Improved Modal Characterization Using Hybrid Data

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Experimental modal analysis (EMA) has a long tradition of use but requires measurement of an applied force. Operational modal analysis (OMA), on the other hand, requires no force measurement but relies on all the system modes to be excited from the unmeasured excitation, which can never be verified. Experience has shown that many times critical modes of the system cannot be obtained from the OMA; EMA will generally find all the modes when proper test techniques are utilized. Both techniques have their advantages and disadvantages and both offer unique opportunities to extract modal characteristics. This work utilizes a hybrid testing approach to merge together the best of both the EMA and OMA techniques to acquire a hybrid set of data. These data sets are used in a combined EMA/OMA extraction approach to find all the modes of the system. Test cases are shown to illustrate how OMA may miss certain modes but that the hybrid testing approach offers a unique opportunity to find modes that may be missed. Various combinations of test cases are studied to show the pitfalls of OMA and the advantages of the hybrid approach.

Traditional experimental modal analysis[1] has proven to be a reliable experimental technique to accurately determine the dynamic properties of structures. Provided proper test techniques are employed and the reference point is carefully selected, the traditional approach will provide very good system characteristics. However, there are many limitations to the practical implementation of this technique, in particular for large civil structures and machinery. This may be due in part to the inability to properly excite the system or bring the structure to a controlled laboratory experimental setup.

Moreover, in many cases, the structure's modal characteristics may be different in situ when compared to the "in-laboratory" test configuration. Suffice it to say that there can be cases where the traditional modal test may be difficult to implement.

In recent years, operational modal analysis methodology (or output-only systems)[2] has gained popularity, because the structure can be tested both in place and in operation. The excitation of the structure comes from its natural environment, whether it be an operating condition with internally generated forces or in an operating condition where the natural excitation comes from ground motion or wind excitation in its working condition. This is a very good approach for determining the modes of a system due to its natural environment.

However, there is a very important concern that the natural excitation must be able to adequately excite all the modes of interest, or else critical modes may be missed or improperly determined. The excitation for the system must be broadband in frequency content and must be spatially rich so that all the modes of the system are adequately excited. If this is not the case, then some of the basic modal characteristics may not be adequately excited or defined from the extraction process.

In addition, many researchers have found that some of the operating modes may have significantly different characteristics describing the system depending on which set of data is used on a day-to-day basis. When this occurs, there is a very serious concern that the extracted modes are not necessarily the primary modes of the system and may be highly dependent on the specific excitation that possibly changes as time progresses. In these cases, the extracted modes are then highly suspect and may not be proper representations of the system modes.

A recent paper[3] showed that the OMA approach may not extract all the modes that would be obtained from a traditional EMA. Due to these difficulties observed and reported by many researchers using OMA, an alternate approach to the problem has been considered to combine both the EMA and OMA approach in a hybrid form that merges together the best of EMA and OMA to identify modes of a system.

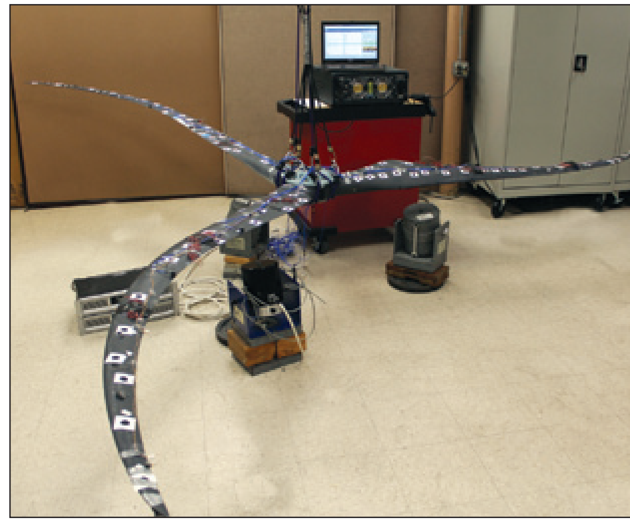

Figure 1. Three-bladed wind turbine system in free-free configuration tested using EMA, OMA, and hybrid techniques.

