Impedance Modeling of Modal Exciters

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Abstract

This paper describes a simple Multiple-Input-Multiple-Output (MIMO) testing procedure for developing an impedance model of modal exciters. This method can be used at the test site: before, during and/or after the test. The impedance model describes the current/voltage input to the exciter to the force/displacement output of the exciter. The method uses a simple back-to-back testing method where two exciters are characterized simultaneously. One exciter provides the boundary condition for the other exciter and vice versa. These impedance models can be used to evaluate the health of the exciter and to determine it's response to impedance loading of the fixture and the structure being tested. The influence of the exciter amplifiers, sensors and acquisition systems which are used in the modal testing are also characterized. Several examples are used to illustrate the usefulness of this method in evaluating the exciter systems used in modal testing.

1 Introduction

A special class of electro-mechanical exciters has been developed in the mid 80's specifically for performing modal testing. These exciters were modification of commercial electro-mechanical so that they can be easily located and connected to the test object with flexible stingers. The main characteristic of the exciter is that the exciter spindle was modified so that a thin rod or wire stinger could be used to transmit the force to the test object. A preloaded wire (e.g. piano wire) or a thin flexible rod could be passed through the exciter and the exciter could be fasten to the wire and/or rod with a collet chuck. This stinger is used to decouple the exciter for the test object in the off-axis directions.

One of the most common applications for this type of exciters is a large Multi-Input-Multiple-Output (MIMO) modal test where two to four exciters are used with fifteen to a thousand or more response channels. For this type of test there have been a number of field calibrations and diagnostic items or systems which have been developed for trouble shooting, repairing and recalibrating components of the test system.

In the paper we will briefly review basic concepts of MIMO testing, setup and the types of diagnostic tools that have historically been used to conduct large scale modal test. In this testing there are normally tremendous redundancies in response measurements, losing a few response channels is acceptable. Losing an exciter during a test run is catastrophic; the test has to be rerun. On a large and important test there may be none or only few spare exciters on-site for the testing in case that one of the shakers fails. Shaker are normally very reliable, but if the fixturing that supports the test article changes position or if shaker experience excessive side loads, the flexures' or armature can potentially be damaged. The latest generation of the modal shakers are smaller and lighter with a higher force rating and are somewhat field serviceable. Instead of having two mechanical flexures, there is only one at the top and the lower end is magnetically centered. The shaker is shipped with sets of elements for the upper flexure with difference stiffnesses so the shaker's armature support can be changed or repaired.

In order to check the health of the shaker several field test can be performed. The first test is that a ratio-calibration of the exciter system that is performed by measuring the driving point Frequency Response Function (FRF) on a free-free supported mass. The FRF should be a flat curve that is proportional to the reciprocal of the mass. This test the exciters, data acquisition system and sensors but also provides a check on the calibration. See Figure 3.

The second method is a newly developed simple test that will described in more detail in this paper. The test is a simple "Back-to-Back" (B2B) testing procedure, using the MIMO testing procedure to develop an impedance model of the shakers which can be used to characterize the shaker system.

2 Background

In the late 70's in order to measure a more consistent modal database, a MIMO testing procedure was developed where the structure was excited from several inputs and the response measured at a large number of outputs. The initial testing was performed with a four channel system with two input and two responses to develop the signal processing and excitation methods. The first real testing was performed in the late 70's using an eight channel system with two inputs and six responses (two tri-axial accelerometers). The accelerometers were roved to approximately 100 points. However, the fantasy was to measure all the response simultaneously but the technology was too expensive for the normal users.

Boeing took the first step towards satisfying this fantasy when they conducted the first large channel count MIMO test on the Boeing 767 Aircraft.[1] In this test they measured 128 response channels simultaneous and ADC throughput the data to a large 125 MB disk platter. After an acquisition cycle, the disk pack was move to a different computer for processing and new disk pack installed to test a different configuration of the aircraft.

