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MODAL AND FREQUENCY DOMAIN BASED TECHNIQUES FOR FINITE ELEMENT MODEL CORRELATION

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Abstract. *It is common for Finite Element Model (FEM) validation activities to be carried out in the modal domain; using finite element modal analysis results and modal parameters extracted from test measured data. In order to obtain the required mode shapes and natural frequencies from the test measured Frequency Response Functions (FRFs), a modal parameter estimation method must be employed. An alternative approach involves correlation based in the frequency domain. In that case the FRFs would be considered directly from the test, without the need to apply advanced modal parameter extraction, and compared to FEM FRFs. In this work, sine sweep test-FEM correlations of two full spacecraft have been considered. A variety of the aforementioned modal parameter estimation methods have been applied and compared in order to establish which approach is most suitable to the considered applications. Findings highlight the issues associated with applying the simple 'peak picking' approach to modal correlation, and as such indicate that more sophisticated parameter estimation techniques often need to be employed in modal correlation. Frequency based methods therefore have potential inherent advantages as the issue of modal parameter extraction, and the associated introduction of further errors, is avoided. Frequency domain method also have several drawbacks, however, including the inflexibility of the FRF based methods to account for a deflected shape being well matched between test and FEM, but occurring at a slightly different frequency.*

1 INTRODUCTION

From a structural perspective, launch is one of the most challenging phases in the mission of a spacecraft. The interaction between the spacecraft and the launch vehicle is an important aspect of this; however for many reasons, not least of which being the size of the launch vehicle, it is not possible to practically test the two systems together. Thus, in order to simulate the launch experience, Coupled Loads Analyses (CLAs) are carried out which couple a Finite Element Model (FEM) of the spacecraft with a model of the launcher to virtually predict flight loads.

If there is to be confidence in the results of the CLA, it is necessary to first validate the spacecraft FEM against test measured data. The analytical and experimental results are compared and the FEM updated where necessary to improve its representation of the behaviour of the real structure at the vibration modes of interest. This correlation and model update process can take a considerable effort and time. Therefore, one means of containing this process is through ensuring that the comparisons made between test and FEM are meaningful and able to accurately quantify the level of correlation.

The focus here is on the ability of the mode shapes extracted from Frequency Response Functions (FRFs) to represent true mode shapes of the structure. This is an important issue to explore as the data collected during the fixed base sine test of the structure is a representation of how the structure behaves when excited at a given frequency; this is known as the Operating Deflected Shape (ODS). When the structure is excited at a resonant frequency, which is well separated and uncoupled from any other modes, the ODS will be essentially the same as the mode shape with the deflection dominated exclusively by that mode. It is, however, often the case that modes are closely spaced and the ODS at a resonant frequency is ‘contaminated’ by other nearby modes and is not equivalent to the mode shape. This issue has led to the development of many algorithms and software, such as Frequency-Domain Direct Parameter Identification (FDDPI) [1], Least Squares Complex Exponential (LSCE) [2] or PolyMAX [3] methods for estimating and extracting modal parameters and mode shapes from test data. Here comparisons are made between: mode shapes estimated from FRFs obtained through sine-sweep analysis of spacecraft FEMs; and those found through direct modal/eigen- analysis of the same FEMs.

As there will always be some level of ‘errors’ introduced through the modal parameter estimation process, one alternative approach is to avoid the effort and uncertainty associated with this process by performing correlation comparisons in the frequency/response domain through direct use of the FRFs. As such, this topic is to be the subject of further investigation.

2 CORRELATION CRITERIA

It is essential that the spacecraft FEM provides a realistic representation of the behaviour of the real structure as the mathematical model will subsequently be employed in the CLA to investigate the spacecraft-launcher interactions and thus ensure that the spacecraft does not encounter unacceptable launch loads. The spacecraft FEM correlation exercise is essentially a comparison between the experimental data and the analytical model. The purpose of the correlation is therefore to evaluate how well the FEM replicates the behaviour of the real structure, as depicted in Figure 1, at important modes such that updates to the model can be made where necessary to achieve a final spacecraft FEM which is ‘fit for purpose’. In order to perform these correlations it is necessary to define some criteria to quantify and evaluate how well matched the FEM is to the test for a given target mode.