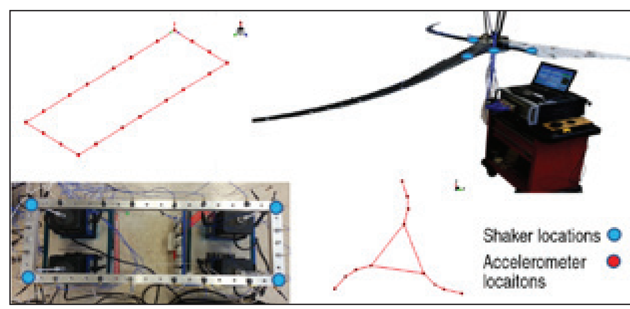

Figure 2. Experimental setup of tested structures showing locations of accelerometers and shakers.

In essence, this hybrid approach uses the excitation from the environment but then augments the measured data by conducting a traditional EMA while measuring and collecting the data from the natural excitation of the structure. This hybrid set of collected data is then processed numerous ways using both OMA and EMA to extract the modes of the system. A simple test structure was used to show a proof of concept,[4] and subsequently the hybrid technique was applied to a complex three-bladed wind turbine system.[5,6] The collected data and the post-processing used to obtain modal characteristics will be shown for both structures.

Structure Description

The hybrid methodology was implemented using two test structures. The first set of tests was conducted on an academic structure consisting of a rectangular aluminum frame in a free-free configuration. The second tested structure was a Southwest Windpower Skystream 4.7, a three bladed wind turbine system as shown in Figure 1.

Testing Methodology

The structures were set up for a free-free test configuration using four shakers to excite the system for a traditional multiple-input, multiple-output (MIMO) modal test. For the aluminum frame, the shakers were attached at the four corners using impedance heads.

For the wind turbine, a shaker was connected to each blade (near the root), and an additional shaker was attached to the hub. Shakers were attached normal to the contact surface but at oblique angles (for the blades) to the reference coordinate system (to excite all modes of the blades).

Two additional sources of excitation were applied to the structures to simulate operating data. One of those excitations consisted of random impacts to the structure but only at locations that were expected to be node points for one of the first modes of the system; the other excitation consisted of random impacts that were spatially distributed around the entire structure. Time data from both accelerometer and impedance head measurements were streamed to disk for processing. For the frame, the out-of-plane response was measured using 20 uniaxial accelerometers as shown in Figure 2.

Measurements on the three-bladed system were performed using 12 triaxial accelerometers measuring both flap-wise and edgewise deformations (also shown in Figure 2). However, the main interest was to identify modes in the flap direction of the blades.

Various combinations of the MIMO shaker excitation and the random impact excitation were combined to create several data sets. These techniques are identified below and were used to create the entire set of data for each structure.

- Test 1 – Traditional MIMO data collected with all four shakers used for excitation (reference data set).
- Test 2 – Random impact excitations spatially distributed around the structure (OMA-type measurement).
- Test 3 – Random impact excitation at locations expected to be the node of a mode.
- Test 4 – Hybrid Technique: MIMO data collection with all four shakers (Test 1) and random impact excitation at node locations (Test 3)

Each of these tests was performed using LMS Test.Lab 12A to acquire and stream data that were then processed using LMS Polymax (for the MIMO data) and LMS Operational PolyMAX (for OMA data) software packages.[7] Each of the four different tests is described next, and then the different sets of data are compared to each other.

Aluminum Frame Test Structure

The hybrid technique was first employed for an academic structure. Four test cases were conducted as outlined above consisting of traditional modal tests, operational modal tests and hybrid OMA/EMA tests.

Test Case 1. A traditional MIMO test was performed using burst random excitation generated by using the four shakers. The system response measured with the accelerometers and impedance heads was used to extract frequencies, mode shapes and damping from the FRF MIMO data. These mode shapes served as a reference solution and are used for comparison to the OMA and hybrid data. Figure 3 shows typical drive-point FRF measurements for the MIMO tests that were conducted. The first five characteristic mode shapes of the frame were extracted from the FRF measurements using Polymax and are shown in Figure 4.

