Effects of shaker, stinger and transducer mounting on measured frequency response functions

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Abstract

Electrodynamic shakers are utilized in many experimental modal tests and general structural dynamic testing. The physical aspects of shaker, stinger and transducer setup can result in anomalies that are often misunderstood. Many times measurement artifacts related to mounting and dynamic coupling between shaker, stinger and test object can appear, affecting test results.

This paper overviews some of the common problems that are typically encountered. Measurements are made on several structures to better demonstrate the effects of these issues. These include shaker alignment, stinger selection, reciprocity and other practical concerns that must be clearly understood in order to make the best possible overall measurements.

1 Introduction

Attention to excitation test setup details is critical for the acquisition of high quality force input measurements. These measurements are critical as they are used in the processing of all Frequency Response Functions (FRFs) which in turn are fundamental for obtaining consistent and accurate modal results.

Therefore the challenges for acquiring good data for experimental modal analysis should not be overlooked. Despite all the advancements in data acquisition hardware and modal analysis software, the old saying “garbage in, garbage out” will apply if high quality measurements are not available.

The following sections present some practical guidelines and experience-based insights related to shakers, stingers, force sensor type, location, alignment, stinger length, force levels, shaker quantity and the effects of them on the FRF measurements and the modal test results.

2 Cases studied

For the development of high quality FRFs for use in any structural dynamic modeling scenario, many times shaker excitations are utilized. There are a variety of test situations that have an effect on the adequacy of the measurements obtained. Issues related to stingers, impedance transducers, force level, reciprocity, single excitation and multiple excitation are a few of the very critical areas of concern. The following sections are broken down to address measurements and considerations in each of these areas. These are measurements from experiences with many different structures over the years. Each subparagraph will discuss some of the issues related to the particular test set up and the results obtained while providing some insights on making improved measurements.

2.1 Stinger location

The function of the stinger (or quill) is to decouple the shaker from the test structure. While all stingers have some bending stiffness, if the proper location is chosen on the structure this stiffness will not contribute to the stiffness of the structure. This can be a major issue when the structure is very compliant, as these structures can have large displacements and corresponding rotations in the structure's response. The most problematic is the rotational stiffness at the location of stinger attachment which may effect higher frequency mode shapes.

A candidate structure shown in Figure 1 was used for SISO measurements; FRFs were taken at three different heights. While no specific discrepancies are consistent at any one of the heights considered, a reciprocity check between upper and lower measurements shows differences as seen in Figure 1. The inconsistency in the measurements indicates that there are effects from adding the shaker at different locations on the structure. Clearly some of the frequencies are different from the various shaker height locations. This can be due to the stinger stiffness which may have a more significant effect on the higher modes as they exhibit greater curvature than the lower order modes of the upright portion of the structure. (Note that all measurements taken are not shown to reduce clutter in figure; this figure is typical of results obtained for all heights investigated.)

One very important item to note is that the stinger is intended to impart motion only in the axial direction and the force imparted is intended to only be in that direction. However, any rotation of the structure causes bending in the stinger and is not accounted for in the FRF measurement; this then introduces stiffness in the structure which affects the frequencies of the structure to some degree. In addition, the force gage does not measure any moments imparted from these rotations and is only designed to measure axial motion.

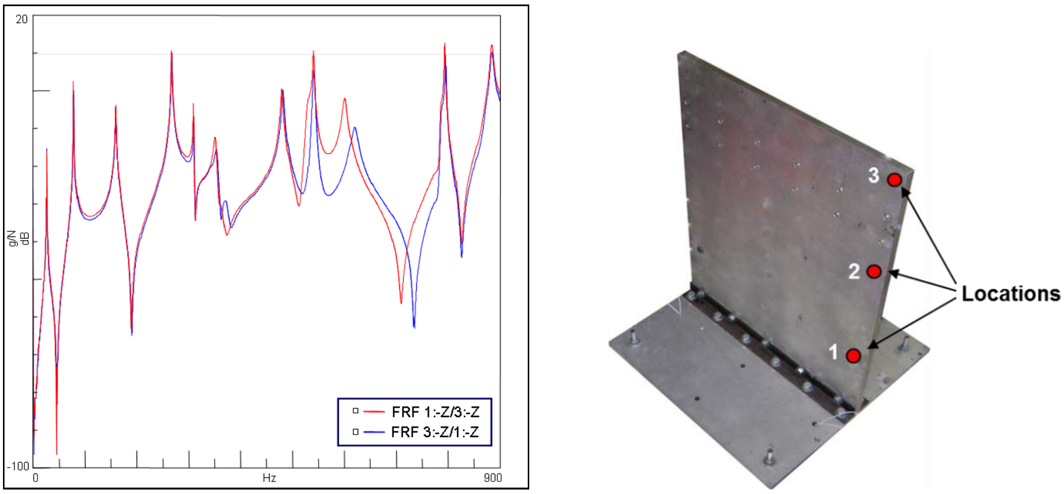

Figure 1: Reciprocity measurement between upper and lower SISO measurements

2.2 Stinger alignment

Many times the set up of the shaker and stinger can be difficult. The alignment of the shaker and stinger is a very important item of concern when the structure and shakers are set up for testing. Misalignments are a cause for concern. The effects of stinger misalignment are examined in this case. A 5 inch (127mm) stinger length (from the shaker head to the structure) was attached to the structure and the shaker was shifted to have approximately 10 degrees of misalignment. Figure 2 displays this measurement compared to the aligned shaker and impact measurements.

With the shaker misalignment, measurement differences are clearly seen in the FRF in the 400-450 Hz region. The specific reason for the differences may be due to a combination of effects including the intentional misalignment that was introduced into the measurement. With a better aligned shaker, this frequency band also had an extra peak, possibly due to a resonance of the stinger. While these results are not completely conclusive, one clear statement that can be made is that care needs to be exercised to assure that the alignment is proper. Misalignment can cause distortion of the measured FRF.

Another misalignment issue lies in the stinger itself. This can result from misalignment of the shaker (as just presented) or can result from poor fabrication of the stinger system. Any misalignment can result in the possibility of bending of the stinger. Figure 3 shows a damaged stinger used for testing and a comparison of the measured FRFs with a good stinger. As shown in the figure, the mode at approximately 1130 Hz is completely distorted when the damaged stinger is used.