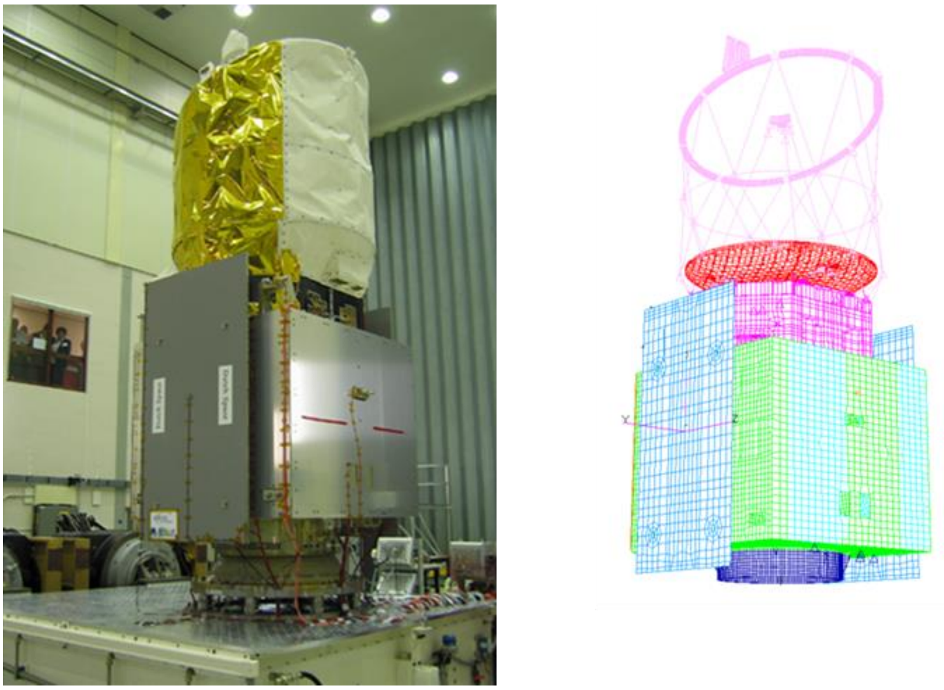


Figure 1. Aeolus STM [4] (left) and Aeolus FEM (right).

There are a wide variety of methods which may be used to perform these comparisons; some of the main methods are outlined in the table below from European Cooperation for Space Standardisation (ECSS) modal survey assessment document ECSS-E-ST-32-11C [5].

Type	Techniques
Vector based techniques	- Modal assurance criterion (MAC) [a] - Orthogonality or cross-orthogonality [a]
DOF based techniques	- Coordinate modal assurance criterion (CoMAC) - Modulus difference [a] - Coordinate orthogonality check
Frequency based techniques	- Frequency difference [a] - Frequency response assurance criterion (FRAC) - Response vector assurance criterion (RVAC)
a Mandatory (see 5.8.1.1b)	

Table 1. ECSS [5] table of commonly used correlation techniques.

2.1 Modal Based Correlation Techniques

At this point one approach to the correlation of spacecraft models is modal analysis and subsequent comparison of FEM eigenvalues and eigenvectors with test derived natural frequencies and mode shapes. Comparisons may be made by using the common vector based techniques: Modal Assurance Criteria (MAC) [6] and Cross-Orthogonality Checks (COC) [7].

Modal Assurance Criteria (MAC)

For MAC, the test mode shapes, ψ, and FEM eigenvectors, φ, are compared, resulting in a value between 0 and 1 which indicates how closely matched the vectors are, with a perfect match yielding a 1.

$$\mathrm{MAC} = \frac{(\psi^{T}\phi)^{2}}{(\psi^{T}\psi)\cdot(\phi^{T}\phi)} \tag{1}$$

It is generally considered, and indicated in the table below from ECSS-E-ST-32-11C [5], that target modes achieving a MAC of at least 0.9 indicates a good correlation and is the minimum required value for the fundamental bending modes of a spacecraft. It is, however, also clear from Table 2 that the required degree of correlation is dependent on the perceived relative importance of the mode under consideration.

Cross-Orthogonality Check (COC)

The COC is also an ECSS [5] required check, and works similarly to MAC, but with the mass matrix employed to weight the relative importance of the DoFs being considered. This approach takes advantage of the orthogonal relationship between normal modes and the system mass matrix. An ideal result of perfectly matched mode shapes which are orthogonal to the mass matrix will yield a diagonal matrix, and for mass normalised modes this becomes an identity matrix. Again, in Table 2, it is shown that off-diagonal values <0.1 and leading diagonal terms >0.9 are deemed to indicate a good correlation. The typical cross-orthogonality check is given by:

$$\mathrm{COC} = \frac{(\psi^{T}M_{TAM}\phi)}{\sqrt{(\psi^{T}M_{TAM}\psi)}\sqrt{(\phi^{T}M_{TAM}\phi)}} \tag{2}$$

where the Test Analysis Model (TAM), or reduced mass matrix, M_{TAM}, is generated by application of an appropriate model reduction method. The experimental and analytical mode shapes are again given by ψ and φ respectively.

The introduction of the mass matrix has potential benefits as the mass associated to the modal vectors is accounted for and as such there is a weighting of the DoFs depending on their relative influence, which is not accounted for by the MAC criteria. Although, the practical benefits are potentially reduced in circumstances where the DoF set is pre-selected and the perceived relative importance of selected DoFs is not necessarily directly related solely to mass weighting.

Item	**Quality criterion [a]**	
Fundamental bending modes of a spacecraft	MAC: Eigenfrequency deviation:	> 0,9 < 3 %
Modes with effective masses > 10 % of the total mass	MAC: Eigenfrequency deviation:	> 0,85 < 5 %
For other modes in the relevant frequency range [b]	MAC: Eigenfrequency deviation:	> 0,8 < 10 %
Cross-orthogonality check	Diagonal terms: Off-diagonal terms:	> 0,90 < 0,10
Damping	To take measured values as input for the response analysis. To use realistic test inputs for this purpose.	
Interface force and moment measurements	For modes with effective masses > 10 %: deviations of interface forces and moments < 10 %.	

a The quality criteria given are not normative and are given as examples for achieving a satisfactory test–analysis correlation.

b The relevant frequency range is, in general, determined by the launcher excitation spectrum up to 100 Hz. This frequency range can, however, be extended due to, for example, high frequency launcher dynamic excitations or specific requirements for AOCS control purposes.