In the mid 80's, the MB-50 a 50 lbf (222N) exciter was introduced which was the first dedicated modal exciter. By the mid 80's to late 80's , multiple channel test were becoming more common place with the commercialization of the HP 3565 data acquisition system and the PCB Stuctcel[2,3] low cost sensor system. Big companies had calibration laboratories and smaller laboratories relied upon the calibrations supplied by the sensor manufactures and periodically the transducers were sent back to be recalibrated at a calibration lab or manufacture. During the test setup phase or during the test where transducers are moved, they can be stressed, likewise cabling, signal condition, data acquisition can fail, therefore on-site calibration and diagnostic tools were developed to validate the test equipment:

Figure 1 – Drop Calibrator

- The check the absolute calibration of accelerometers and load cells, a simple drop calibration which uses gravity and Newton's law can be used. When the modal acquisition system is used in the calibration this method provides an end to end calibration. The calibration standard is earth's gravitational force at the testing location. The gravitational constant is slightly location dependent but it distribution is known (see Figure 1).

- A second device is a hand help calibrator which calibrates accelerometers against a reference accelerometer build into the hand calibrator. The reference is used to control a small servo loop to generate a $1g_n$ or 9.80665 m/s^2 sinusoidal acceleration level to the base of the accelerometer. The output of the sensors which is cause by the calibrated input signal can be measure directly with voltmeter or can be sampled with data acquisition system providing an end-to-end calibration. See Figure 2.
- A ratio-calibration method which used Calibration Masses to calibrate the force sensor – acceleration sensor combo. The exciter, load sensor, accelerometer, data acquisition system are all used in the ratio calibration process which results in a diagnoses of complete exciter system. Historically, the ratio testing was the primary method of checking the health of the exciter systems.

Since the newer modal systems have the potential of being serviced in the field, a new MIMO testing method has been developed for measuring an impedance model of the shaker in terms of two port input and output model. This model can be used as a potential diagnostic tool.

In the past the mechanical, electrical, magnetic properties of the exciters have been experimentally measured. In fact, very often this has been a laboratory exercise in undergraduate measurement courses. It is not necessary to measure to physical properties of the exciter system, the input output characteristic are sufficient for operational diagnosis.

Figure 2 – Hand Calibrator

Figure 3 – Ratio Calibrator

3 Impedance Modeling (FRF Modeling) a Electro-Mechanical Exciter

A simple two port system is used to model the exciter. A two point system is defined as a system with two ports for energy transfer with two variable at the input and two variables at the output. The input variables are Voltage and Current and the output variables are Force and Acceleration. An impedance model of the system, it this cases refers to a system model based upon using Frequency Response Function (FRF) matrix between the inputs and outputs of the system or:

$$\begin{Bmatrix} F(\omega) \\ A(\omega) \end{Bmatrix} = \begin{bmatrix} H_{FV}(\omega) & H_{FI}(\omega) \\ H_{AV}(\omega) & H_{AI}(\omega) \end{bmatrix} \begin{Bmatrix} V(\omega) \\ I(\omega) \end{Bmatrix} \quad (1)$$

Where $V(\omega)$ = Fourier Transform of Voltage (input)

$I(\omega)$ = Fourier Transform of Current (input)

$F(\omega)$ = Fourier Transform of Force (output)

$A(\omega)$ = Fourier Transform of Acceleration (output)

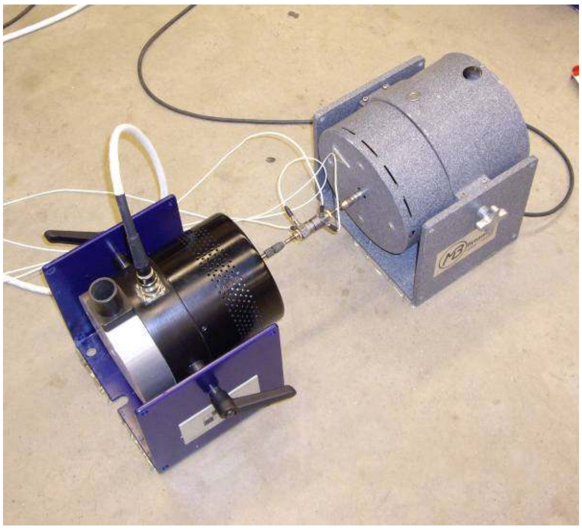
$H_{FV}(\omega)$ = Typical FRF in the case between V input and F output

A standard method for determining the FRF Matrix is to test the exciter in two different configurations:

1. Clamping the armature of the exciter; in this case the acceleration of the output is equal to zero, therefore, the 1st row in the frequency response matrix can be measured.
2. Unclamped the armature, in this case the force is equal to zero; therefore, the 2nd row of the frequency response matrix can be measured.

