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TASK 2.3.2: “TEST SIMULATION, PLANNING & MEASUREMENT”

EARLY TEST INTERPRETATION METHODS

by

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Abstract:

This document presents methods to assess the quality of test data during the test session itself, in order to be sure the measurements are providing the desired information with the required quality. A process leading from the initial CAD part to the test session is discussed, on which the methods suggested are framed, with an eye on software capabilities for the accomplishment of these tasks.

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1. EXECUTIVE SUMMARY

This document presents methods to assess the quality of test data during the test session itself, in order to be sure the measurements are providing the desired information with the required quality. A process leading from the initial CAD part to the test session is discussed, on which the methods suggested are framed, with an eye on software capabilities for the accomplishment of these tasks.

Essentially, the main part of this deliverable, rather than being a report, is an extensive set of reference data that was used in this subtask, but can also be used further in the project. The data consisted of both CAE (FE models) and Test (FRF, EMA results) data and involved 3 components of the Rolls-Royce Trent 500:

- Combustor Outer Casing (COC)
- High / Intermediate Pressure Turbine Casing (HIPC)
- Low Pressure Turbine Casing (LPC)

The CAD data, shell & beam FE models and the physical structures were provided by Rolls-Royce plc.

This report relates to subtask 2.3.2.3 “Early test interpretation methods“, in task 2.3.2 “Test simulation, planning & measurement”. The document is a Month 30 deliverable for the project.

2. DEFINITIONS AND GLOSSARY

CMIF: Complex Mode Indicator Function

DP(R): Driving Point (Residual)

EMA: Experimental Modal Analysis

FRF: Frequency Response Function

SVD: Singular Value Decomposition

3. INTRODUCTION

Test is a very demanding part in the design cycle. It can be performed in difficult-to-reproduce conditions, or involving a large amount of resources from the people or companies in charge. For these reasons, there can be no space for errors and the data must fulfil the desired quality standard; to attain this requisite, there’s the need of procedure made in two steps: the first, purely virtual/CAE, provides the best test configuration fitting the purpose desired, the second implements methods that quickly evaluate, during test, whether the output data are consistent and satisfactory for the purpose.

In order to practically implement these procedures, dedicated software packages are needed, capable of producing quickly on-site results and exchanging information between the virtual, CAE related models and computations and test proceedings.

The subject treated in this deliverable refers to and integrates the test procedures exposed in deliverables 2.3.2 “Test simulation, planning & measurement”, which topics it is strictly related to.

Background information related to the concepts described in this deliverable can be found in [1] and [3].

4. TEST PROCESS IN THE FRAME OF COMPONENT DESIGN CYCLE

4.1. INFORMATION TARGET

In these last ten years, as the design processes involved in their cycle the use of virtual models validated through the use of updating procedures, the role of testing, from being a stand alone procedure has turned into a crucial step of designing itself, thus worthy of optimization and efficiency, and providing the best performance in the shortest time.

The criteria the session has to obey to, depend on the information the test must provide to the design cycle. It takes then to develop a method that allows being constantly informed and aware the test is being done correctly and fulfils the purposes.

4.2. ROLE OF CAE IN GETTING THE MOST FROM THE TEST SESSION

Far from being quoted amongst early test interpretation methods, CAE computations on the structure help to find out how to get the most from the test in terms of sensitive information for forthcoming stages. The use of finite element models plays a fundamental role in this session. The results provided hold information about the dynamical behaviour of the structure, from that, by the use of analytical tools it is possible to arrive to the definition of a test configuration of the desired capability, defined in detail in terms of number and location of sensors and driving points. Although not strictly belonging to test session, given the importance this procedure has in its definition, it is not possible to neglect the contribution it gives to the final accomplishment.

5. TEST PLANNING: CAE TOOLS TO GET THE BEST RESULT FROM TEST

5.1. GEOMETRY, MESHING AND FE

A large number of software packages offer tools useful to go through structural dynamics; from this knowledge CAE session starts.

This process is entirely performed via virtual computation; the input required is a detailed geometry of the component to be tested; on which a dynamic analysis must be performed in order either to define or to analyze the modal behaviour in the bandwidth of interest, and even to assess whether the extent of the chosen domain should be extended or not.

Tools like ANSYS, PATRAN/NASTRAN, CATIA or LMS V.LAB are just an example of the packages available for this purpose.

The model to perform the dynamic analysis on is obtainable by meshing a CAD part (Figure 1), this is the detailed geometry model retaining a highly detailed shape of the structure, it is the necessary input for all the pre test phase, and from this geometry a solid FE model will be calculated. Meshing operation is made of three steps: first creates and arranges a discrete model of the structure; then superposes material properties to this entity and eventually defines its constraints, thus transforming the geometrical entity into a dynamic model. Though nowadays, thanks to the spread availability of high performance PCs, this task can be worked out more easily in terms of time and accuracy, it always takes to consider carefully the choice of the finite element, or the type of mesh that can guarantee a reliable result into an acceptable computing time.

Figure 1: Graphical synthesis of meshing process on geometry (RR Trent 500 COC).