Table 2: ECSS [5] required correlation levels.

Co-Ordinate Modal Assurance Criteria (COMAC)

Co-Ordinate Modal Assurance Criteria (COMAC) [8] is similar to MAC, however, it compares the test and FEM responses at a given DoF across all modes, rather than comparing the response at all DoFs for a single mode. This method is therefore useful in situations where the level of correlation for an individual DoF, or set of key DoFs, is of particular interest.

For a given DoF, i, the COMAC is given by:

$$\mathrm{COMAC_i} = \frac{\left(\sum_{n=1}^{N} |\psi_{in}\phi_{in}|\right)^2}{\sum_{n=1}^{N} \psi_{in}^2 \sum_{n=1}^{N} \phi_{in}^2} \tag{3}$$

The experimental and analytical mode shapes are again given by ψ and φ respectively. The subscript n represents the index of the considered mode pair, whilst N denotes the number of mode pairs to be considered.

This method is less commonly applied than the aforementioned MAC and COC checks, and is not considered mandatory by ECSS [5], see Table 1. One drawback of this method is that it requires all of the modes under consideration to be pre-paired, most likely through the use of MAC to match the modes from the test to the correct corresponding FEM mode shape. [9]

2.2 Frequency Based Correlation Techniques

Frequency Difference

Frequency difference is simply the difference between the resonant frequencies identified from the test data and the eigenvalues from the FEM analysis, and is often given in the form of a percentage difference. The equation given below can be used to calculate the frequency difference, where f is the natural frequency in Hz corresponding to the mode being considered.

$$\text{Frequency Difference} = \frac{|f_{FEM} - f_{Test}|}{f_{Test}} \times 100\% \tag{4}$$

Frequency Response and Response Vector Assurance Criteria (FRAC and RVAC)

The frequency based equivalents of MAC and COMAC are Response Vector Assurance Criteria (RVAC) [10] and Frequency Response Assurance Criterion (FRAC) [11], respectively. For the frequency based methods, rather than comparing mode shapes, the FRFs are compared as shown in Figure 2. FRAC compares the FRFs, for a given DoF, across all measured frequencies. RVAC compares Operating Deflected Shapes (ODSs), i.e. the responses of all measured DoFs at a given frequency.

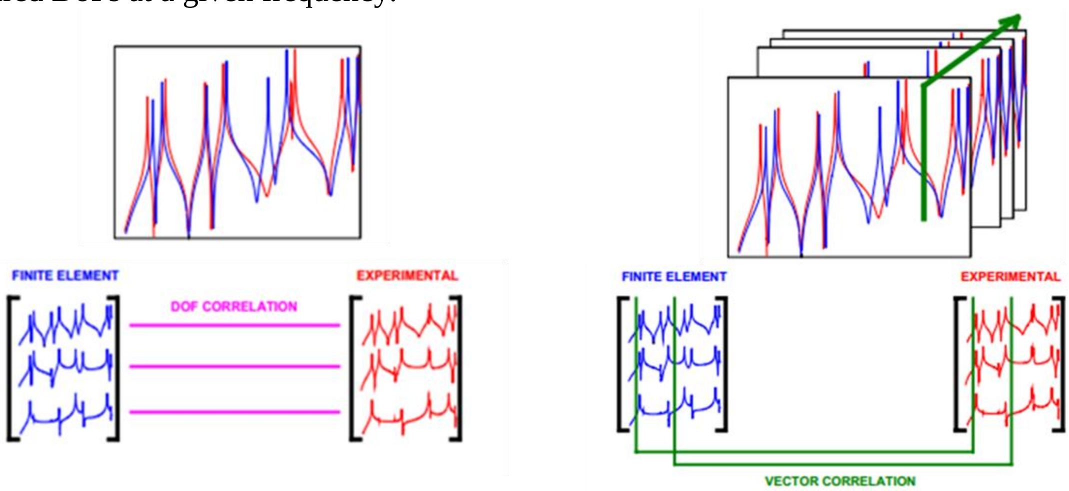


Figure 2. Illustration of FRAC (left) and RVAC (right) FRF Based Correlation Criteria [9]

The equations for FRAC and RVAC are given below. For FRAC, the FRF for a given DoF across the entire frequency range of interest is given by H. RVAC makes use of the ODSs, U, at a given frequency across all DoFs from the MPP.

$$\mathrm{FRAC} = \frac{\left(\{\mathrm{H_{Test}}\}\{\mathrm{H_{FEM}}\}^{\mathrm{T}}\right)^2}{\left(\{\mathrm{H_{Test}}\}\{\mathrm{H_{Test}}\}^{\mathrm{T}}\right)\cdot\left(\{\mathrm{H_{FEM}}\}\{\mathrm{H_{FEM}}\}^{\mathrm{T}}\right)} \tag{5}$$

$$\mathrm{RVAC}(\omega) = \frac{\left(\mathrm{U}(\omega)_{\mathrm{Test}}^{\mathrm{T}}\mathrm{U}(\omega)_{\mathrm{FEM}}\right)^2}{\left(\mathrm{U}(\omega)_{\mathrm{Test}}^{\mathrm{T}}\mathrm{U}(\omega)_{\mathrm{FEM}}\right)\cdot\left(\mathrm{U}(\omega)_{\mathrm{Test}}^{\mathrm{T}}\mathrm{U}(\omega)_{\mathrm{FEM}}\right)} \tag{6}$$