This method requires a fixture which can clamp the exciter's armature which forces the acceleration to be zero. This is difficult to impossible due to fact that the housing of the exciter is sheet metal and would have to be removed in order to insure that local modes of vibration can be suppressed. Fixed boundary conditions are difficult to build over a wide frequency range. In a large MIMO modal test, very often there are exciters being used from different manufactures of different sizes or vintages. This would require a different adapter for the each type of exciter.

A method was developed for measuring the impedance model which uses the MIMO testing procedure and equipment used in the modal test. Two shakers can be used back-to-back with the same hardware and instrumentation used in the MIMO modal test. An impedance model can be measured for both shakers simultaneously. See Figure 4 for a picture of the back-to-back configuration.



Figure–4 -- Back-to-Back Configuration with MB-50 (50lbf) and 2100E11 (100lbf exciters hot glued to floor

In order to use a MIMO testing procedure the inputs have to be uncorrelated and there is not an option in most exciter's amplifier to generate an uncorrelated signal for the two exciter inputs the voltage and current. If the loads on the exciter changes then the relationships between the two inputs are changed, this is due to the "Back-EMF" cause by the motion of the armature. The Back-EMF is an electromotive force that opposes the current flow input to the exciter but only if the armature is in motion. In other words, the outputs of second exciter have an influence of the inputs of the first exciter and vice-versa.

An uncorrelated random excitation input is applied to each exciter's amplifier. These two input signal are the input signals and the V, I, F and A signals for both exciters are the response signals in the [2x8] MIMO procedure. This measures a FRF matrix that is 2 by 8. This matrix is computed and archived but is not the measurements that characterizes the exciters but may be important in a future diagnostic effort.. The two port system described by equation (1) is the desired impedance model. This two port model for each shaker corresponds to the two by two MIMO solutions for each shaker. The two input signals for each exciter are uncorrelated by the influence of the other exciter.

One of the requirements for using this procedure is that the exciter amplifier must have both a voltage and current monitor for the signals send to the exciter. Most modal shaker has an amplifier that does monitor these signals because they are frequently used for MIMO and Tuned Normal Mode Testing. If the current is not monitored then it is necessary to build or buy a current monitor. The voltage is easy to monitor although it may be necessary to make a special cable adapter.

3.1 Examples of the MIMO Back-to-Back Testing Method

Two tests of the MIMO testing method for measuring an impedance model of a modal exciter system:

1. The first test was performed in the University of Cincinnati's Structure Dynamics Research Laboratory (UCSDRL). This test was used to measure an impedance model for the shakers used to test the H-Frame structure which is a UCSDRL Laboratory test structure. The H-Frame has been used in the Vibration III, SDA II and SDA III graduated courses and as a test item for many Master and PhD thesis projects for the past twenty plus years.
2. The second was conducted at The Modal Shop on two of model 2100E11, The Modal Shop's 100 lbf modal exciters:
    a. The 1st was a shaker that was sent back for refurbishment.
    b. The 2nd was a new shaker which was fresh from manufacturing and was going through acceptance testing.

3.1.1 UCSDRL H-Frame Test

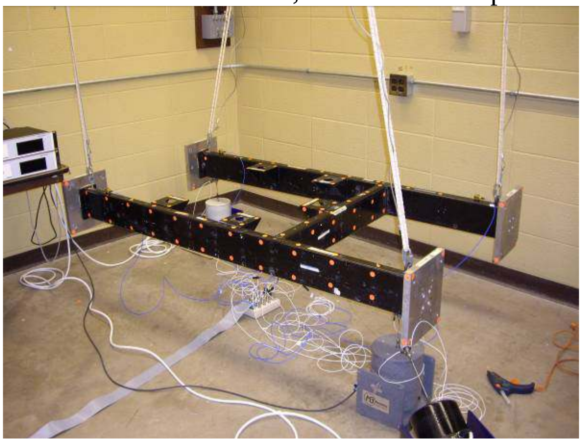


Figure 5 – H-Frame MIMO Test Setup

The 1st test of the MIMO test was conducted in the UCSDRL, using the historical H-Frame test structure. This structure when not being used in research or for thesis work is used as a teaching tool to demonstrate various testing procedures and signal processing methods and as a test item for the SDA II and III graduate courses. One of the demonstrations is MIMO testing. Figure 5 shows the test set-up with three modal exciters mounted to H-Frame, with two vertical exciters on the two opposite's corners of the H-Frame and one skewed with a component in the vertical, lateral, and axial directions.