Test Case 2. The frame was set up in the same configuration as Test Case 1 – free-free with four shakers attached to the structures by impedance heads. In this case, however, the input excitation originated from spatially distributed random impacts to the frame, while the four shakers were left attached but not in use. The shakers were left attached to preserve the experimental setup for all test cases to obtain consistent data across test cases.

Time data from the test was streamed to disk and used to calculate auto- and cross-spectra from selected reference accelerometers. Curve-fitting was done using Operational Polymax, and the characteristic operating shapes were extracted. The stability diagram and typical mode shapes for the processed OMA data are shown in Figure 5.

Test Case 3. Random impact excitations were performed at two locations on the frame using the same configuration as Test Case 2. The locations were chosen to be nodes of the first torsion mode of the frame and therefore some modes of the system were expected to be missed. The impacts were done randomly at the locations, and the throughput time data streamed directly to disk. The processing

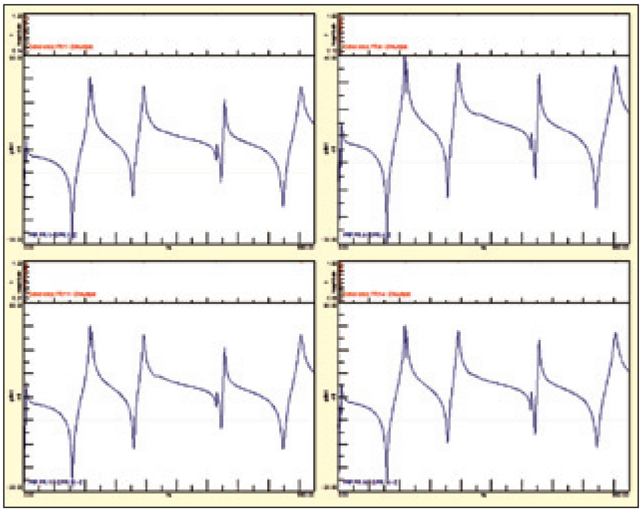

Figure 3. Drive-point FRF measurements of frame from traditional shaker modal tests (MIMO).

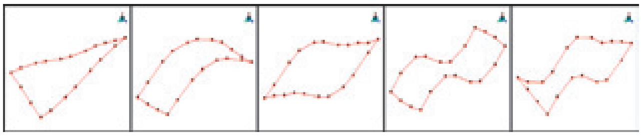

Figure 4. Typical first five mode shapes from four-shaker MIMO tests of frame.

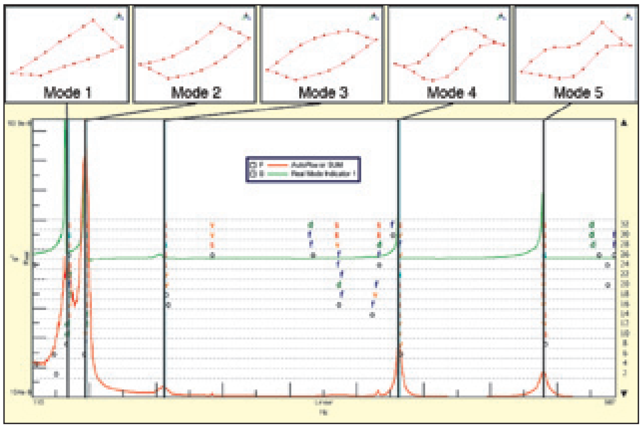

Figure 5. Mode shapes and stability diagram for OMA test on frame.

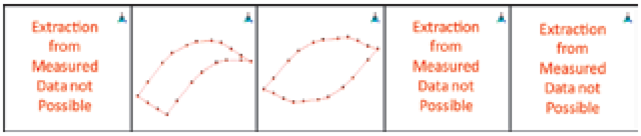

Figure 6. Characteristic operating shapes of frame found through OMA test using random impact excitation restricted to the nodes of the first torsion mode.

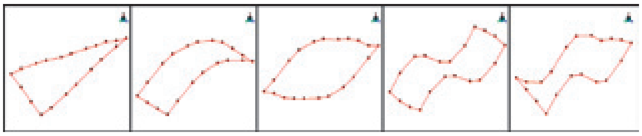

Figure 7. Characteristic operating shapes of frame found through hybrid EMA and OMA test using four-shaker random input excitation and restricted impact excitation at nodes of first torsion mode.

of auto- and cross-spectra as well as curve-fitting were completed using the same OMA methodology of Test Case 2. The mode shapes that were found for the frame system are shown in Figure 6; clearly fewer modes were extracted, as expected.