Tetrahedrical elements imposed themselves as a standard for general solid models, the choice to be made is always which element to choose, whether linear (TET4) or parabolic (TET10) (Figure 2). TET4 element in fact often brings problems related to “numerical locking”. This widely known problem in Finite Elements theory deals with a numerical instability, resulting in a “overfeeding” of a parasitic shear deformation term. This takes away energy from the (real) bending deformation term, thus reducing it and revealing a rigid behaviour of the structure, far from the truth. Further explanations of this phenomenon fill a lot of essays about FE theory, but will be not object of further analysis. As suggested by manuals [4][5], the easiest way to get over the locking problem is avoid the use of linear elements; otherwise, at least it should be imposed that more than one element lie along the thickness of the model. It resulted from calculation performed on the RR TRENT 500 COC that, even reducing the TET4 dimension up to the 80% less than the TET10 element’s, the result is yet affected by error: though dwindling as the element gets shorter, it is a 10% far from the (correct) estimated values.

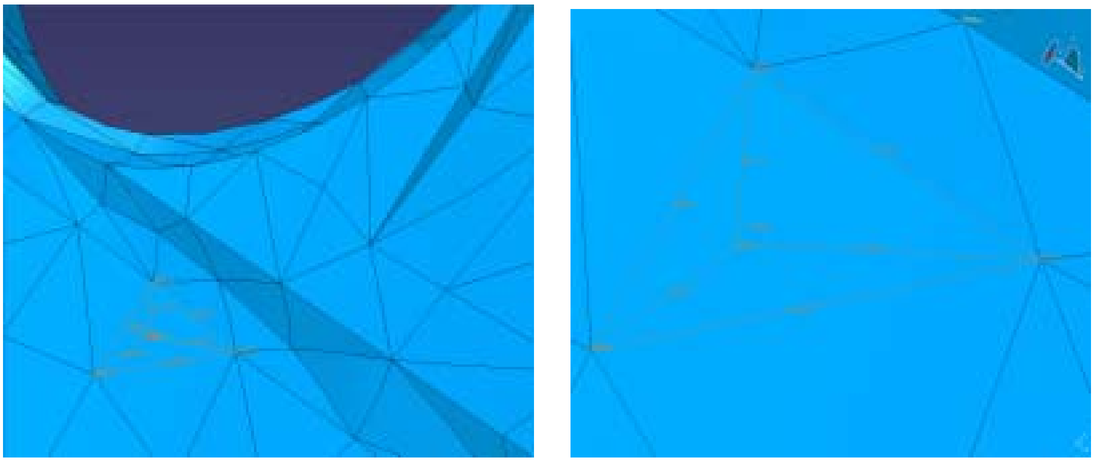


Figure 2: Details of TET10 elements in the mesh (RR Trent 500 COC mesh in LMS Virtual.Lab).

5.2. MODAL ANALYSIS

Managing a meshed model in order to obtain its natural frequencies is a common task for many programs dealing with structural dynamics; some of them have their built in solver, but give the user a chance to run widely-spread solvers like NASTRAN, ANSYS or ELFINI.

The analysis must take into account the constraints that will feature in the test phase. The range of frequency must be decided, it comes from design conditions and test requirements.

As for the starting frequency, in order to skip the rigid body modes, it is recommended to start from a value close to zero, like 0.05 Hz; this could be an easy check on the FE model as well, because if a rigid body mode occurred, this would mean the mesh process of solid model has failed. The top value should come of the max excitation frequency, like the rotating speed of the shaft for airplanes, but usually the bandwidth is spread in order to get up to the highest frequency possible: there in fact stiffness influences are significantly high, and this information could be important for all the study. A critical review of mode shapes resulting from the analysis must be done: it is important to recognize their peculiarities in order to design a test session capable of describing the whole modal kinematics (Figure 3 – Figure 6).

Figure 3: Modes I and III ("Pumping" front only and front-back with 45 degrees shift).

Figure 4: **Modes V and IX (triangular deformation front only and front-back with 45 degrees shift.**

Figure 5: **Modes VII and XIII (rectangular deformation front only and front-back with 45 degrees shift).**

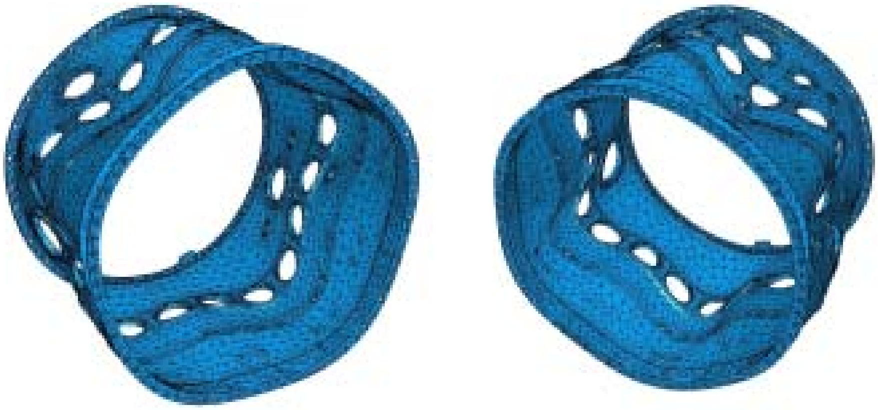


Figure 6: **Modes XI and XV (middle part deformation, 5 and 6 waveforms).**

5.3. PRE TEST ANALYSIS

The pre test phase starts here: its steps are first to build a geometrical entity for the test configuration, that is supposed to be the candidate wire frame (Figure 7), and then to evaluate its capability and to go ahead to the test session, if the desired level of accuracy is reached.