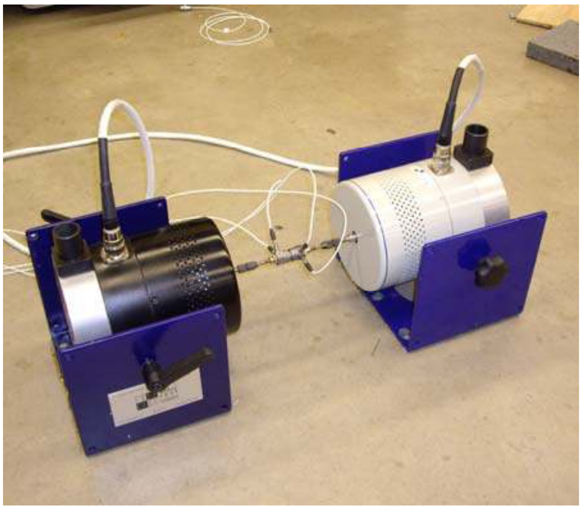


Figure 6 -- Back-to-Back new 2100E11 (black) and old 2100E11 (white).

The three exciters were tested using the B2B testing method. The MB-50 and the older 2100E11 were tested with the newer 2100E11 common to both. The exciters were carefully aligned and mounted to the floor of the Laboratory using hot glue. Each exciter was tested with its amplifier, stinger, impedance head, using the MIMO test system. The test system consisted of a Dell notebook computer connected to VXI Technology's VXI system; the three exciters systems listed above; three PCB model 288D01 Impedance Heads and a small number of other accelerometers. The test setup for the newer 2100E11 and MB-50 is shown in Figure 1 and the test setup for the newer 2100E11 (black) and older 2100E11 (white) is shown in Figure-6. A close up of the stinger-impedance head installation is shown in Figure 7.

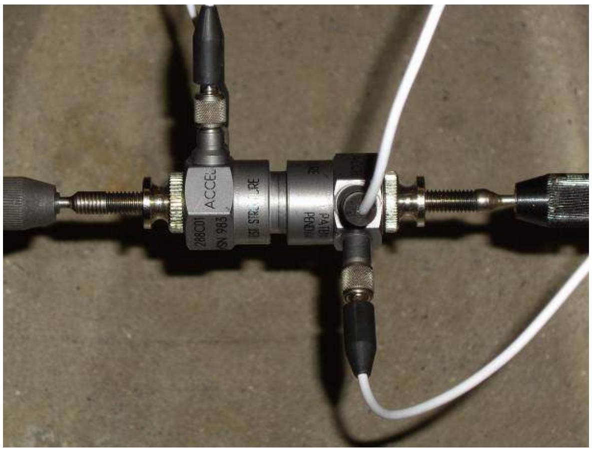


Figure 7 -- Close up of impedance head installation

The test procedure was to use a MIMO testing procedure but the data was recorded using the HP DAC Express program into an throughput file. The data from the throughput file was processed with a small MATLAB script which was written on-site. The [2x8] FRF matrix was computed for the complete Back-to-Back configuration and for the [2x2] FRF impedance model for each exciter. A typical plot generated for the FRF elements of the impedance matrix is shown in Figure 8 for the new Modal Shop 100 pound exciter. These FRF’s were measured with the B2B setup mounted rigidly with hot glue to the floor of the laboratory floor. This will be compared to data taken with a quick test set-up configuration which was used in the 2nd test case.