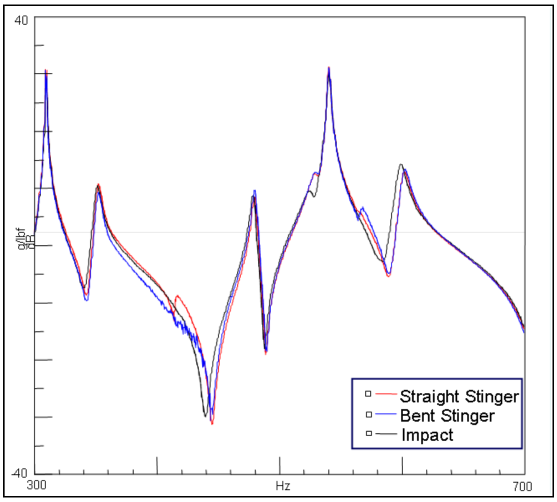

Figure 2: Intentional stinger misalignment

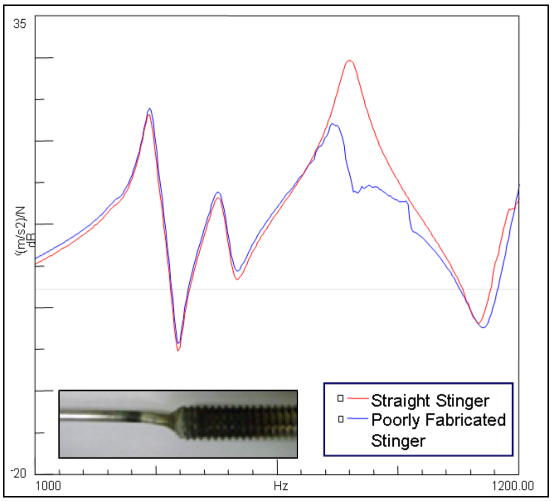

Figure 3: Poorly fabricated stinger assembly

2.3 Stinger length

While the location of stinger attachment may already be pre-determined, the stinger length can be adjusted. This parameter can have a significant effect on measured FRFs. If care is not taken in a shaker test setup, measured FRFs can be easily corrupted. A quick preliminary impact test is recommended in order to confirm the accuracy of the shaker test.

In this case, three different quills supplied by The Modal Shop were used - a 2150G12 (1/16 inch [1.59mm] diameter steel rod), a 2155G12 (3/32 inch [2.38mm] diameter steel rod), and a K2160G (0.028 inch [0.07mm] steel piano wire). Lengths were varied from 1 to 7 inches (25.4 to 178mm), and the shaker was used in both fixed and hanging positions. Figure 4 shows the measured FRFs of the 1/16 inch (1.59mm) drill rod at different lengths. For these measurements the shaker was fixed at the lowest attachment point, although similar results are obtained with all the stingers.

The discrepancies in the measured FRFs are clearly illustrated in Figure 4. No stinger length matched the impact measurement exactly, although a 3 inch (76.2mm) stinger length seemed to be ideal for this structure. While a 3 inch (76.2mm) stinger is ideal, a 5 inch (127mm) stinger yields differences in the FRFs. Piano wire obtained accurate FRFs at shorter lengths than the quills, typically around 1 inch (25.4mm). Generally, if the stinger is too short, the structure will have increased stiffness which can lead to shifts in mode frequencies. On the other hand, a stinger that is too long can introduce additional peaks due to stinger resonances.

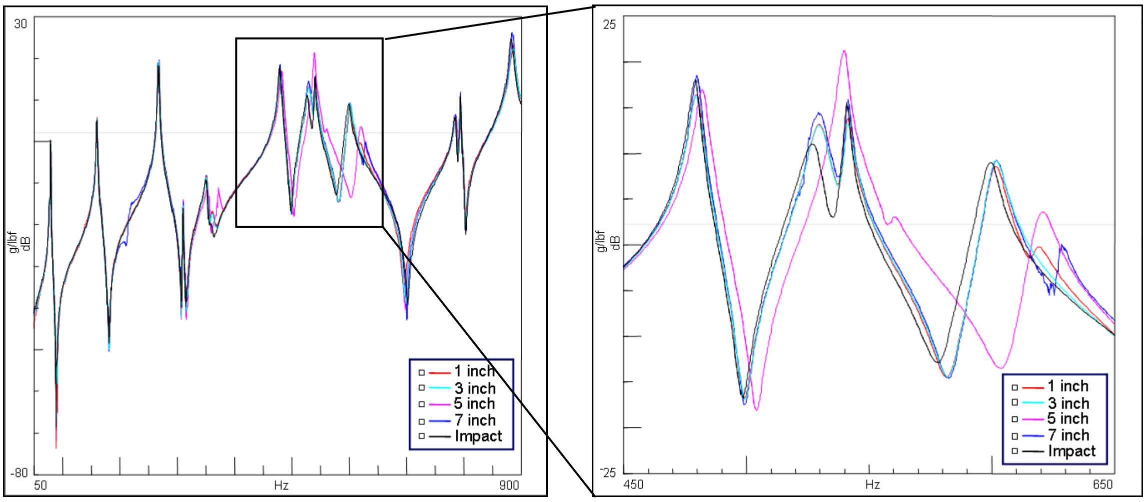

Figure 4: Stinger length comparisons

2.4 Stinger type

While steel threaded and drill rods are the most commonly used stingers, piano wire and nylon threaded rods are also available. This case will compare these stingers to show what effects each can have on the test structure. Five different types of quills supplied by The Modal Shop were used - a 2150G12 (1/16 inch [1.59mm] diameter steel rod), a 2155G12 (3/32 inch [2.38mm] diameter steel rod), a 2120GXX (10-32 Threaded Steel Rod with three different lengths, 9, 12 and 18 inches [228.6, 304.8, 475.2mm]), a 2110G12 (10-32 12 inch [304.8mm] Threaded Nylon Rod), and a K2160G (0.028 inch [0.07mm] steel piano wire). Ideal lengths determined by the previous case were used with the steel rod and piano wire, whereas the threaded rod was at set lengths. The shaker was used in both fixed and hanging positions. Figure 5 shows typical FRFs comparing measurements obtained with the various stingers.

While the overall measurements compare well, closer examination shows discrepancies in the threaded steel rod measurement. The discrepancies were not surprising as the 2120GXX stingers are much thicker and stiffer compared to the thinner and lighter 2150G12 and 2155G12 steel rods. An extra mode appears around 520 Hz and the amplitude is slightly decreased in the following two modes. With all stingers a common frequency shift occurs and increases with frequency. When setting up the test, the effects of each stinger can vary dramatically depending on the mass and stiffness of the test structure and must be considered.