Measurement points locations are decided after a review of the results of structure dynamics and must be able to reproduce in detail, and without the occurrence of spatial aliasing, the mode shapes of the component. This is the most important requisite for the test session, and stresses the very importance of this pre test phase in improving its quality.

The mode matrix coming from the dynamical analysis is projected on the wire frame in order to obtain a set of reduced modes. To handle the information on the mode shapes is up to a set of virtual sensors: they are nothing more than markers put on the wire frame nodes (future candidate sensor locations), and their function is to reduce once more the degrees of freedom of the reduced eigenvector matrix in order to store the selected degrees values (of eigenvectors' components) for future calculation. Their capability over the 6 degrees of freedom may be of course customized, switching on the desired ones, so as to emulate the type of sensor that will be used in the test; it could be either possible to do the opposite, in order to decide which kind of sensor to use, comparing the results coming from different scenarios.

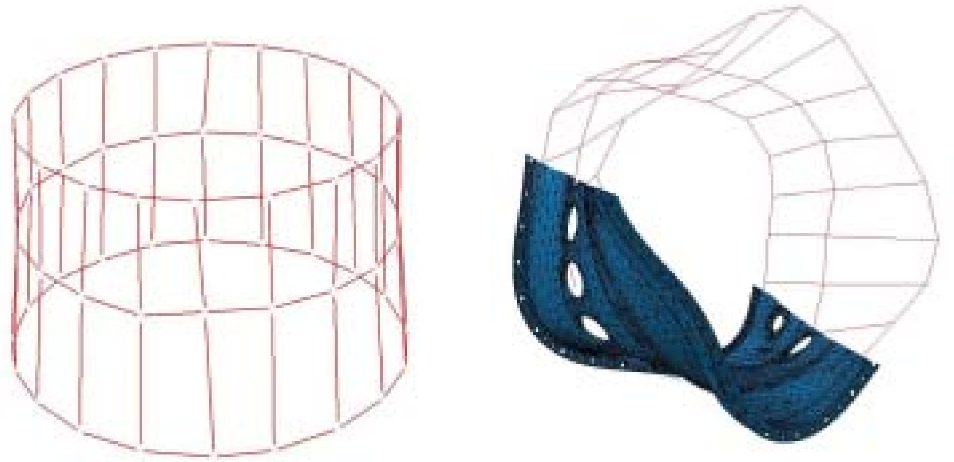


Figure 7: A candidate wireframe and a visual example of mode shape projection.

The eigenvector data retained by those sensors will be used as input by the tool called to rate the candidate test configuration: the AutoMAC. This operation is performed to assess the incidence of highly correlated modes coming from low mode shapes resolution. AutoMAC formula yields:

$$AutoMAC_{ij} = \frac{\left| \overline{\Psi}_{Ai}^{H} \overline{\Psi}_{Aj} \right|^{2}}{\left(\overline{\Psi}_{Ai}^{H} \overline{\Psi}_{Ai} \right)\left(\overline{\Psi}_{Aj}^{H} \overline{\Psi}_{Aj} \right)}$$

where Ψ_{Ai} and Ψ_{Aj} are eigenvectors, projected on the wireframe and reduced to the desired DoF number. They are multiplied (scalarly) one with each other; focusing on the off diagonal values, they rate how much correlated the modes isolated in the bandwidth of interest are, in order to exclude (or state!) problems of spatial aliasing. This is the only and most reliable assessment tool, if the result of AutoMAC (Figure 8) is satisfactory (off diagonal values below 60% generally) the candidate configuration fits the test purposes.

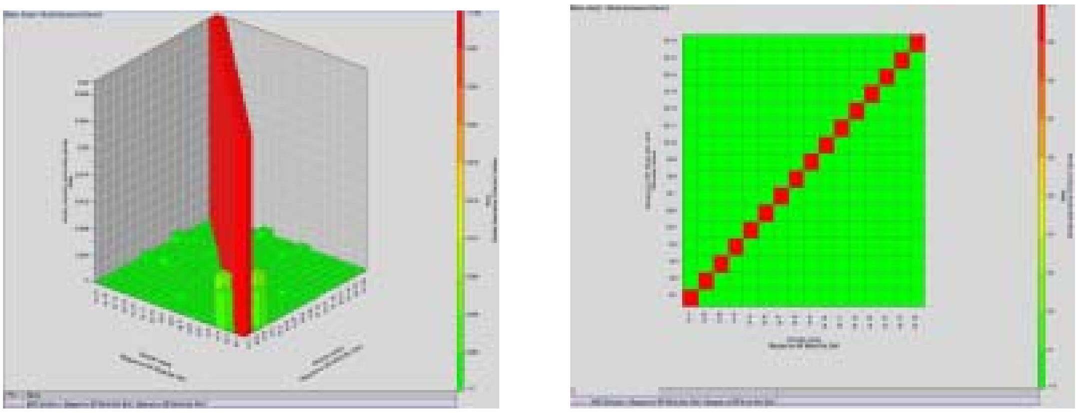


Figure 8: **Examples of AutoMAC: Iso 0-3% zoom and top (LMS Virtual.Lab).**

From the CAE session, as additional information, the position of the driving points can be obtained. These are the locations where the structure should be hit in order to excite all the target modes of the bandwidth; the formula rating each point is:

$$DPR_{jr} = \frac{\psi_{jr}^{2}}{2 m_r \omega_{d\,r}}$$

where DPR stand for driving point residual, Ψ_{jr} is the eigenvector (module) value for the j-th DoF at the r-th mode normalized with respect to r-th modal mass and r-th natural frequency. The indication this formula gives is repeated for all the points of the wire frame at each mode; the performance of the DPR must be rated over the modes of interest: each DoF will be given a mark, coming from this relation

$$DP_j^{*} = \overline{DPR}_j \cdot Worst(DPR_j)$$

The first term of the right hand side is the average driving point residual, the second, the lowest value amongst all the studied modes. The higher in value will be selected as driving points for the studied candidate test configuration.

As a complementary approach for pre testing, test strategy methods deserve to be quoted. Amongst them the authors would like to remember the one dealing with test on components that will fit into an assembly [2].

Its aim is to find an ideal constrained test configuration that mimics the dynamical behaviour of the structure when put in the assembly. Basically, the way to obtain this configuration is a trial and error process: FE model of the part in the assembly is correlated through a MAC to differently constrained FE models of the standing alone component; the most satisfactory correlation obtained will identify the test configuration. Thence a pre test procedure as the one here presented can be undertaken.

5.4. GATEWAY TO TEST SESSION

The CAE session provided both the wire frame and the driving points, this information suffices the requirements of an effective test session, as regards to mode shape controllability and absence of spatial aliasing. This achievement is possible as long as a detailed geometry of the structure is available, by which a dynamical behaviour predictive finite element model was built. The pre test session reduces the risks of failure of test, but doesn't exclude them at all: it sometimes happens during measurements that apparently correct procedures yield fake, unreliable results: they are related to different peculiarities of test and a review is given in following section. To prevent these ambiguous and faulty occurrences, early test interpretation methods survey the quality of the session worth of much less concerns as long as a careful pre test is performed.

6. TEST SESSION OVERVIEW: EARLY INTERPRETATION OF TEST RESULTS

6.1. COMMON DRAWBACKS AFFECTING RESULTS

Getting information to reconstruct through signals the modal parameters and the dynamic of a structure entail, generally speaking, the presence of an interface between the physical part and acquisition system. In this “interface” as it is generally referred to, shakers or hammer, sensors, cables, a signal acquisition system are comprised, and depends on what happens during the transit of information the quality of test data, and their validity. It is possible to aggregate in two categories these sensitive parameters: set-up depending, like sensors, hammer, or cables, everything dealing with the physical interaction with the structure; and signal depending. To these two categories different drawbacks happening in test phase dwell.

6.1.1.Set-up depending

Occurrences of this kind are related to problems, often due to scarce attention to the sensors’ set up; the triviality of this point is just apparent: in fact the level of accuracy due to every action during test must be the highest, a session may in fact be unrepeatable and very expensive. Furthermore, some of this problems might not be that evident: the sensor are in fact attached to the structure with layers of wax or special glues, which mustn’t bring any local alteration to the structure, like stiffening or damping. Without the proper checks on measurements’ quality, effects of improper mounting not only remain concealed, but could affect the confidence of all the data set collected from the test. A dedicated method able to identify such drawback of course doesn’t exist, but the checks presented in next paragraph can reveal some anomalies this problem produces.

6.1.2.Signal quality depending

When it’s dealt with signals, and especially when on their quality the result of measurements depends, the main concern is to be sure that no source of noise affects them and that the input source (for a modal test it is an impact hammer, or a shaker) provides the desired waveform. Acoustic sources of noise are common, but the easiest to remove since they can be immediately detected (hearing) and devices to muffle its effects, e.g. reverb in hollow structures, can be quickly set as long as they do not affect measurements. More dangerous, though not so common, are electromagnetic sources that could the electronic devices of measurement chain.

For input signals, a big contribution to reduction of quality is given by incorrect application of input force: typical example is the position and the direction of the impact for hammers: if the hit point position is not correct or the direction of the force slightly changes, the measurements result affected, because of the non accomplishment of the ideal impulse impact condition. Averaging over a stated number of hits is a typical practice in impact testing, so as to make the tries converge on the desired conditions close to the ideal standard. Common practice suggests a number of hits between 5 and 8, this number may be defined or increased evaluating on site the output quality.

6.2. METHODS OF EVALUATION OF RESULTS

Here starts the early test interpretation phase, where by means of checks done test session output an evaluation is done in order to know whether the data collected are consistent or not. The importance of having such feedback almost instantaneously must be kept in mind, preventing, in case, from wasting time and money into a low performance session.

Main features of this stage are some checks to be done on the early output of experimental modal analysis with an eye on their modal properties, these are resumed in ω check and Reciprocity, Coherence, SVD-CMIF.