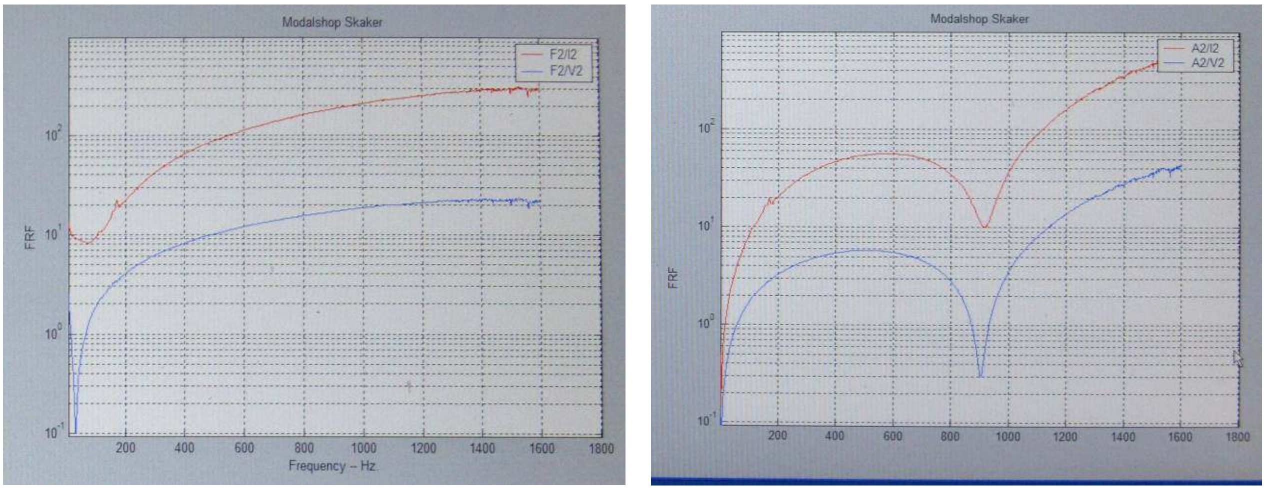


Figure 8 – B2B impedance data for The Modal Shop 2100E11 – 100 lbf shaker.

3.1.2 Modal Shop Testing

A second test was performed at the Modal Shop where an old Modal Shop 100 pound exciter and newly manufactured exciter which had not completed the acceptance testing. This test was to evaluate:

1. A quick setup which could easily be implemented in the field.
2. A standard MIMO testing program which was used to compute the [2x8] B2B matrix and the two [2x2] FRF matrices for the two exciters.
3. The case where mass was added to the stinger-armature of one of the shakers.

In this test instead of hot gluing the shakers to a stiff laboratory floor the two shakers were mounted upon a fairly flimsy table top and connected together with a stiff beam using two c-clamps (See Figure 9). The beam and the plane of the table top aligned the two shakers in two axes and the vertical axis of the shakers was aligned by sight. The shakers in many tests are mounted on support systems which are not very rigid and this testing configuration sort of simulates this condition.

The time required to setup this configuration was a few minute given the beam and c-clamps. This did not include the time to setup the VXI measurement system and to connect it to the B2B testing site. The B2B testing configuration is shown in the following set of pictures.

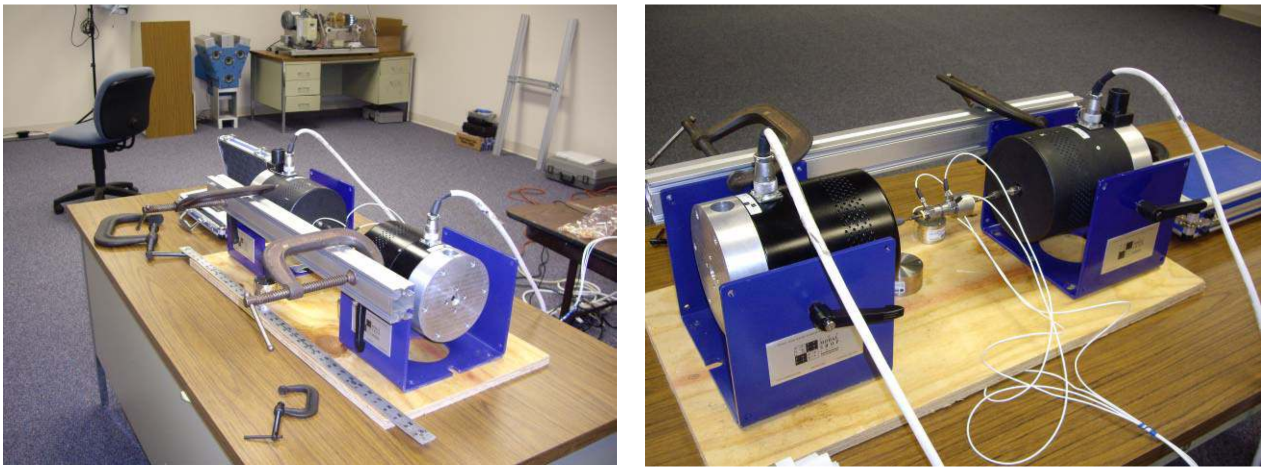


Figure 9 -- Pictures of the test setup for The Modal Shop test. The B2B is not glued to the desk top or to the plywood board. The two shakers are connected by the beam which is c-clamped to the shaker stands.