Test Case 4. The structure was configured as in Case 1 but using a random input excitation from the 4 shakers in conjunction with random impact excitations at the locations used in Case 3 (nodes of a mode). The FRF measurements obtained through the EMA portion of this case were only used to corroborate the OMA test mode shapes. However, main interest was placed on the hybrid data streamed to disk from the EMA and OMA sources (MIMO and random impacts respectively).

The throughput streamed time data were processed and used to calculate auto and cross spectra as in the two previous OMA tests. Operational Polymax was used to extract the frequencies and operating shapes and these can be seen in Figure 7 for the frame.

Comparison of Aluminum Frame Cases

The mode shapes obtained in Case 1 were used as a reference solution and also verified with an available finite-element model of the frame and impact testing previously performed. Only mode shapes, which are the primary focus of this work, are presented in the comparison.

Comparison A. The traditional MIMO modal test results (Test Case 1) were compared to the spatially broad excitation from the operating modal test (Test Case 2), and it was clear that the operating modal data are very similar to a traditional modal test. Obviously, the unmeasured excitation for the operating test was sufficient to excite the modes of interest of the structure. This is an ideal situation in which use of either type of test methodology does not bring any significant loss in the quality of the characterization of the structure.

In typical experimental settings, however, there is no *a priori* guarantee that the unmeasured OMA excitation will yield the same results as the measured traditional input from EMA. Table 1 shows a MAC comparison of Test Cases 1 and 2. There is high correlation for all modes, with some slight differences on the third mode of the frame (second torsion mode), but all modes are represented reasonably well for the OMA Test 2.

Comparison B. The traditional MIMO modal test results (Test Case 1) were compared to the spatially restrictive excitation from the operational modal test (Test Case 3), where the operating modal data did not adequately excite all the lower-order modes of the system when compared to the reference set of modes. Table 2 shows the MAC comparison of these test cases.

Clearly, if the excitation does not contain spatially rich excitation then the operating modal test cannot extract the necessary information as expected. Because the input excitation may never be known, however, there is no way to assure that the modes of the system will be obtained from the operational test. The results of the OMA test clearly missed modes.

Comparison C. The traditional MIMO modal test results (Test Case 1) were compared to the spatially restrictive excitation from the operating modal test augmented with the hybrid testing approach (Test Case 4) that uses a random input excitation from the four shakers similar to a traditional MIMO test.

Table 3 shows the MAC comparing Test Cases 1 and 4, and it is very clear that the operating modal data are dramatically improved and all the modes that were not previously found on Test Case 3 are better represented with the alternate testing approach proposed. This shows the benefit of the hybrid approach, because all the modes are represented reasonably well.

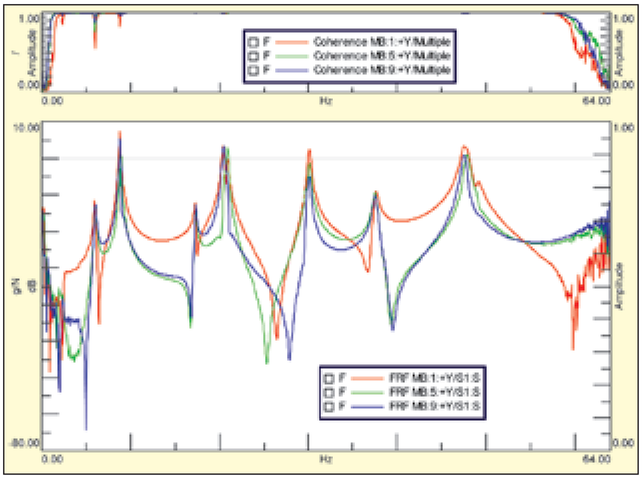

Figure 8. Typical FRF measurements of three-bladed wind turbine structure from traditional shaker modal tests (MIMO).