6.2.1.Frequency check

This is by far the most simple and straightforward, and can be performed at the very beginning of the session, when the first result is available. The frequencies from the FE model used in pre test phase are compared to the peaks registered on the FRF after the first impact. This procedure may reveal problems with the finite element model (like the ones related to bad element choice) and depending test settings on that, if any problem occurs now, it means whole measurement session is close to complete failure.

6.2.2.Reciprocity check

Together with the matching of natural frequencies, comes the check on reciprocity. FRF matrix is symmetrical values with respect to its diagonal or, on in general:

$$H(\omega) = H^T(\omega)$$

This means the FRF obtained hitting a driving point position and registered on a different node must hold the same shape as the one obtained switching the two positions. Overlapping the two diagrams fits exactly this purpose (Figure 9). Failure of the check means problems with signals acquisition, or local modification of physical properties related to bad alignment of the sensors, and at last, less remarkable but frequent drawback as the dimensions of the structure are huge, mistakes in label the points of the wire frame.

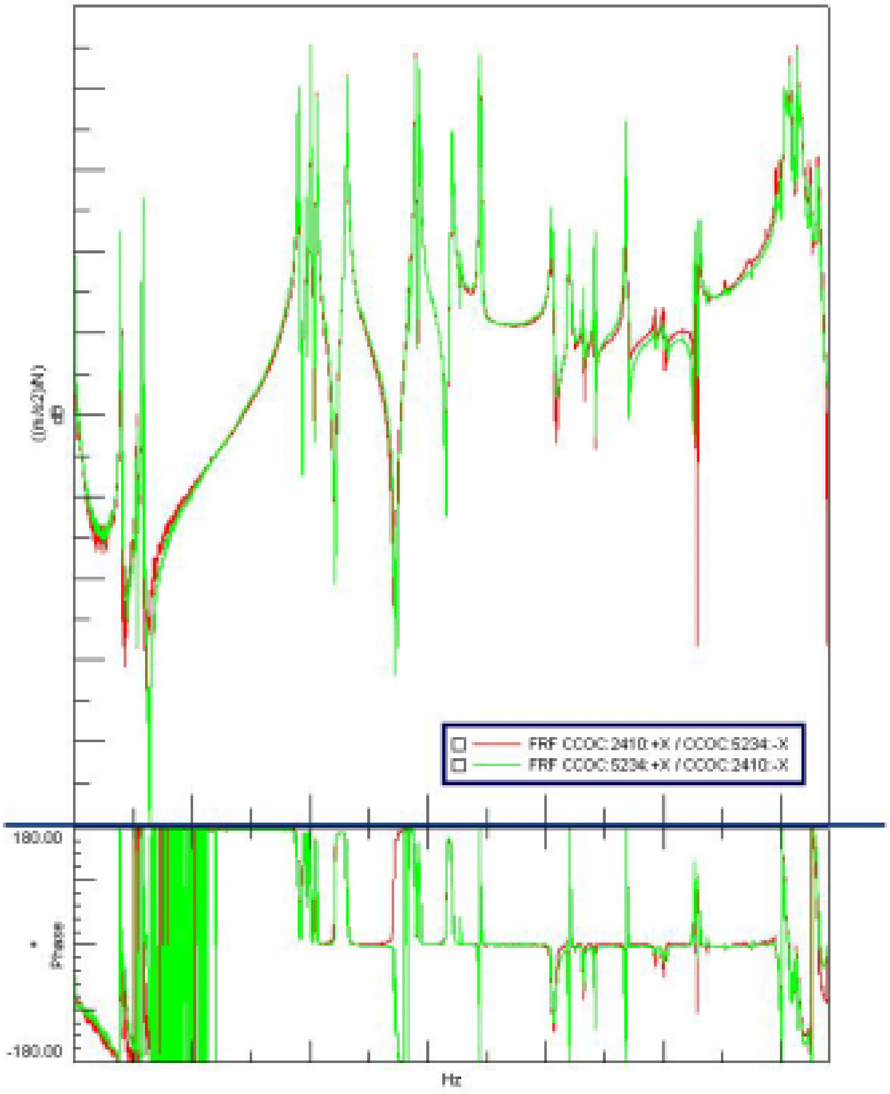


Figure 9: **Coherence check example (LMS Test.Lab).**

6.2.3.Coherence

Coherence is defined as the ratio between measured and predicted FRF, taking into account the presence of noise during acquisition. To better understand this definition it's worth introducing the meaning of estimator function H_1 and H_2. They are used to calculate the frequency response function reducing uncorrelated noise affecting input force or output displacement. H_1 may be obtained starting from the equation

$$H(f)F(f) = X(f) - \eta_0$$

Where η_0 is uncorrelated noise affecting response X(f), F(f) is the force and f is the frequency. Post multiplying by F* the equation becomes:

$$H(f)F(f)F^*(f) = X(f)F^*(f) - \eta_0 F^*(f)$$

If sufficient measurements are averaged and being the noise uncorrelated with force, the second term on the right hand side evolves to zero; the terms remaining are auto and cross spectra. The expression of H_1 is:

$$H_1 = \frac{\hat{S}_{xf}}{\hat{S}_{ff}}$$

where the superscript means the quantity was obtained through averaging.