An alternative to RVAC is the Frequency Domain Assurance Criteria (FDAC) [12], which is also based on comparing ODSs. Where RVAC compares the ODSs for test and FEM FRFs at a particular frequency, with FDAC the corresponding resonant frequencies for test and FEM are identified separately and thus $\omega_{\mathrm{Test}} \neq \omega_{\mathrm{FEM}}$. In this manner, the deflected shape can be compared and the issue of differing resonant frequency can be considered separately by considering the frequency difference.

These frequency based methods have the advantage that the FRFs from the test can be used directly in the correlation, without requiring the modal parameter extraction used to compare modal data [13]. This is a benefit in that it not only circumvents the effort required to extract the modal parameters, but also avoids the potential errors introduced to the test data as a result of modal parameter estimation issues.

There are, however, significant drawbacks associated with these frequency base correlation methods. One main issue is that damping, which is neglected in modal analysis, must be accounted for in the FEM in order to produce the FRFs required for frequency based correlation [14]. It is also the case that both FRAC and RVAC can be influenced by the potential for a shift in resonance frequencies between test and FEM, although variations on these techniques have been developed which introduce shift parameters attempt to compensate for this effect. The use of ODS rather than mode shapes also has the drawback that a conventional orthogonality check cannot be applied with frequency domain correlation.

As such, modal based correlation is more common and, as shown by Table 1, is mandated by the ECSS modal survey assessment [5] where the FRF techniques are optional. Due to the more frequent application of modal techniques, the results of MAC and COC checks are more widely understood and values indicating good correlation are well established. The required level of correlation in terms of FRF based methods is less clear [15].

3 MODAL PARAMETER ESTIMATION

It is not possible to directly measure the modal parameters of a structure through physical testing alone; therefore it is important to perform appropriate experimental data processing such that as close a representation as possible to the true mode shapes of the structure is obtained for comparison with the analytical modal analysis results from the FEM. If this is not accomplished, then any subsequent modal data based correlation is undermined, possibly triggering FEM updates which are unnecessary.

3.1 Introduction to Modal Parameter Extraction Methods

The data collected during the base-shake sine-sweep test of the structure is a representation of how the structure behaves when excited at a given frequency; this is known as the Operating Deflected Shape (ODS). In theory, the ODS will be a linear combination of all modes contributing to the response of the structure. In practice, when the structure is excited at a resonant frequency, which is well separated and uncoupled from any other modes, the ODS is likely to closely approximate the corresponding mode shape, with deflections dominated by that mode pattern having negligible contribution from adjacent modes, as illustrated in Figure 3. It is, however, often the case for complex structures that modes are closely spaced and the ODS at a resonant frequency is ‘contaminated’ by the influence of other nearby modes, and as such is not equivalent to the mode shape.

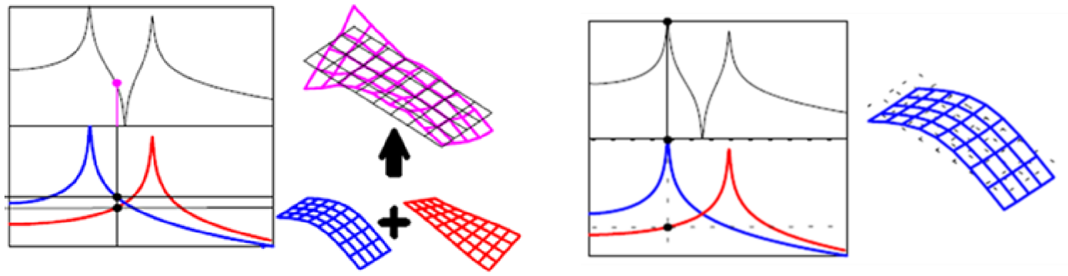


Figure 3. ODS between resonances, left, and ODS at resonant frequency, right. [16]

This issue has led to the development of many algorithms and software packages for estimating and extracting modal parameters from test measured FRF data. The following subsections explore the classifications of these methods and the advantages and disadvantages of each. The method must ideally be selected as appropriate the application under consideration.