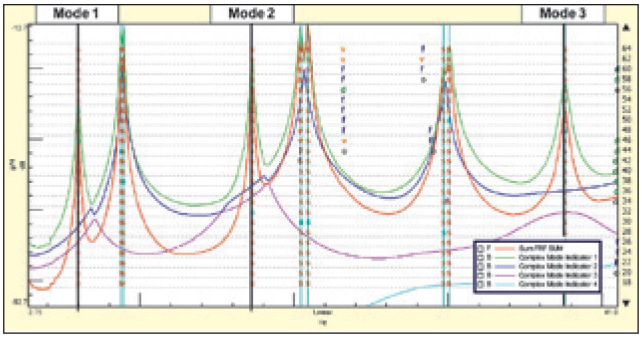

Figure 9. Stability diagram from MIMO test showing first three collective flap-wise modes of wind turbine structure.

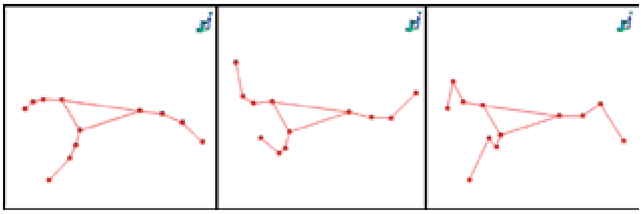

Figure 10. Typical first three flap-wise mode shapes from four-shaker MIMO tests of wind turbine structure.

With the demonstrated effectiveness of hybrid methodology on a simple structure, a more complex system was then tested. Testing was conducted on a three-bladed turbine system, which included aluminum and steel coupling elements at the hub.

Three-Bladed Wind Turbine Structure

Three wind turbine blades were attached to a hub consisting of aluminum and steel plates and connected by 12 steel bolts to form the turbine assembly. The system was hung from above in a free-free configuration as seen in Figure 1. Four test cases were conducted in a similar manner to those of the aluminum frame.

Test Case 1. A traditional MIMO test was performed using burst random excitation from the four shakers, and the mode shapes extracted served as a reference solution and were used for comparison to the OMA and hybrid data. Figure 8 shows a typical FRF

Table 1. MAC of MIMO modal test (Test Case 1) and operational modal test (Case 2).

	Operational Modal Test (Shakers Off)				
Mode	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
1	98.99	1.23	0.07	0.02	0.50
2	0.48	93.84	5.40	0.00	0.15
3	0.02	0.10	73.65	0.07	0.08
4	0.01	0.00	0.00	99.50	1.44
5	0.03	0.06	0.00	0.12	98.16

Table 2. MAC of MIMO modal test (Test Case 1) and operational modal test (Case 3).

	Operational Modal Test (Node Line – Shakers Off)				
Mode	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
1	–	1.45	0.08	0.00	0.05
2	–	94.61	0.61	0.04	0.58
3	–	0.08	50.07	0.19	0.15
4	–	0.01	0.01	0.46	0.02
5	–	0.06	0.01	0.01	1.01

Table 3. MAC of MIMO modal test (Test Case 1) and operational modal test (Case 4).

	Hybrid Modal Test (Node Line – Shakers On)				
Mode	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
1	98.53	1.28	0.02	0.06	0.90
2	0.39	91.16	0.01	0.02	0.13
3	0.05	0.21	81.69	0.07	0.20
4	0.01	0.05	0.01	99.54	0.72
5	0.14	0.12	0.00	0.03	98.47

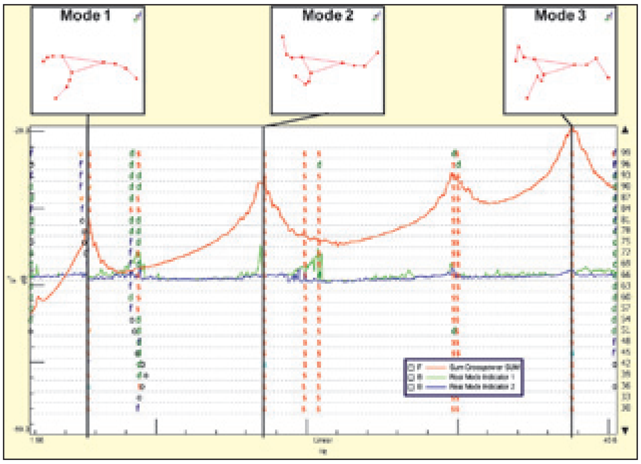

Figure 11. Mode shapes and stability diagram for OMA test on three-bladed wind turbine.