Figure 10 -- Pictures of the B2B Impedance Heads no-mass and mass additive configurations.

The B2B testing was performed with a VXI Technology's VXI system connected to an IBM tablet computer and using the MIMO MATLAB testing module which is used by UCSDRL to perform routine MIMO testing. The VXI system included a 6 channel source card and 16 channels of data acquisition. The set-up was similar to the test performed in the 1st test except that the data was processed in real time instead of being ADC throughput. Two uncorrelated signals were output to the exciter's amplifier and the [2x8] FRF matrix was measured in a 1st pass and the two [2x2] B2B FRF matrices was measured in a 2nd pass to determine the impedance model for each exciter.

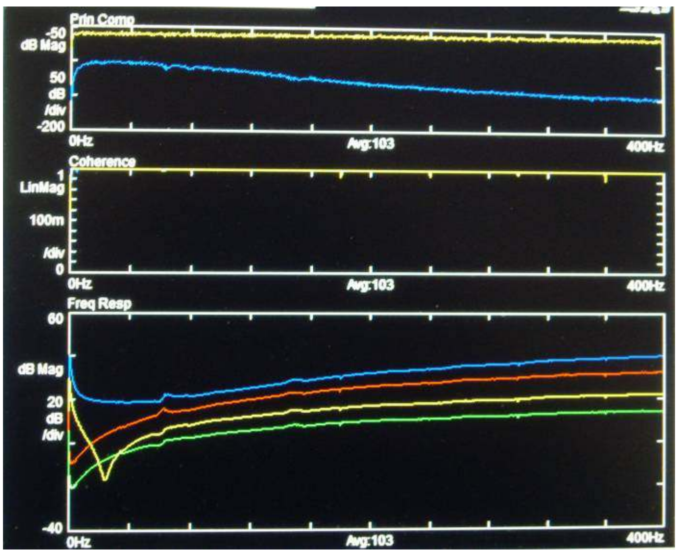


Figure 11 – Screen capture of the MIMO acquisition of a typical measurement cycle.

In Figure 11 a picture taken of the MIMO real time display for the [2x2] FRF matrices is shown for a typical measurement. The upper display is the Principal Component, the middle is the multiple coherence function and the bottom is the four FRF measurements. It is clear from the principal component display that the voltage and current inputs are highly correlated. This was expected. The small differences are measurable and are due to the Back EMF that is generated by the motion of the armature. This effect can be measured and is included in the [2x8] matrix of the response on the voltage measured at the inputs to exciter 1 due the random signal input in the amplifier of exciter 2 and vice versa.

The measurement involved in the B2B testing is very simple and straight forward process which can be perform using any commercial modal system capable of MIMO testing.

The test was performed on several configurations where mass was added to the stinger – armature of the older exciter. There were three configurations

1. No, mass added to the exciter.
2. A small mass.
3. A larger mass.

The results are consistent for the three cases so the two extremes will be presented in the following figures. The results were plotted in MATLAB for the configurations -- the no mass case and the large mass case.

The 1st Figure in this sequence is the data collected for exciter(1) with the added mass applied to exciter(1) and the influence of the mass is apparent for the F/V and the F/I FRFs. See Figure 12.

The next Figure demonstrates the results for the exciter(2) when the mass is added to exciter (1). This was the expected result.

In the next two figures the data for a higher frequencies range is shown. In Figure 14, the FRF measurements for the exciter (1)with mass added to the exciter(1) for the 1600 Hz. Range. There is significant influence of the response between the no mass added and the large mass added result. The large dips in the FRF measurements are most likely due to modes of vibration that influence the motion between the area in the exciter where the magnetic force are generated and the location of the