Single or Multiple Degrees of Freedom

Single Degree of Freedom (SDoF) methods determine modal parameters for each mode individually. The main benefits of these methods are the ease and speed of application. SDoF approaches work under the assumption that the structure behaves as an SDoF system when excited at resonance, i.e. that the ODS is equivalent to the corresponding pure mode shape with no influence from the other modes of the system. This assumption is only valid under the condition that the system modes are not heavily coupled. When this condition is met, these methods can be appropriate to use and accurate; if, however, this is not the case then Multiple Degree of Freedom (MDoF) methods are required in order to achieve a reasonable approximation of the modal parameters. MDoF methods generate an estimation of modal parameters by analysing data for multiple modes simultaneously. [17, 18]

Local or Global

Local (otherwise referred to as single output) methods are so called as they are applied to one output at a time, such as an individual FRF curve for a particular sensor. As such, any modal parameters estimated will apply to the FRF under consideration and not necessarily to the global system. This has the disadvantage that the outcome is a set of multiple locally estimated values for a single parameter, such as for the natural frequency of a given mode, which may vary slightly between the different FRFs. In such a case, it would be up to the analyst to determine which natural frequency value was most appropriate, or simply apply the average given the results for all of the considered FRFs. [17, 18]

Global (otherwise referred to as multiple output) methods are applied to many output sets, such as the FRFs considered in this work, simultaneously. This allows parameters to be estimated based on all available data on the full system, rather than locally for one sensors data at time. [17, 18]

Single or Multiple Input

Experimental modal analysis can be conducted through the use of single or multiple exciters. Where multiple excitations are applied, it can be advantageous to then employ a modal parameter estimation method which can globally assess the FRFs by taking into account all applied inputs simultaneously. This is possible as the modal parameters are not input dependent, and as such should be consistent regardless of varying applied input location. The main advantage of methods accounting for multiple input scenarios is improved estimation in the occurrence of closely coupled modes and even double poles (two distinct modes occurring at the same excitation frequency). Methods which can accommodate multiple-inputs and multiple-outputs (MIMO) are sometimes referred to as 'polyreference' techniques. [17, 18]

3.2 Single Degree of Freedom Modal Parameter Estimation

SDoF methods are generally very straight forward to implement, computationally efficient and can give sufficiently accurate results under the right circumstances. Where modes are well separated in frequency, see upper plot in Figure 4, these simple SDoF methods are known to be reasonably effective and may therefore be applied without the need to employ more sophisticated techniques for manipulation of the test data. It should be noted, however, that where there is heavy modal coupling, see lower plot in Figure 4, these methods are not sufficient and a method considering the influence of the interactions between multiple modes is required. [19, 20]

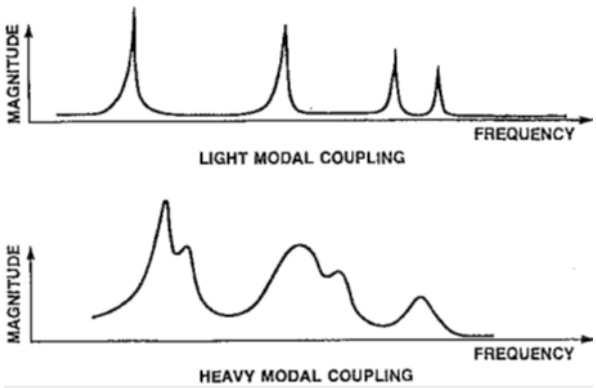


Figure 4. Modes well separated or heavily coupled [20]

'Peak/Mode Picking' Method

One simple SDoF method is to use the peaks in the imaginary part of (acceleration/force) FRFs to identify the resonant frequencies ('peak picking'), and to estimate the mode shapes ('mode picking') as equivalent to the ODSs at those frequencies, as depicted by Figure 5. The validity of this method for some example spacecraft cases has been investigated.

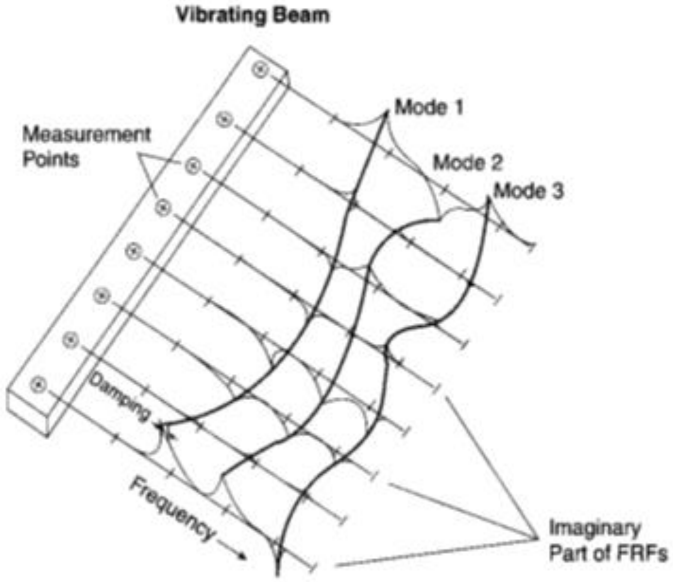


Figure 5. FRF imaginary part ‘peak picking’ method of SDoF mode approximation [20]

3.3 Multiple Degree of Freedom Modal Parameter Estimation

When modal coupling is such that the simple SDoF methods are not sufficient to provide a sufficiently accurate estimation of the required parameters; more advanced curve fitting methods, which simultaneously consider multiple modes or even an entire set of FRFs, may instead be applied. Various methods have been developed over the years to deal with this important issue in experimental modal analysis.