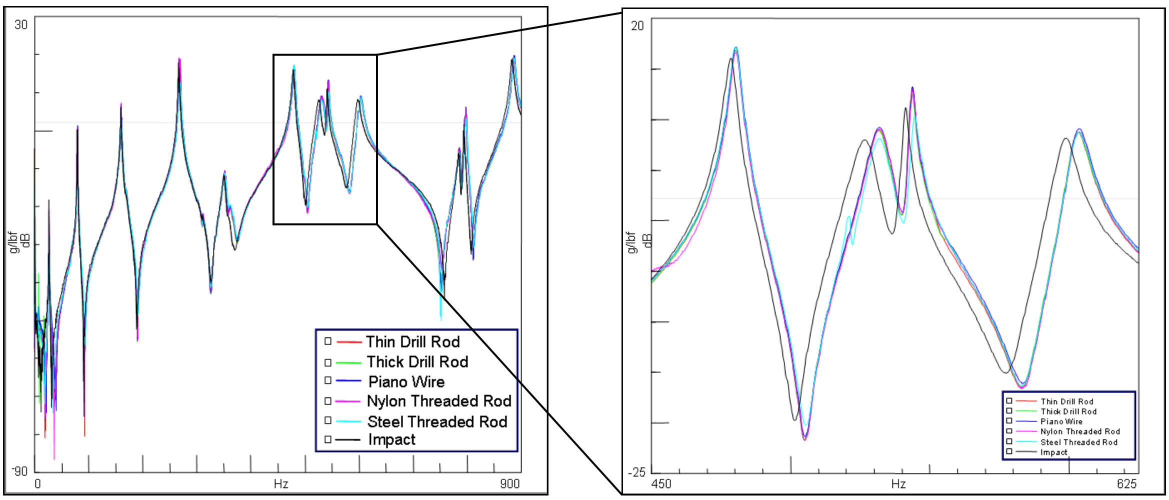

Figure 5: Stinger type comparison

2.5 Sleeved stingers

Many times sleeves can be added to the stinger to stiffen the stinger in an attempt to impart more force to a higher frequency and prevent the stinger from buckling. It is important to realize that this may have an effect on the measured response function, especially when the structure has local flexibility at the shaker attachment point. Figure 6 shows the comparison of the measurement of a system with and without sleeves attached to the stingers. When comparing the sleeved and unsleeved stinger setup, the first thing to notice is that the higher frequency portion of the FRF is very different. The sleeves have an obvious effect.

However, at a lower frequency range the two FRFs show very little difference. In the mid-frequency range, the results show some change in the measured FRFs (especially when looking at the zoomed in portion of the measurement). The sleeves tend to stiffen the stinger arrangement. As the frequencies and mode shapes at higher frequencies have more curvature, the effect of the sleeves on the stingers becomes more and more pronounced. The effects of the sleeve stiffening becomes more pronounced as the local flexibility of the structure becomes smaller and smaller. This may not be readily apparent when performing the test. The easiest way to identify if this is a concern is to test the structure with and without the stiffening sleeves on the stingers.

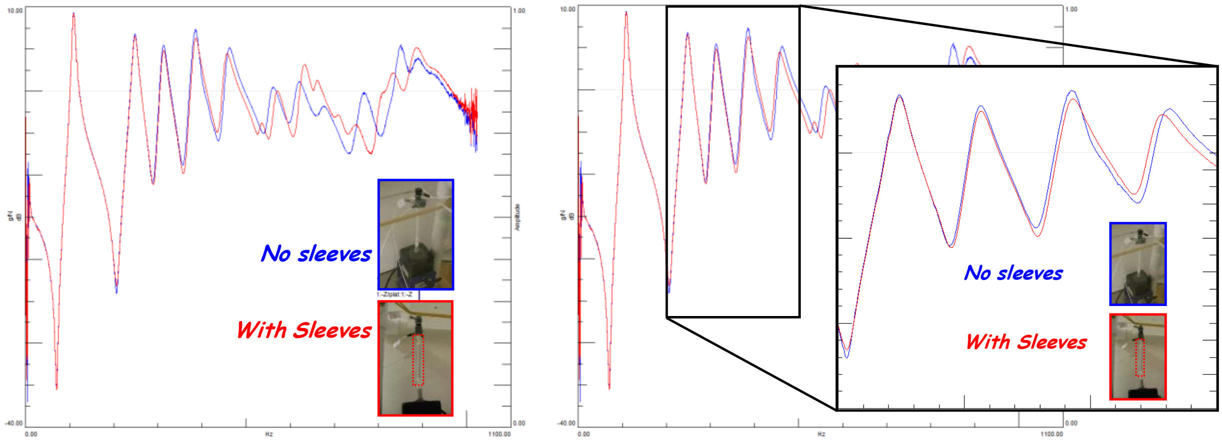

Figure 6: Sleeved vs. unsleeved stinger comparison

2.6 Location of force gauge or impedance head

The force gage or impedance head must always be located on the structure side of the shaker and stinger test set up. If the force gage is mounted on the exciter side, then the dynamics of the stinger become part of the measured function. In Figure 7, two configurations are shown – one with an incorrect force gage or impedance head setup and another with the proper force gage or impedance head set up. The left portion of the figure shows the incorrect set up and the right side of the figure shows the correct set up. The FRF measurement on the left results from the improper arrangement and the one on the right shows the measurement with the proper set up. Clearly, the two drive point FRFs are significantly different. That is because the improper test set up configuration contains the dynamics of the structure which includes the dynamics of the stinger set up. It is imperative to mount the force measuring transducer on the structure side of the test set up.