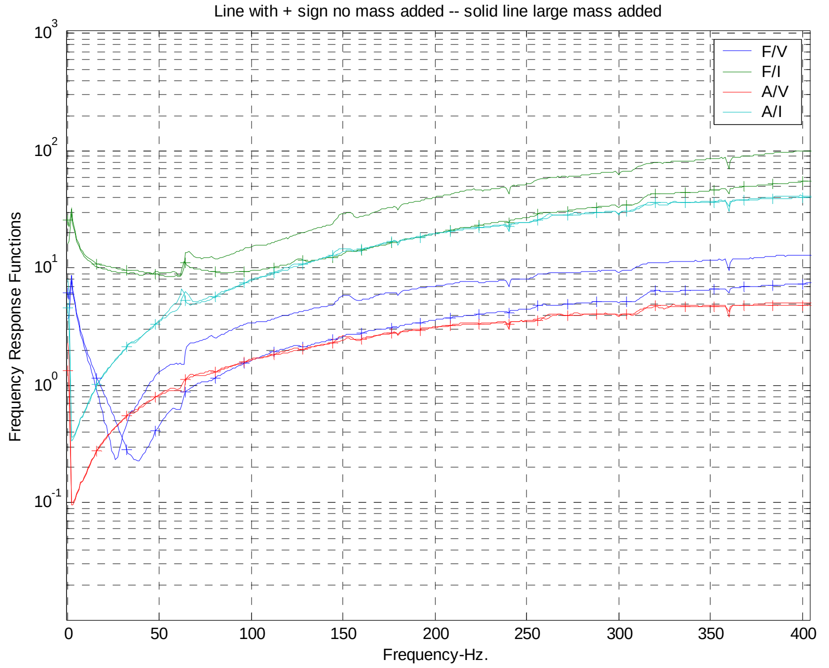


Figure 12 – Impedance measurement for the exciter(1) with additive mass attached to exciter(1) – 400 Hz. Range.

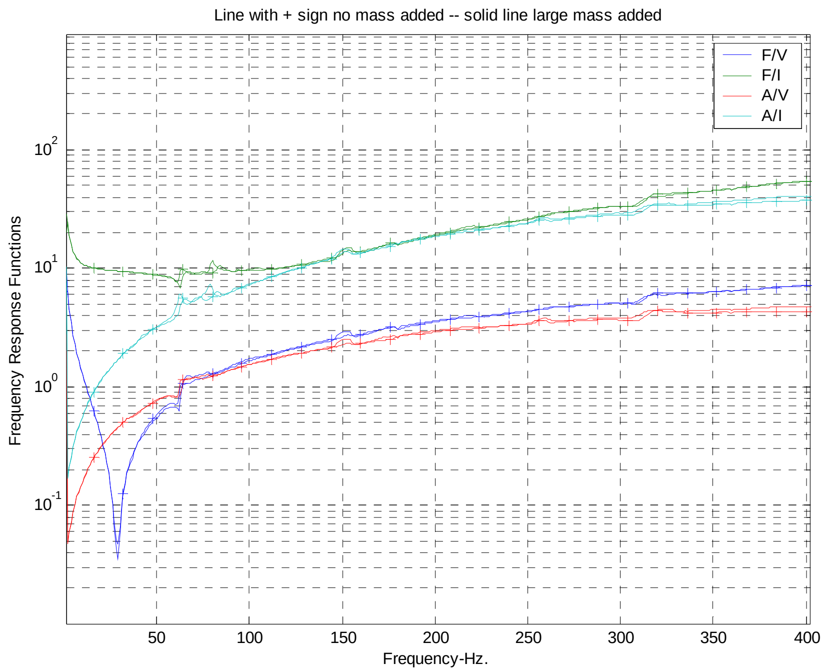


Figure 13 -- Impedance measurement for the exciter(2) with additive mass attached to exciter(1) – 400 Hz.

impedance head. The nature of the modes cannot be determined from these measurements that would require a modal survey of the exciter, armature, and stinger system.

In Figure 15, the data for the exciter(2) with mass added to exciter(1) shown.. There is an effect near the 800 Hz dip which not expected. It is most likely due to an internal mode of vibration in the armature-stinger and this mode is being influenced by the other exciter. It should be noted that the impedance heads, only measures the force and acceleration in the axial direction. This mode could be a lateral mode or a non-linearity response. It would require a modal survey of the exciter to determine the characteristics of this mode.

There is a second, interesting observation on the 800 Hz dip.

During this testing four 2100E11 – 100 lbf exciters were tested using the B2B testing method and all the exciters had a dip in the 800 to 880 Hz. Three had a sharp single mode dip due to a mode at approximately 800 Hz. The fourth and the one which was affect by the other exciter in the above example had two modes in the 800 Hz range which may indicate a potential alignment, adjustment, and/or assembly problem. This would require additional testing to determine what causing the problem.