Maia and Silva [21] observed that the Complex Exponential (CE) [22] method has been one of the most important and influential modal parameter estimation methods. It is a time domain single-input-single-output (SISO) method and appeared in 1970 when proposed by Spitznogle and Quazi [22]. CE was eventually developed further to produce one of the most established methods; the least-squares complex exponential method (LSCE), introduced by Brown et al [2] in 1979. This LSCE method has the advantage of being a global method and has been widely used for processing data from single-input-multiple-output (SIMO) experiments. A frequency domain version of the least squares method, known as Least Squares Complex Frequency (LSCF) was subsequently created [23].

More recent work, such as that of Guillaume et al [24], has overcome some of the limitations of previous techniques by generating a poly-reference version of the LSCF method, capable of handling multiple inputs. There are many important potential benefits to the use of a multi-reference method for the cases to be considered in this work. One of the main benefits from the perspective of this work is that it allows closely coupled modes to be more accurately identified than previous methods [24].

MDoF modal parameter estimation methods often consist of two main procedures: first to determine the global parameters, such as system poles/resonant frequencies; and subsequently to estimate the local parameters, i.e. the modal displacements from which the modal vectors are comprised. Different methods are typically employed to perform each of these key procedures. For the initial phase, Polyreference-LSCFD methods are now the most popularly employed, although Polyreference-LSCE are also still relatively common; whereas for the second phase of the process, Least Squares Frequency Domain (LSFD) techniques are the most commonly implemented. [17]

4 EXAMPLE APPLICATIONS

As described previously, the simple SDoF 'peak picking' method uses the peaks in the imaginary part of the FRFs to identify the resonant frequencies and to extract the ODS at those frequencies. More sophisticated MDoF methods of modal parameter estimation have been developed to account for structures, for which the SDoF method is not sufficient. Poly-reference LSCF methods are currently among the most commonly applied. In order to examine the validity of these method for mode shape estimation in spacecraft applications, a frequency response analysis has been performed on the spacecraft FEMs and the resulting mode shapes estimated from FRFs are compared to the FEM mode shapes obtained directly from modal/eigen- analysis of the same reference spacecraft FEMs.

The studies presented herein focus on two large, unique, scientific spacecraft:

- The ESA/JAXA collaboration spacecraft BepiColombo for the exploration of Mercury which has a stacked configuration comprising of two planetary orbiters and a propulsion module. The spacecraft has a mass of 6446kg and the FEM consist of approximately 1,800,000 DoFs. During base-shake sine-sweep vibration tests, data was collected using accelerometers capturing the response at approximately 400DoFs. The corresponding 400 DoFs from the FEM will be considered in these investigations for the generation of FRFs and mode shape vectors.
- ESA's Atmospheric Dynamics Mission Aeolus spacecraft for global wind-component-profile observation, which aims to improve weather forecasting. This spacecraft has a mass of 1800kg and the FEM consist of approximately 575,000 DoFs. Again, these investigations focus on the 300 DoFs used as measurement points in the sine-sweep vibration test of the spacecraft.

Figure 6. BepiColombo (left) and Aeolus (right) STMs during vibration test preparation [4]

For the purposes of this investigation, the modes of interest have been selected based solely on the modal effective mass of each mode in the translational directions, as shown in Table 3 below. The modal effective mass gives an indication to the level of participation of each mode in the loads analysis and is often used to highlight significant modes for correlation [25].

BepiColombo				Aeolus			
Freq. (Hz)	Effective Modal Mass (%)			Freq. (Hz)	Effective Modal Mass (%)		
	TX	TY	TZ		TX	TY	TZ
12.68	0.66	25.96	0.02	15.96	42.35	0.02	0.00
13.01	25.30	0.73	0.00	16.62	0.02	45.31	0.00
26.50	4.79	0.23	0.00	40.94	0.00	6.89	0.02
27.12	2.40	0.55	0.00	41.30	0.00	3.40	0.02
27.68	1.21	0.00	0.00	48.95	1.50	0.00	0.02
28.43	0.02	8.97	0.07	54.58	2.39	0.14	0.32
32.43	0.11	0.10	1.21	55.63	0.75	0.15	6.76
33.44	0.00	0.12	5.96	56.94	3.65	0.20	0.00
35.82	0.33	1.14	0.08	58.68	0.47	0.58	1.65
37.03	2.91	0.01	2.94	60.00	0.00	0.00	1.84
37.19	0.36	0.19	3.38	61.47	0.00	0.15	1.46
37.55	2.19	0.16	0.05	63.86	0.08	0.00	5.43
37.77	0.50	0.52	13.15	64.35	0.47	0.00	22.90
38.01	0.00	1.13	1.61	64.69	5.45	0.07	2.47
44.07	0.02	0.03	1.32	69.60	0.01	1.04	0.01
44.37	0.16	2.34	0.01	84.64	0.26	0.05	3.65
45.01	0.00	0.00	1.20	85.01	0.02	0.03	1.52
49.10	0.08	0.03	6.95	85.23	0.02	0.01	8.33
49.77	0.00	0.12	1.03				
57.01	1.12	0.00	0.02				
57.17	2.10	0.00	0.02				

Table 3. Modal Effective Masses of Selected Target Modes

Figure 7 shows the MAC comparison of the BepiColombo X-direction target FEM eigenvectors/mode shapes (partitioned to the ≈400 DoFs from the test measurement point plan) compared to their closest matching modes as estimated from the FEM frequency response analysis; with 'peak picking' results on the left and results from a poly-reference LSCF method on the right. From 'peak picking' there is a reasonably good match for the 1st target mode, however higher order modes show some degradation of MAC, as is depicted by the bar charts in Figure 9. Attention should be drawn here that the MAC here is based upon ≈400 DoFs and illustrations here do not present influence of elimination of user identified DoFs to investigate their sensitivity into the MAC. Correlation for example, in this case, for the second order cantilever modes showed the MAC was heavily influenced by certain DoFs which were deemed of low criticality to the mode considered (e.g. high DoF responses on local light structural features within the second order cantilever modes). Once eliminated, via technical justification, such modes were deemed reasonably well correlated.