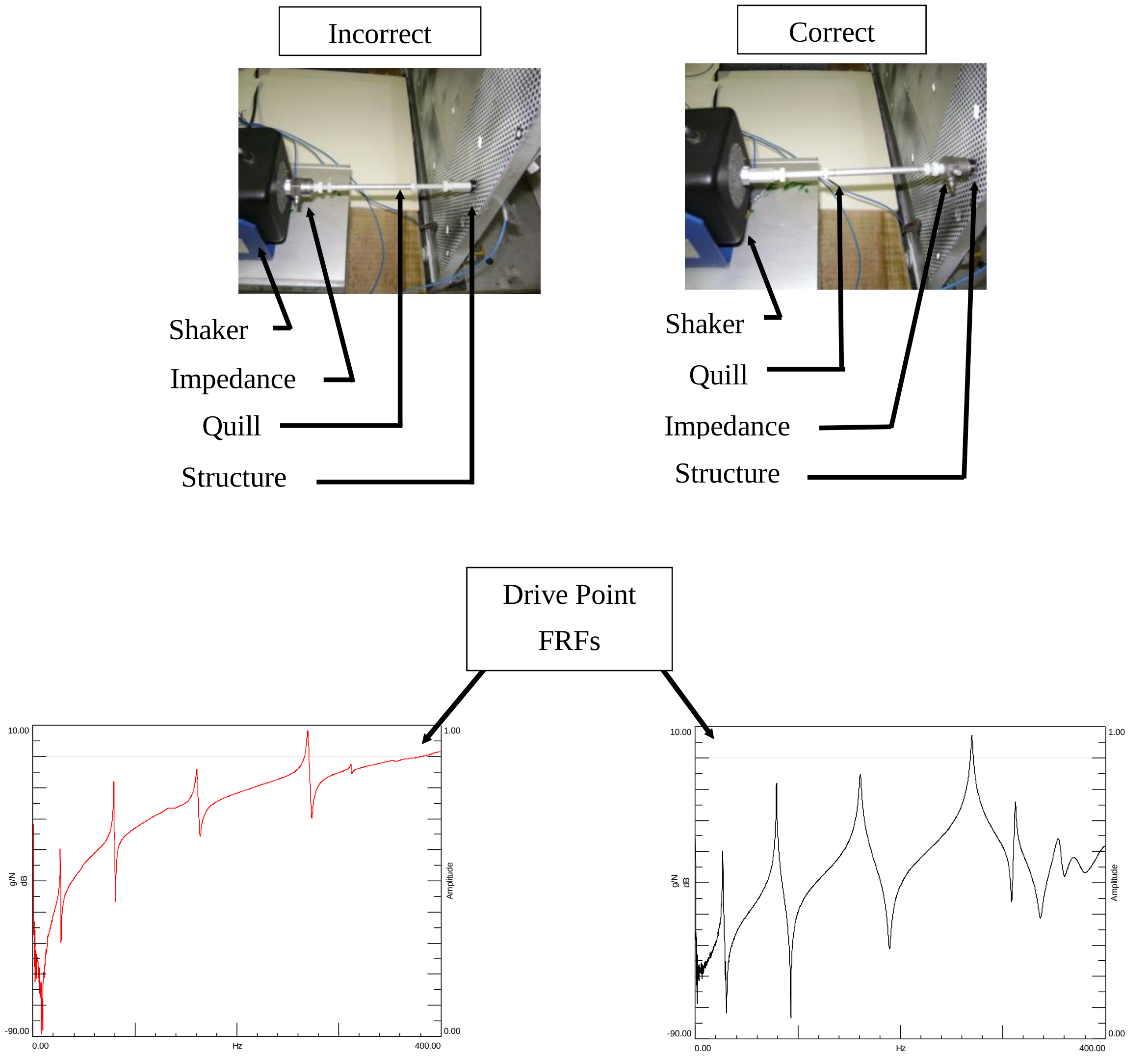

Figure 7: Effects of incorrect and proper test setup of the stinger/force gage arrangement

2.7 Impedance transducer vs. force transducer with accelerometer

An impedance head is a transducer that measures both force and response in one device. FRF measurements that involve reciprocity require special attention to alignment of the force gage and accelerometer. In Figure 8, three scenarios are shown. In the upper left FRF, the accelerometer is intentionally misaligned with respect to the force gage to illustrate the resulting differences. In the lower left FRF, the accelerometer is aligned as best as possible but differences can still be seen. In the lower right FRF, an impedance head is used to minimize the alignment issues that can result. Clearly, the measurement with the impedance head is preferred method of measurement for these critical FRFs. A combination of a separate force gage and accelerometer is often used, but time and time again this measurement proves less accurate than those obtained with an impedance head.

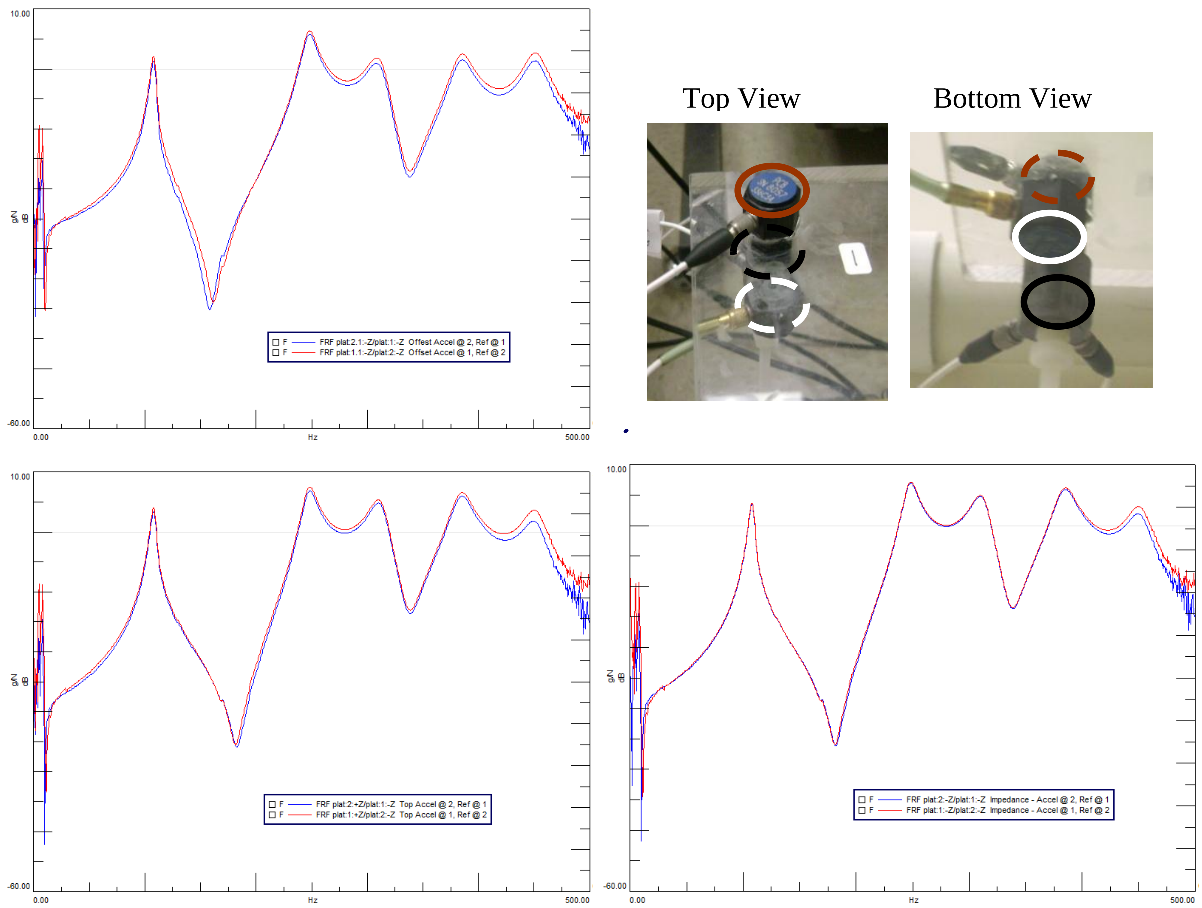

Figure 8: Comparison of FRF with offset accelerometer (top left), with accelerometer aligned as best as possible (lower left) and impedance head (lower right)

2.8 High shaker force levels

In modal testing, the intent is to use lower levels of excitation and identify system characteristics – the test is not intended to provide operating level input excitations. In fact, if higher levels are used, sometimes nonlinear characteristics of the structure are excited. The overall measurement becomes distorted and not particularly useful for modal parameter estimation. This is also dependent upon what kind of structure is being testing. If it is a very simple component of a larger system and the component itself is fairly linear, using a single shaker with an appropriate force level specified will not present problems.

But when the structure becomes more complicated (with many components assembled together to form a system), then the ability to provide a force excitation to measure all the locations on the structure to identify the mode shapes can become more difficult. This can then be compounded when the various components are attached with mounting devices to isolate all the components from each other. It becomes difficult to provide an adequate excitation from one shaker location while making adequate FRF measurements at all the specified response points. It then becomes necessary to “crank up the signal” to obtain measurable vibration at all the response locations. When this is done, nonlinearities will likely be excited and the overall measurement will be degraded.