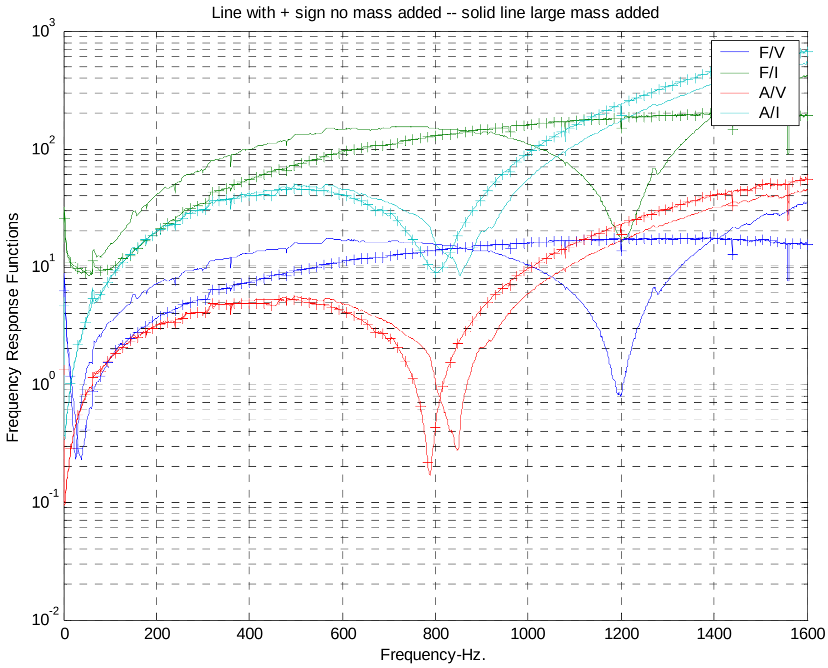


Figure 14 – Impedance measurement for the exciter(1) with additive mass attached to exciter(1) -1600 Hz.

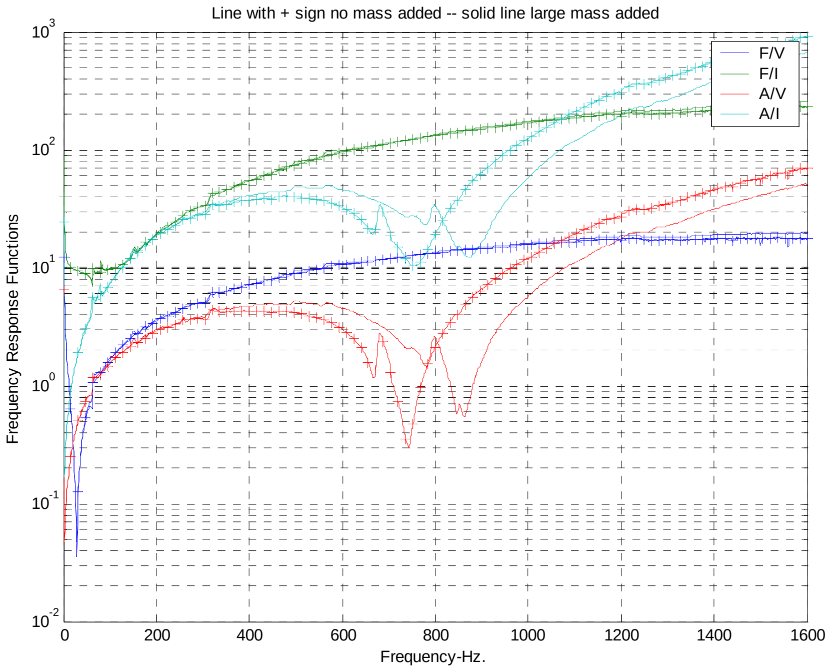


Figure 15 -- Impedance measurement for the exciter(2) with additive mass attached to exciter(1) – 1600 Hz.

4 Conclusions

In this paper the feasibility of a simple testing method that can potentially be useful as diagnostic method for evaluating the general health of exciter system was evaluated. This testing procedure uses the standard measurement and signal processing techniques that is used in conducting a large MIMO test. The fixturing is simple and only a few non standard cable may be required. For the testing used in this study, non-correlated random excitation was used but sine testing or any other testing methods for measuring FRFs could be used. For example, in order to study the linear of the exciter sine testing could be useful.

The main purpose of this study was to evaluate the feasibility of the testing method and it appears that it justifies a more complete study. It would make an excellent Masters Thesis project where exciters with known defects are tested to construct a diagnostic database and to develop aids for field servicing the exciters system.

A second application is using the impedance model of the shaker for modeling and controls applications.

5 References

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