Figure 8 provides plots of the imaginary part of the FRFs corresponding to selected example DoFs, with vertical lines to indicate the target mode natural frequencies. From these plots, it can be seen that, other than the 1st mode which is well separated, there is heavy coupling between modes and at higher frequencies the curves resemble the lower plot in Figure 4 above. As such, it is to be expected that these 'peak picked' modes/ODSs will not closely match the corresponding mode shapes, and the more sophisticated poly-reference LSCF method will provide a better match, which is consistent with the MAC results given in Figure 7.

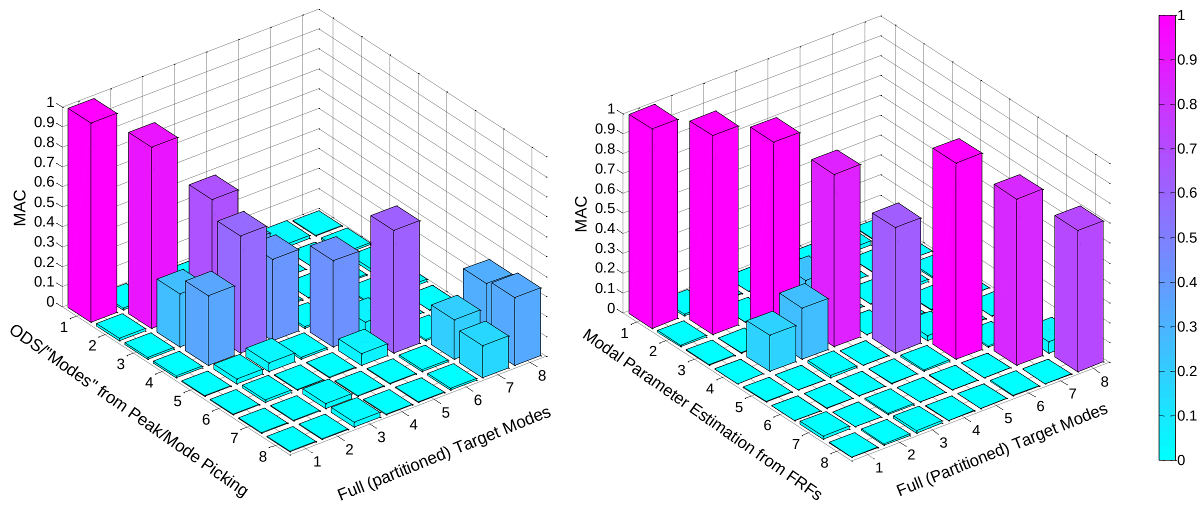


Figure 7. BepiColombo MAC results of FEM X-direction target modes compared with:
Left - FEM ODS/modes from peak picking, Right - FEM modes from modal parameter estimator