A recent test on a large propulsion system had an isolation system intended to isolate all components for vibration transmission considerations. Specific data is not able to be shown. A laboratory structure with several components attached through an isolation system illustrates the problem of using just one shaker to excite the system.

The laboratory structure is shown in Figure 9 with three plate components attached with isolators to a larger frame structure.

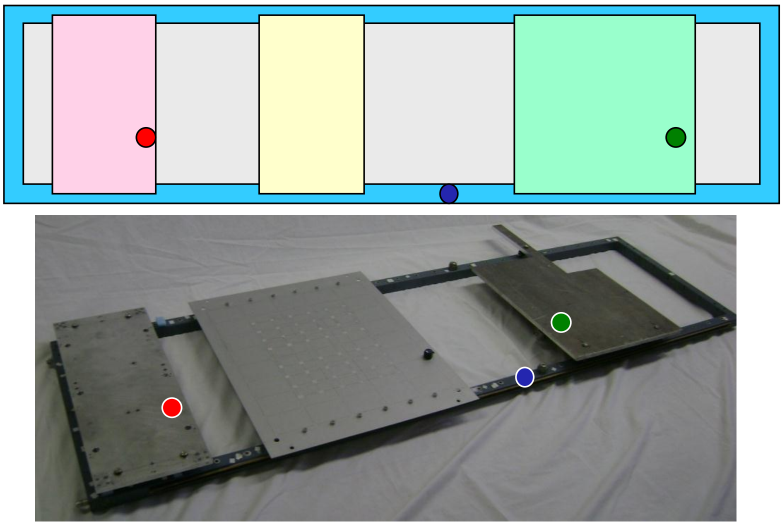

Figure 9: Laboratory structure with isolated components

A single shaker was attached on the main frame and FRF measurements were made. In addition, a three shaker MIMO test was also conducted to compare the measurements obtained. Figure 10 shows a typical drive point measurement (on the main frame in this case). The FRF in red is related to the SISO test. Figure 10 also shows the same FRF (black) obtained from the three shaker MIMO test conducted with much lower overall excitation.

In looking at the FRF, it is clear that the SISO FRF obtained is not the same quality as the MIMO FRF obtained using lower overall shaker excitation levels. This is especially true when looking at the coherence. A cross measurement of even poorer quality is shown in Figure 11. Again the FRF and coherence are seen to be much worse from the SISO test.

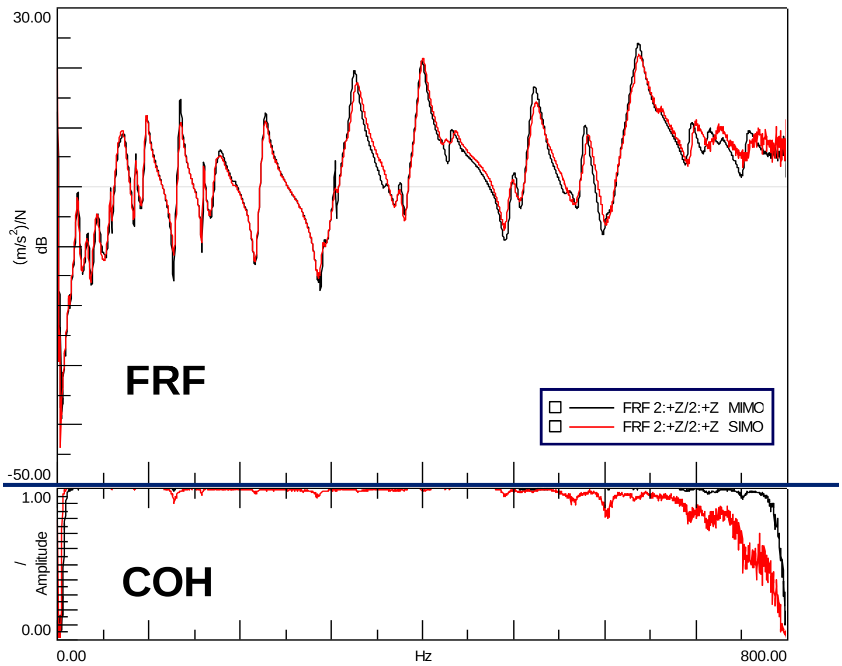

Figure 10: SISO vs. MIMO FRF drive point measurement

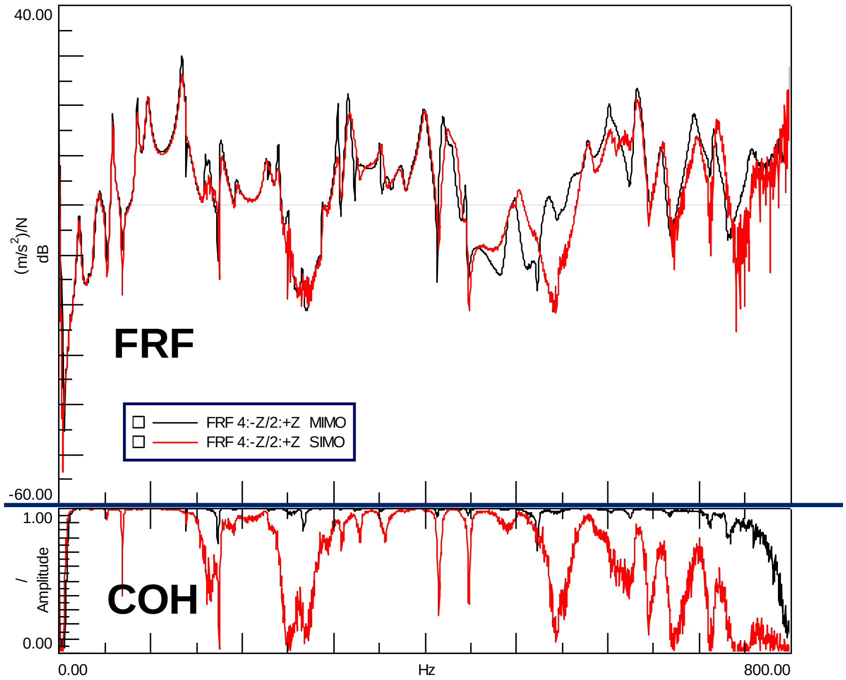

Figure 11: SISO vs. MIMO FRF cross measurement

2.9 MIMO vs. SISO shaker testing

In the previous case, the single shaker input with a high force level clearly showed that the FRF was distorted and coherence was poor. Sometimes the multiple reference data is obtained from a single shaker and then the shaker is moved to other locations to obtain the multiple referenced data. This may seem to be a viable solution but there are limitations to this approach. The first problem was already discussed – the level of force with one shaker will need to be much higher in order to get adequate response at all the measurement locations in the structure and this will cause measurement distortions.

