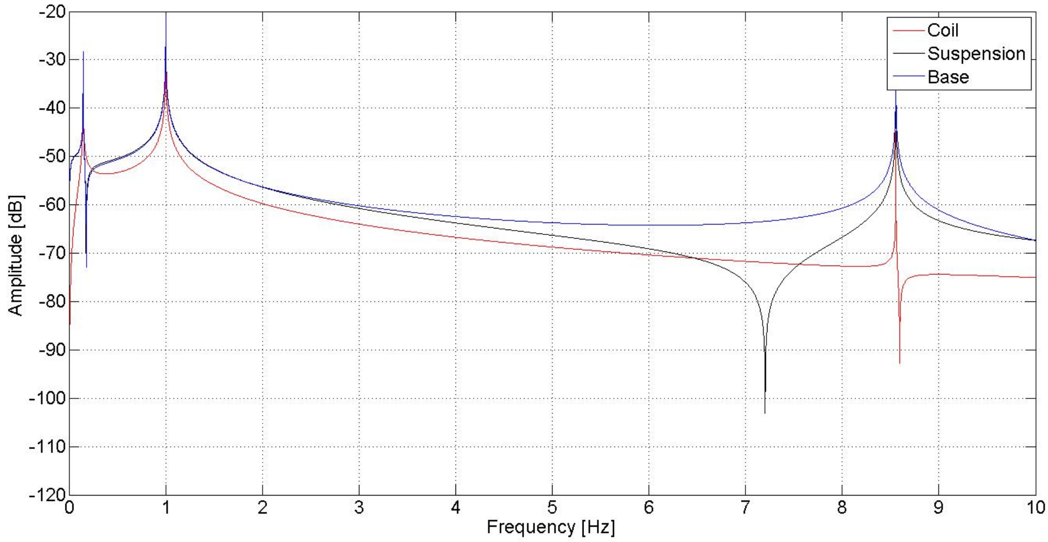

Figure 8: Frequency domain analysis to identify modes of vibration.

4 DISCUSSION

The most important thing to take from the analysis are the features within the frequency plot. Most (if not all) electrodynamic shaker manufacturers provide an optimum frequency range of operation for their shaker. This is based on the resonance conditions shown in Figure 8. This is because at the optimum operating frequency the mass of the components are moving in phase with the mass of the structure, this then means that it takes less power to operate the device, thus there is less voltage and current demand on the coil. One of the main failure modes of a shaker is voltage overload leading to excessive heat in the coil causing blistering of the windings, as such keeping the voltage to a minimum is preferred and knowing the frequency that requires minimum power for operation is crucial to the longevity of the device.

One such shaker performance envelope is given in Figure 9. It is clear from this diagram that a particular frequency the voltage and current demand for a shaker is a minimum and as such so is the power required.

Knowing the frequency of operation of a system prior to actuator selection allows one to design the actuator accordingly so the resonance peaks from Figure 8 coincide with the frequency that the minima occur in the analysis in Figure 9.

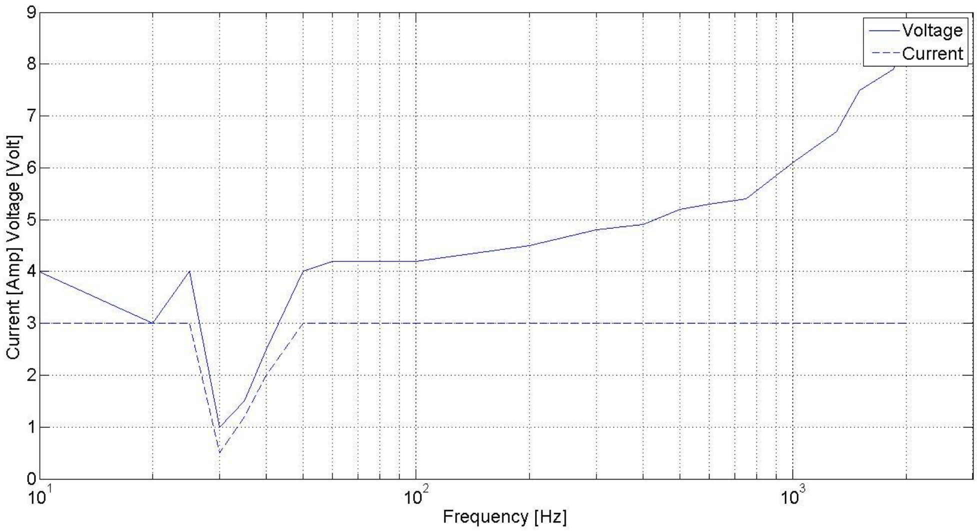

Figure 9: Voltage and Current Demands as a function of frequency for a typical electrodynamic actuation device.

5 CONCLUSIONS

- The mechanical and electrical components of an electrodynamic shaker are introduced.
- A mathematical model consisting of mechanical and electrical components is formulated.
- The model is solved numerically and the results are analysed.
- A discussion is provided giving insight into the importance of the results and the importance of the initial design stage.

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