H_2 is obtained the same way, this estimator takes into account the presence of noise in force input:

$$H(f)[F(f) - \eta_0]F^*(f) = X(f)F^*(f)$$

H_2 is expressed by

$$H_2 = \frac{\hat{S}_{xx}}{\hat{S}_{fx}}$$

Theoretically the two estimators for the same function should give identical result; going back to Coherence formula, it is:

$$\gamma^2 = \frac{H_1}{H_2}$$

$$\gamma^2 = \frac{\left|\hat{S}_{fx}\right|^2}{\hat{S}_{xx}\hat{S}_{ff}}$$

Where S_{fx} is the cross spectrum and S_{xx} and S_{ff} are respectively the response and force auto spectra, and should equal unity ever. If this doesn't happen it could mean:

1. Extraneous noise is present in FRF measurements
2. Non linearity of the system under investigation
3. Measured response is due to other external inputs besides force
4. Leakage

An example of the coherence graphic plot can be seen in Figure 10.

Coherence turns to be the most important indicator of system's illness, the availability of this feedback all through the measurements helps to evaluate step by step the correct carrying out of test.

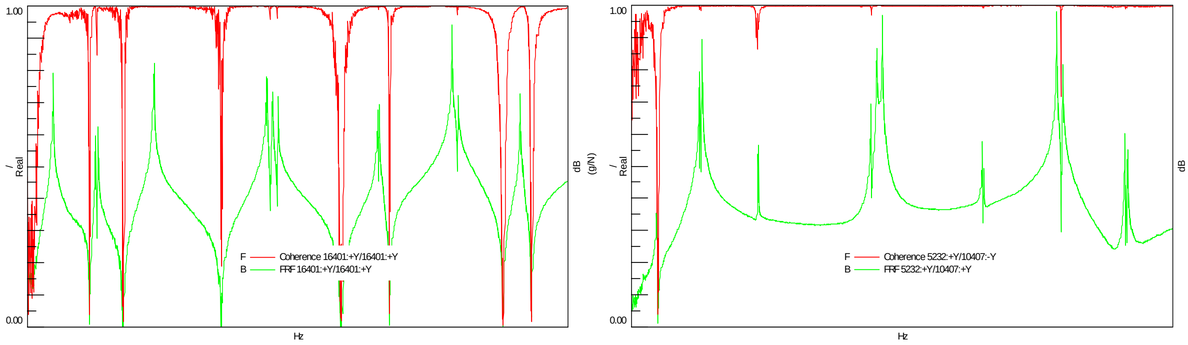


Figure 10: Typical Coherence (red) on FRF(green) displays (LMS Test.Lab).

6.2.4.SVD-CMIF

Peculiarity of symmetric structures, especially axisymmetric, is that many modes appear paired, and they are very close in frequency one to the other; in order to tell between double and distinct-close modes, a Complex Mode Indicator Function (CMIF) is used.

Theoretically, this function comes from the application of a SVD (Singular Value Decomposition) to every spectral line $H(\omega)$ of the FRF matrix:

$$H(\omega) = U(\omega)\ \Sigma(\omega)\ V^H(\omega)$$

where U and V are unitary matrices containing respectively the left and right singular vectors and S is a diagonal matrix with nonnegative diagonal elements in decreasing order. The CMIF is nothing but the graphic representation of singular values as a function of frequency

$$CMIF = [\text{diagonal elements of } \Sigma(\omega)]^2$$

Near resonance, as the frequency approaches the natural frequency of the system, the singular value reaches a maximum, comprising information about the amplitude of the FRF (Figure 11). Since the number of significant singular values at a specific spectral line indicates the number of linearly independent characteristics (modes) that contribute significantly to the content of the frequency response function matrix, there it is the indicator sought.

CMIF is a multiple reference algorithm, and it can detect multiple roots (Figure 12). In this case, several significant singular values will be peaking at that frequency, indicating the number of modes present in the interval.

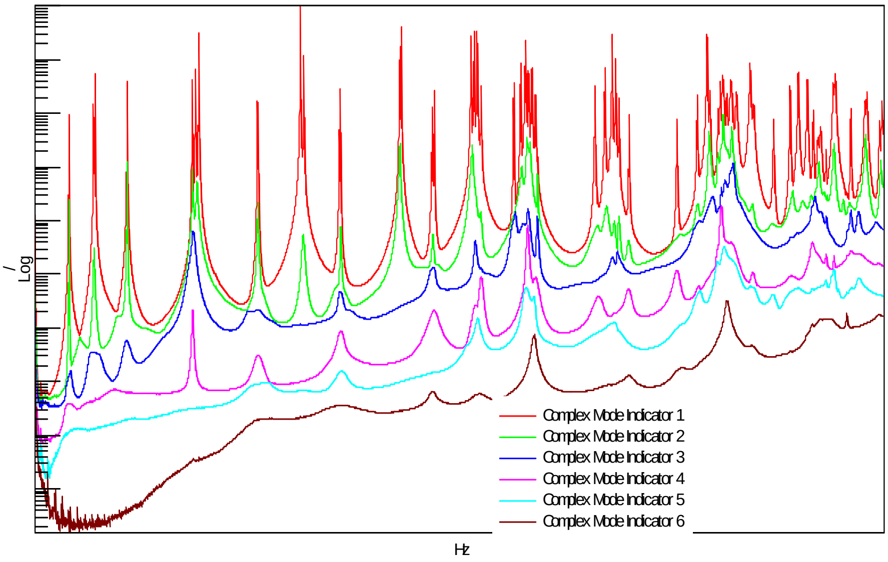


Figure 11: Example of CMIF in the whole bandwidth.