A single shaker may work for structures that are uncomplicated. Structures composed of many components and substructures attached in a manner to minimize the flow of energy through the subsystems can cause difficulties. The situation is much different when the components are isolated from each other. In these situations, it is very hard to get adequate response throughout the structure with just one excitation source. Multiple references are needed. A comparison of a SISO and MIMO test set up will be investigated here.

A laboratory structure is shown in Figure 12. This structure was assembled with three components mounted to a frame. Each of the components was attached with a very soft mount, an intermediate mount and a very hard mount. The main frame and the attachments do have some of the typical “pesky” rattles and noise that plague the collection of FRF data. No attempt was made to minimize any of these noise sources. They are welcome, here, to illustrate a typical structure measurement.

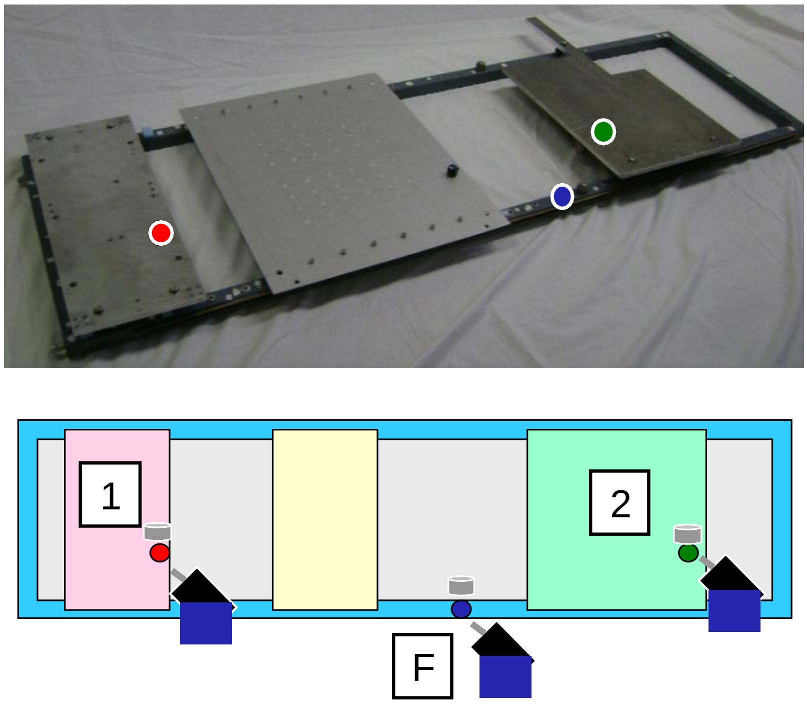

Figure 12: Laboratory structure with isolated components

The structure was tested in many different configurations. Only a few are presented here to show the problem with the FRFs collected with single shaker set up and with a multiple shaker set up. The three shaker reference locations are shown in Figure 12.

Separate tests were run with each of the individual shakers used to collect FRF data from the structure as well as a multiple reference MIMO set of data. In order to make the best possible measurements, the individual SISO shaker tests needed more force excitation level to make suitable measurements. The MIMO configuration needed lower force levels in order to make acceptable FRF measurements.

In order to evaluate all the measurements, several FRFs in the 0-800Hz range were compared. In all FRFs the reference was made to the shaker mounted on the frame. The other references could be used and yielded essentially the same results as those presented next. In Figures 13, 14 and 15, the FRF in red was obtained from the SISO test and the FRF in black was obtained from the MIMO test. Two measurements are shown from the frame to the attached components and one of the measurements was a drive point on the frame itself.

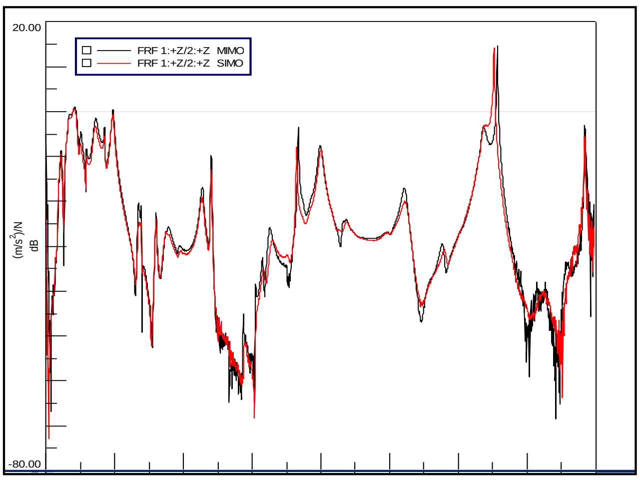

Figure 13: FRF component (1) to frame (F) reference

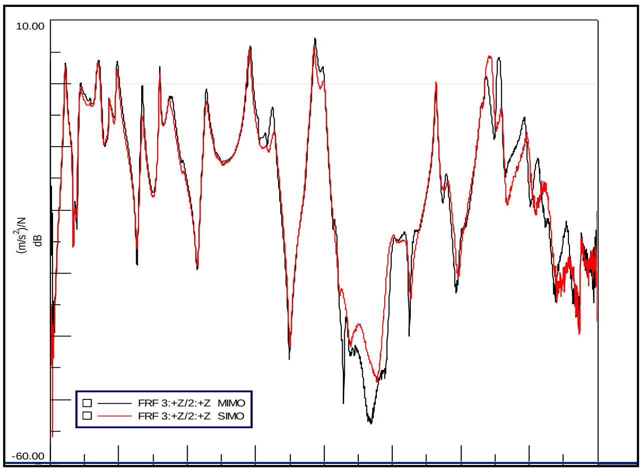

Figure 14: FRF Component (2) to frame (F) reference

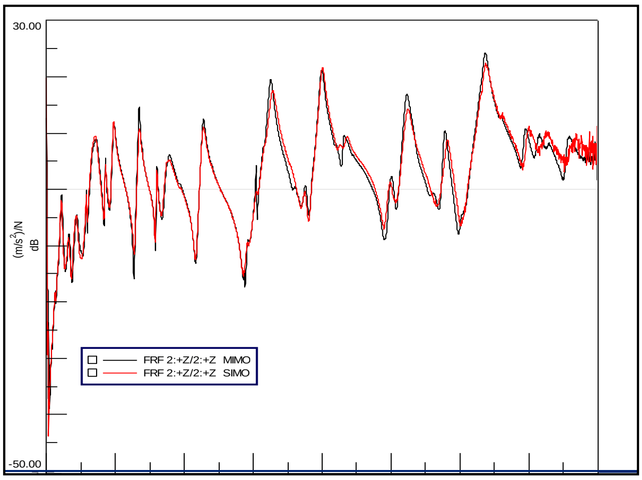

Figure 15: FRF frame (F) to frame (F) reference

So at first glance, the data in Figures 13, 14 and 15 does not look terribly different and many might actually say the data is acceptable. But in looking more closely at some of the reciprocal FRFs, it becomes clear that the peaks of the FRFs from the SISO tests are inconsistent with the others performed. This causes a discrepancy between the different data sets. A few are shown in Figure 16.