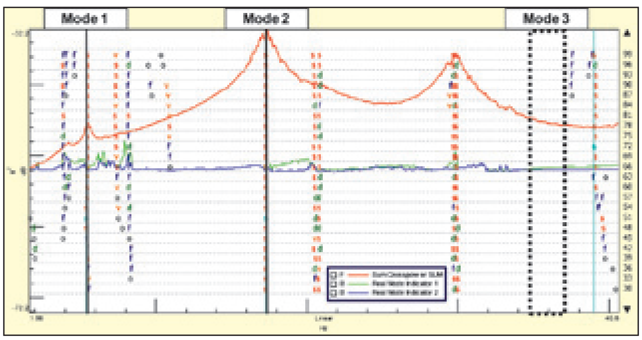

Figure 12. Stability diagram from OMA test with restricted impacts at the node of the third flap-wise mode of the structure.

measurement from the MIMO test conducted, and Figure 9 shows the stability diagram from the curve-fit data. Note that the shakers were set up at oblique angles to the reference coordinate system.

As can be seen from Figure 9, there are many modes located in the frequency span. (For the current work however, only flapwise collective (in-phase) modes are studied.) The first three collective mode shapes of the three–bladed assembly in the flap-wise direction extracted from the traditional MIMO test are shown on Figure 10.

Test Case 2. This test exemplifies a typical OMA test. The structure was set up in the same configuration as Test Case 1, free-free with 4 shakers attached to the structure by impedance heads, but in this case the input excitation originated from spatially distributed random impacts to the blades while the four shakers were left attached but not in use. The impacts were made along the three blades with very soft-tip impact hammers. The stability diagram and typical mode shapes for the processed OMA data are shown in Figure 11; again, only the collective flap-wise modes are used in this study.

Test Case 3. As seen with the previous structure, this test exemplifies those testing situations where the input excitation is not sufficient to activate all modes of the system. Random impact excitations were performed at one location on each blade using the same configuration as Test Case 2. The locations were chosen to be nodes of the third flap-wise mode of the three-bladed system. Therefore, this mode is expected to not be excited well and will be difficult to extract, if at all. The stability diagram for the OMA test with restrictive impacts is shown in Figure 12; again, only the collective flap-wise modes are used in this study.

Test Case 4. This test shows implementation of the hybrid data collection to improve the deficiencies of the OMA data collected in Case 3. The structure was configured as in Case 1 but using a random input excitation from the four shakers in conjunction with the random-impact excitations at locations used in Case 3 (nodes of third flap-wise mode). The EMA/OMA hybrid data were processed as in the two previous OMA tests. Operational Polymax was used to extract the frequencies and mode shapes. Figure 13

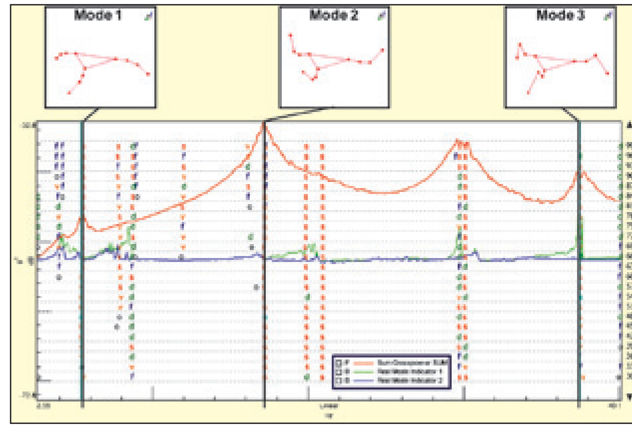

Figure 13. Characteristic mode shapes and stability diagram of three-bladed wind turbine found through hybrid EMA and OMA test using four-shaker random input excitation and restricted-impact excitation at nodes of third flap-wise mode.

shows the stability diagram and mode shapes obtained from this test considering only the flap-wise modes of interest.