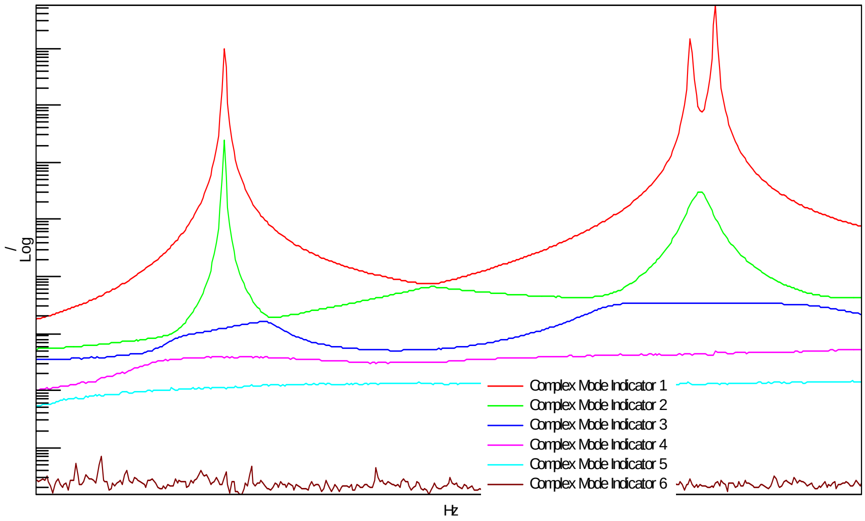
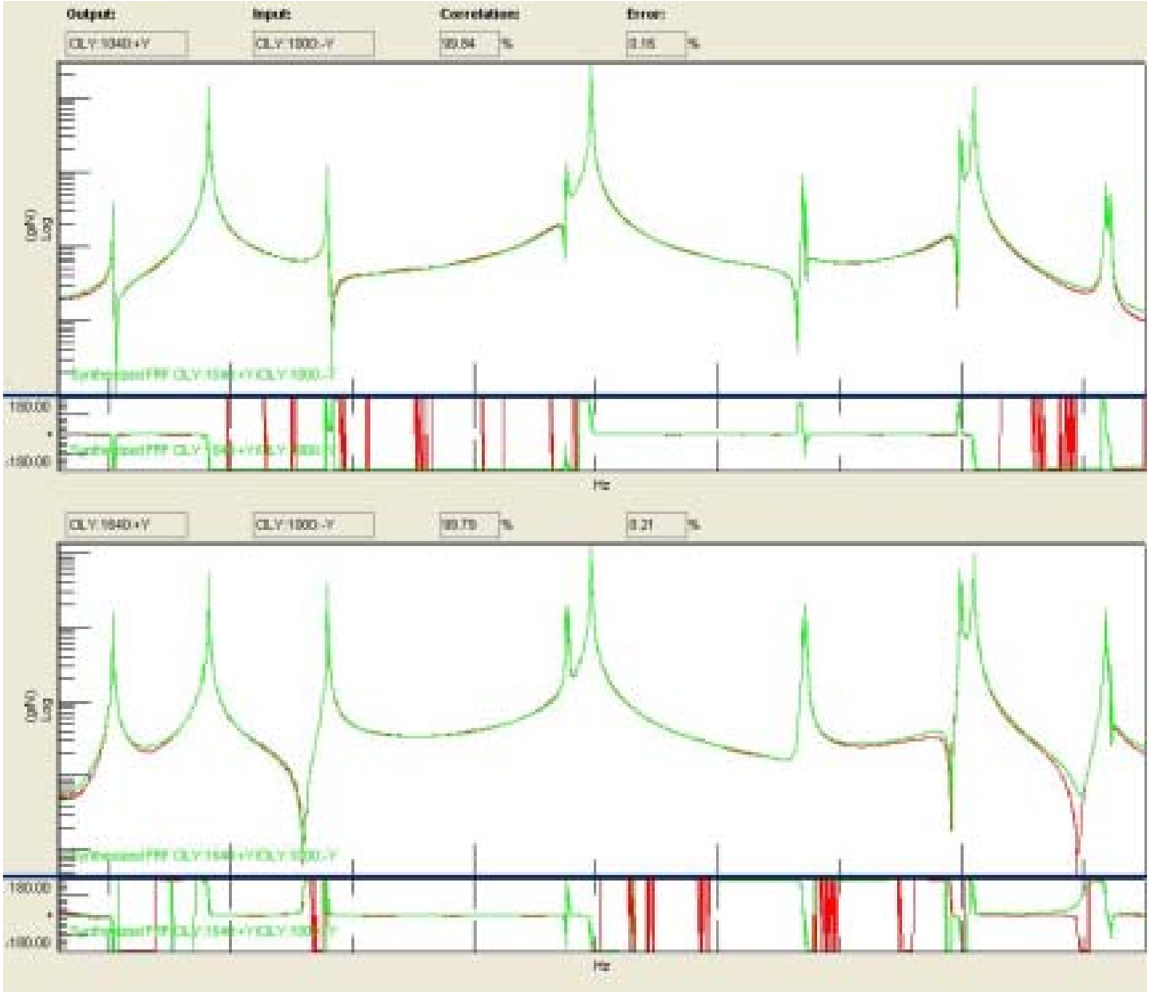


Figure 12: Particular on a double mode compared to close modes CMIF plotting.