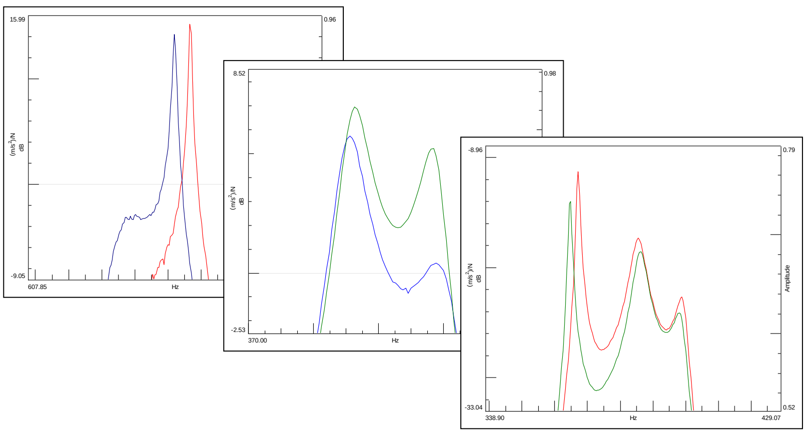

Figure 16: Close up of several FRFs showing inconsistency

The reciprocity between the different data sets is not satisfied. This will have a significant effect when modal parameters are extracted (and will be discussed in the next section).

2.10 Effects of FRF measurements in the modal parameter estimation process

From a purely theoretical standpoint, modal parameters can be extracted from any reference location as long as it is not at the node of a mode. But of course, practicality of the measurements possible on a real structure need to be evaluated. In the last two sections, several aspects of the measurements were discussed. The FRF measurements are always much better overall when the data is collected simultaneously in a MIMO test. If a single shaker is used two issues arise that tend to provide FRFs that are not of the best quality for modal parameter estimation.

In one case, a single shaker needs to have a higher excitation level in order to make adequate measurements but this invariably cause nonlinearities to be excited and generally tends to increase the variance. The FRF measurements are not as good as one would like. The second issue noted is that when multiple referenced data is formed from single reference tests, generally the FRFs are likely to not be related in a consistent fashion. The FRF peaks may show some slight variation in frequency. While the structure may be time invariant, the test set up can have an effect on the measured FRFs when the tests are obtained from separate tests. Another variability results from data collected at different times. Slight environmental changes can compound this problem.

For the sake of continuity with the two previous test cases, the test data for this discussion will be the same data used previously. Shifting of the frequencies was noted for some modes. The reciprocity was not satisfied for all the SISO data collected and used to form the multiple reference data set.

The laboratory structure is schematically shown in Figure 17. Three reference sets of data were collected using SISO methodology in three separate tests. Data was also collected for all three references simultaneously using MIMO methodology.

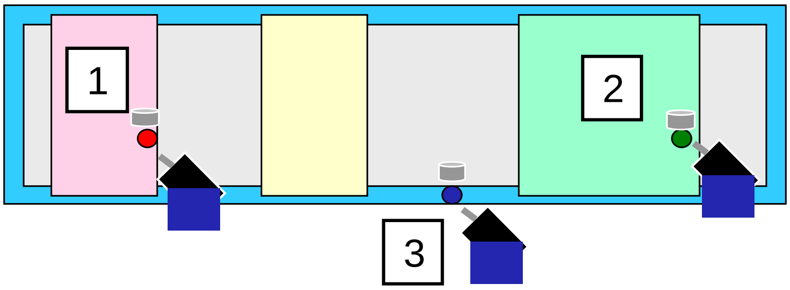

Figure 17: Laboratory structure with isolated components

The previous cases discussed some inherent measurement issues. This data will be processed to show the difficulties in identifying modal parameters. In all cases, the stability diagram will be used to show how some of the variance in the data will present challenges for identification of the system poles.

The first challenge is to take all three separate SISO test FRFs and form one set of multiple reference data for processing. (Note that this is absolutely not MIMO data because it was collected separately.) The first step in the modal parameter estimation process is to identify the system poles. This is usually done using the stability diagram with an overlay of one of the mode indicator function; for the plots here, the CMIF is used in all cases.

Figure 18 shows the stability diagram for this case. While this diagram may be acceptable to many, there is definitely some variation in the system poles and there is not a strong, stable pole identified for every one of the system poles. (As the data is processed, the improvement in the stability diagram will be seen when considering different subsets of data.)

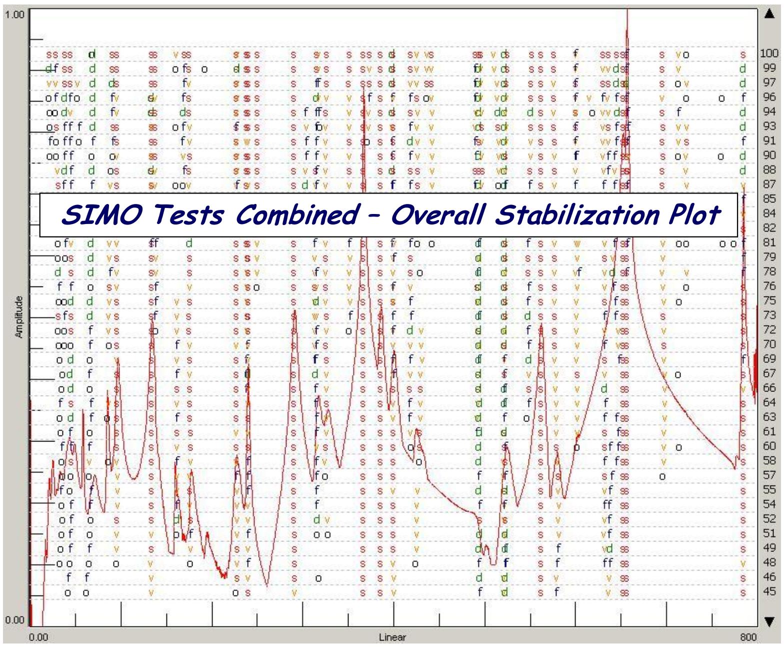

Figure 18: Stability diagram for combined SISO FRFs

Before the MIMO data set is evaluated, it is important to look at the individual SISO data sets. Figure 19 shows the three separate SISO test data sets processed individually before being combined into one multiple referenced data set. The stability diagram for each of the separate test cases produces very consistent stable system poles. There is no question what the system poles are with data that reads this clearly.