Comparison of Three-Bladed Wind Turbine Cases

The mode shapes obtained from the MIMO test (Case 1) were used as a reference solution and also verified with an available finite-element model of the three-bladed wind turbine and impact testing previously performed.[5,6]

Comparison A. The traditional MIMO modal test results (Test Case 1) were compared to the spatially broad excitation from the operating modal test (Test Case 2). There is high correlation between both tests techniques, and either can be implemented at the experimenters' choice. As was the case with the aluminum frame, this is an ideal situation in which use of either type of test methodology does not bring any significant loss in the quality of the structure characterization.

For most OMA testing, however, there are no guarantees that the excitation is broadband spatially and rich in frequency content. Table 4 shows a MAC comparison of Test Cases 1 and 2 and shows very similar shapes from the OMA Test Case 2.

Comparison B. The traditional MIMO modal test results (Test Case 1) were compared to the spatially restrictive excitation from the operational modal test (Test Case 3). As the impact excitations were performed at the node of a mode, poor results were expected from the operating modal data, since the excitation did not adequately excite all the modes of the system. Table 5 shows the MAC comparison of these test cases.

With this second test structure, it is once again clear that if the input does not contain a spatially rich excitation, then the operating modal test cannot extract the necessary information. This is the

Table 4. MAC of MIMO modal test (Test Case 1) and operational modal test (Case 2, random impacts, shakers off).

Flap-Wise Mode	MAC	MIMO, Hz	OMA, Hz
1	94.80	5.98	5.48
2	98.85	17.28	17.17
3	99.22	37.59	37.57

Table 5. MAC of MIMO modal test (Test Case 1) and operational modal test (Case 3, restricted impacts, shakers off).

Flap-Wise Mode	MAC	MIMO, Hz	OMA, Hz
1	92.13	5.98	5.40
2	98.73	17.28	17.27
3	1.22	37.59	39.00

Table 6. MAC of MIMO modal test (Test Case 1) and operational modal test (Case 4, MIMO vs. hybrid EMA/OMA).

Flap-Wise Mode	MAC	MIMO, Hz	Hybrid, Hz
1	95.31	5.98	5.40
2	99.40	17.28	17.21
3	99.75	37.59	37.46

typical testing situation where the experimenter does not know if the input excitation is sufficient; so the characterization of the structure will not yield good results through OMA testing.

Comparison C. The traditional MIMO modal test results (Test Case 1) were compared to the spatially restrictive excitation from the operating modal test augmented with the hybrid testing approach (Test Case 4) that uses a random input excitation from the four shakers similar to a traditional MIMO test. Table 6 shows the MAC comparing Test Cases 1 and 4.

There is high correlation between both tests, and from comparison to Case 3, it is very clear that the operating modal data is dramatically improved and all the modes that were not previously found are better represented with the alternate testing approach proposed. Given sufficient broadband excitation, the hybrid mode of data collection can be expected to complement and improve operational modal analysis and serve as a safeguard that no important modes of the system are missed.

Observations

This article presents some of the test findings that were evaluated; many other tests were performed to verify the findings but are not all presented here due to space limits. One very important observation was that the hybrid approach provided the additional excitation needed to assure that all the modes of the system were adequately excited and observed in the measured response. This provides a tremendous boost to the success of the OMA approach.

As far as implementation is concerned, the operating test can be augmented with either a shaker excitation setup or by applying arbitrary, randomly, spatially distributed impact excitations to the structure while the operating data are collected. This way the structure is exposed to a broadband, spatially rich excitation to augment whatever the actual operating condition may provide. Clearly from the results shown, the extracted shapes are improved, and modes were not missed. While more work is needed to explore this in depth, these initial studies that combine OMA and EMA show great promise.

Conclusions

A hybrid method of data collection and reduction that blends traditional EMA and OMA testing was presented through a series of test cases. Operational modal tests were shown to depend highly on broadband frequency and spatially broad input excitation. Since these cannot always be guaranteed, important modes of the system may be missed even in simple structures.

The hybrid approach improves the OMA test by applying a measurable broadband force input to the system that ensures all modes of interest receive sufficient excitation. For those modes that were found on the OMA test, the hybrid approach showed the same or better correlation to the reference set of modes that were obtained for this study.

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