A final remark on this function is that the number of contributions can't exceed the number of reference points: coming H(ω) matrix from test, it is never square, but rectangular with the number of columns equal to the reference points, and being Σ of the same dimension, it turns out that it can't be possible to detect a multiplicity of modes (in case they occur) greater than the number of references/driving points. This suggest that where the degree of symmetry of the structure is high, it would be always better to do measurements with more than two accelerometers, to have a better coverage of occurring multiple nodes, but also to supply a more complete information on its behaviour.

6.3. ON-SITE REAL TIME MODAL PARAMETERS ESTIMATION

The accomplishment of the checks so far explained depends on the capability of the software used during the test session. Data handling is the basic requisite, an interface to easily visualize and compare the FRF (Figure 13), the coherence results and the input autospectrum is a must. The latter is used to evaluate, during the preparation phase of test, the extent of the excited bandwidth. This is important information to neither fall short nor exceeding the desired target; to vary this parameter, different tips for the hammer are chosen.



Output: CLY:1040:+Y
Input: CLY:1000:-Y
Correlation: 99.84 %
Error: 0.16 %

Output: CLY:1640:+Y
Input: CLY:1000:-Y
Correlation: 99.79 %
Error: 0.21 %

Figure 13: Synthesized FRF on measured FRF.

Further performance is provided by the availability of on site modal parameters estimation, to be run whenever the test engineer considers it worthy, even with just a limited number of points measured; it is a very valid assessment of test data quality (Figure 14).

This remark introduces what is a real additional value to the session: the use of a platform, to which both pre test/virtual model computation and test data handling software belong. The benefits coming from this coincidence are to be found in the possibility of quickly performing a correlation between test and virtual data with partial availability of measurements results. With respect to test practice up to a few years ago, this is really a breakthrough.

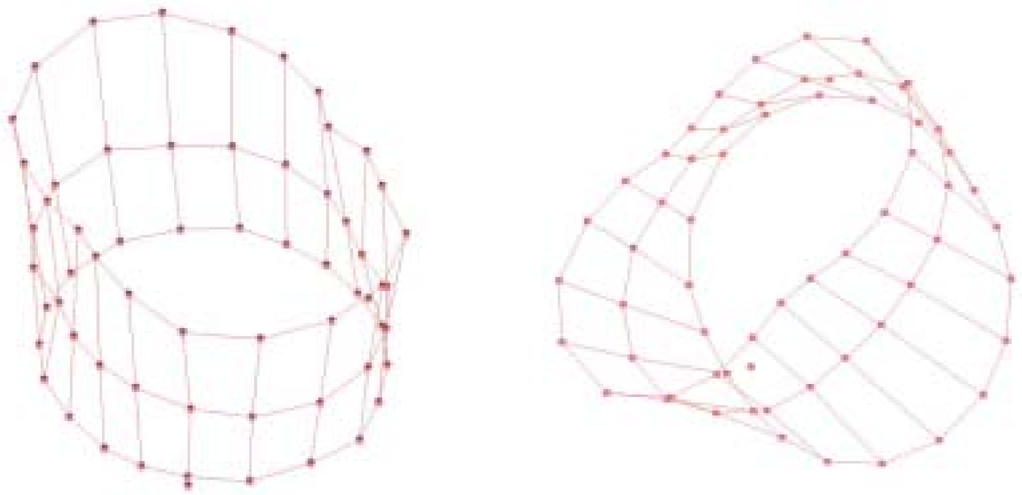


Figure 14: Full set test mode I and III shapes calculated on site.

The experience in using the platform by the engineer gives way to a large number of additional controls to be performed on site simply combining the tools the two programs offer: an example could be the MAC contribution check: during a correlation, also partial, it is possible to evaluate how the single points contribute to MAC highlighting the less efficient. This makes possible to change their locations or even eliminate them with test already ongoing, according to the degrees of freedom in terms of time and resources the engineer has.

7. CONCLUSIONS

It is a common mistake in tests, when the first, expected, or sometimes just consistent results appear, to believe everything is going the right way. Problems might hide beneath the surface of a satisfying feedback, and if not properly investigated, they remain undiscovered compromising or voiding in the worst case the session in its wholeness. Accomplishment of checks like the ones proposed not only prevents the test from failure, but can be used to diagnose “illnesses” related with it. The effectiveness of the control procedures are related not only to the capability of single software, but on the availability of a platform of programs, that link together allow the data transfer and comparison between virtual and test session. Future improvement in this field is related to enhanced automated computation the programs of the platform will be supposed to perform: a tool to handle the session from pre test to post process, providing the engineer (that now still has to manually set these comparison procedures) with “value added engineering time”, limiting his/her actions just to the supervision of the test campaign or to exceptional, mid stage actions, like the one described when talking about the MAC contribution.

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