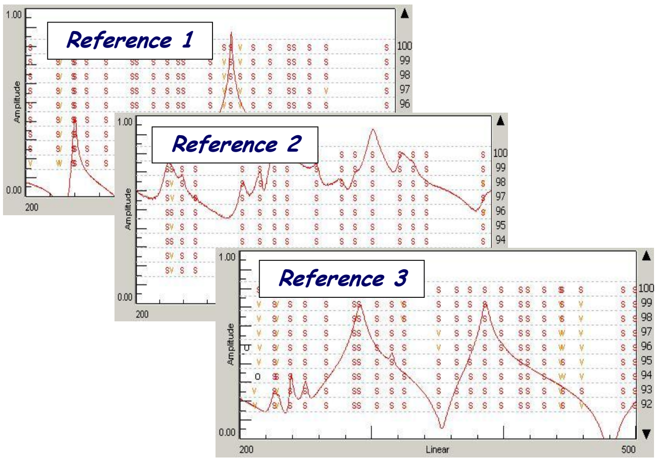

Figure 19: Stability diagram for three separate SISO tests

The individual data sets (Figure 19) clearly show the system poles but it is not as clear (Figure 18) when all the data sets are combined. Remember that SISO data was collected consistently for each of the individual SISO tests. Even in light of some of the noise and nonlinearities that were discussed in the previous two cases, the identification of the system pole is not difficult here. But when all the individual SISO data sets are combined, there is no guarantee that the data will be consistently related between the three different SISO tests that were performed. The shifting of the peak of the FRF measurements was pointed out in the previous case. This shifting was noted in several measurements such as the reciprocal FRFs. The main problem is that the data was collected in three separate tests and the data was not guaranteed to be consistently related. This is why the stability diagram in Figure 18 becomes more difficult to interpret and the system pole identification is not as straight-forward.

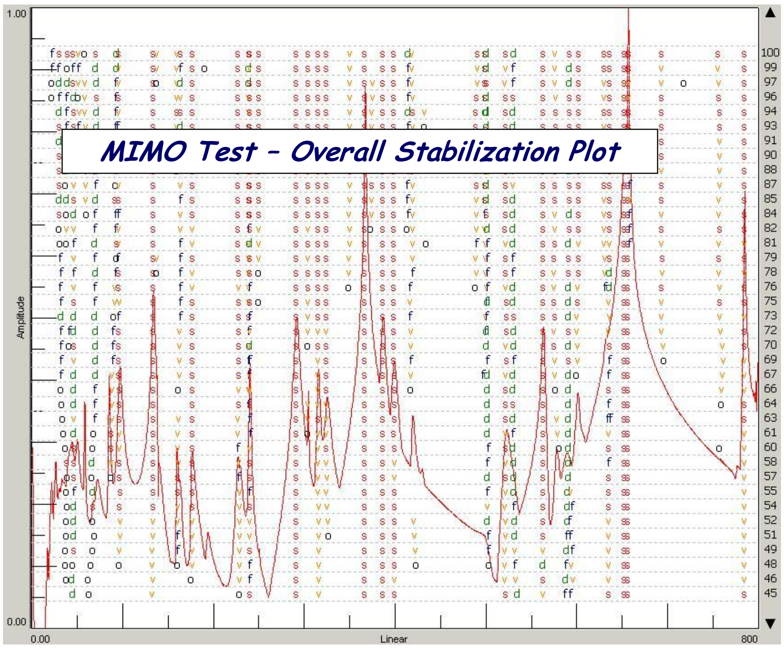

Figure 20: Stability diagram for MIMO FRFs

To confirm this, the MIMO data set (where all data is collected simultaneously in a consistent fashion) is used to generate a stability diagram. This is shown in Figure 20. This stability diagram is much better than the one shown in Figure 18. Some frequencies remain imperfect – but this is much better than the previous scenario. There the data was collected separately and the consistency could not be guaranteed.

The real problem here lies with the data. The FRFs must be collected in a consistent manner. The SISO test cannot provide data with this consistency but the MIMO test generally does due to the nature by which data is collected.

3 Some thoughts and observations from previous experiences

While this paper has presented specific examples, some general thoughts and observations are presented in this section. In performing shaker testing, general rules of thumb are typically followed.

Shaker testing is commonly utilized to obtain high quality FRFs. Care must be exercised to assure that accurate measurements are obtained. When setting up for shaker testing, the shaker location, stinger length and stinger type need to be checked to determine that proper FRFs are obtained.

Shaker testing and shaker set up is improved with shakers specially designed for experimental modal testing. These typically have some special features not found on conventional, general use shakers. One important feature is the through-hole in the armature of the shaker along with the collet clamping design (as well as the shaker trunnion). This allows for easy use of stingers of arbitrary lengths and types. Conventional shakers do not have this feature and the set up of arbitrary length stingers is extremely cumbersome and difficult. With the collet and through-hole set up, the shaker can be easily shifted closer or farther from the structure to investigate stinger length effects on the measured FRFs. Typically, the length of the stinger should be varied with +/- 25% of the suggested length to understand the effects of variation in stinger length. If the FRFs are all similar, then the effects of the stinger are not critical to the accuracy of the measured FRFs. If variations are observed, then additional studies need to be performed in order to identify the appropriate stinger length to be used during testing.

One very important check that should always be performed is related to the actual attachment of the stinger to the force gage or impedance head. This threaded attachment should be made with very simple finger threading of the stinger to the mating thread in the force gage or impedance head. Any resistance in the thread is a clear indication that the alignment is not correct and misalignments may exist. This should also be checked at the end of the test. Any resistance in the disconnection of the threaded stinger is again a clear indication that misalignments may exist. If resistance is noted, the drive point FRFs should be checked at the end of the test and compared to those taken at the beginning of the test. (These measurements should be made as standard practice in any modal test.)

Misalignments can also be seen when an experimental modal test is conducted over several hours or even over the course of one or two days. Many times the structure may shift during testing. The shakers may shift during test, or the structure support system (most common in flexible free-free testing) may even creep with time. Standard practice is to disconnect the shaker/stinger during periods of extended time when testing does not occur. However, the structure alignment to the shaker stingers may vary slightly with time and realignment may be necessary. If the shaker/stingers are continuously attached during periods of inactivity (overnight for instance), then shifting or creep in the test set up may cause stinger misalignment to occur. This may have an effect on the measured FRFs and again drive point FRFs should be checked at the beginning and end of the experimental modal test (and possibly at intermediate points during the experimental modal test).

While some brief points are mentioned here, a more detailed set of Frequently Asked Questions related to shaker testing can be found online (**http://www.modalshop.com**).

4 Conclusion

Shaker testing for the development of experimental modal models can be affected by a variety of different test set up conditions. These effects must be understood in order to obtain the best possible FRF measurements. Several different sets of FRF measurements were obtained with a variety of different parameters studied to show the effects of shaker/stinger set up on the measured FRFs.

While explicit parameters are impossible to identify due to the wide variation in types of structures that may be subjected to this type of test, the measured FRFs do show that the parameters of shaker/stinger location, stinger length and stinger type/material can have a pronounced effect on the measured FRFs. In addition, effects of transducer orientation, use of impedance heads and force levels, as well as consideration of SISO vs. MIMO test configurations can have additional effects on the measurements obtained. Modal parameter estimation processing can be seriously hampered by these measurement difficulties; also implied is that any use of the measured functions for dynamic modeling are sensitive to these issues.

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