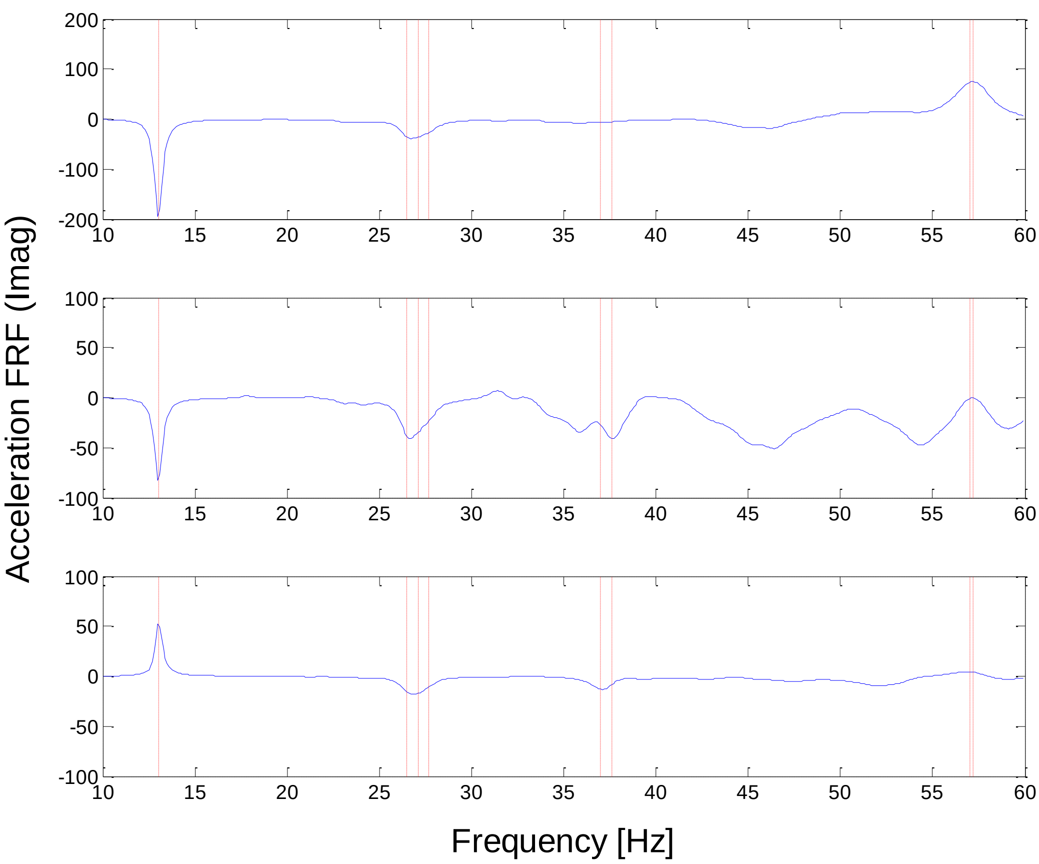


Figure 8. Imaginary part of example FRFs for FEM 'Peak/Mode Picking'

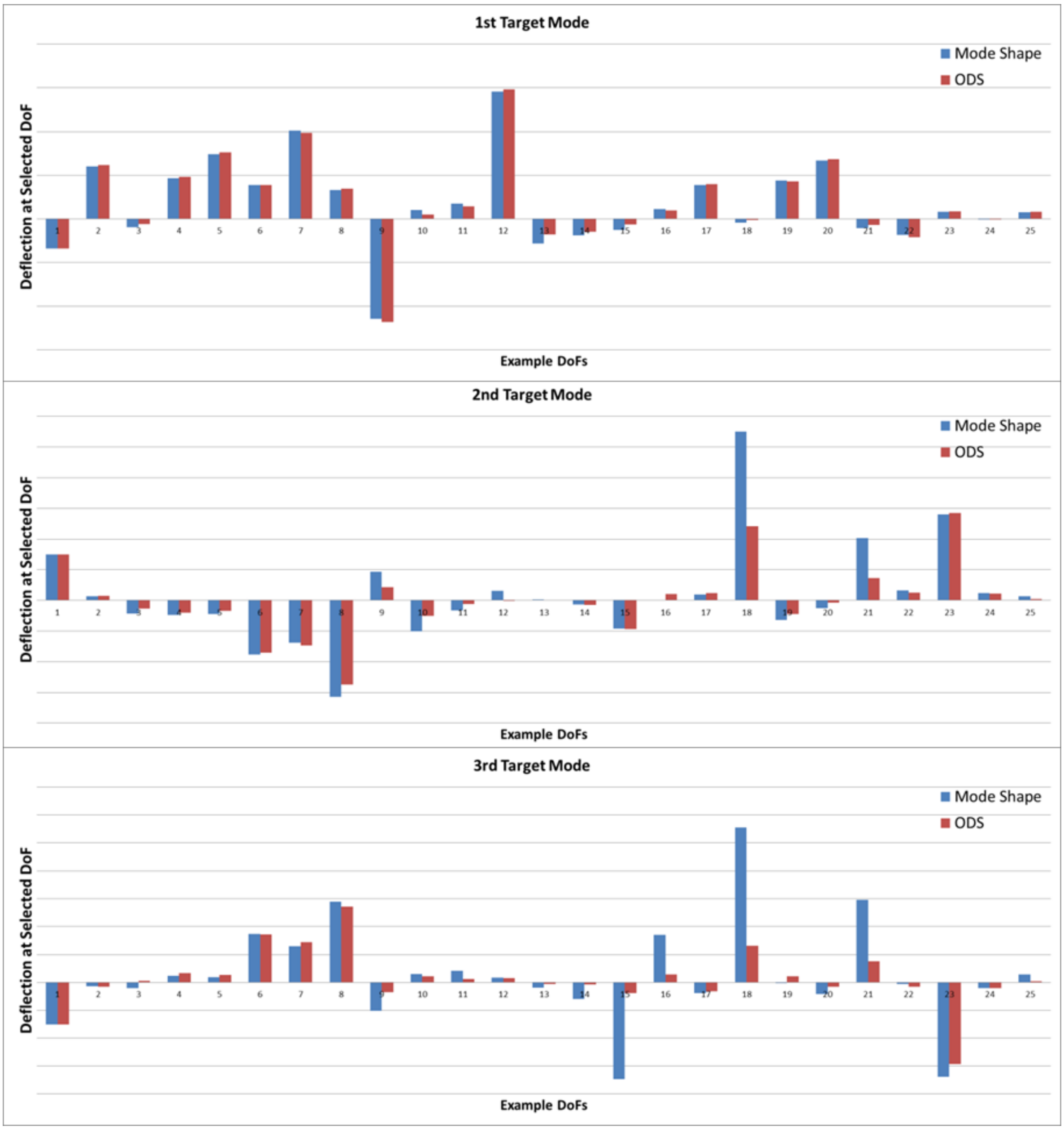
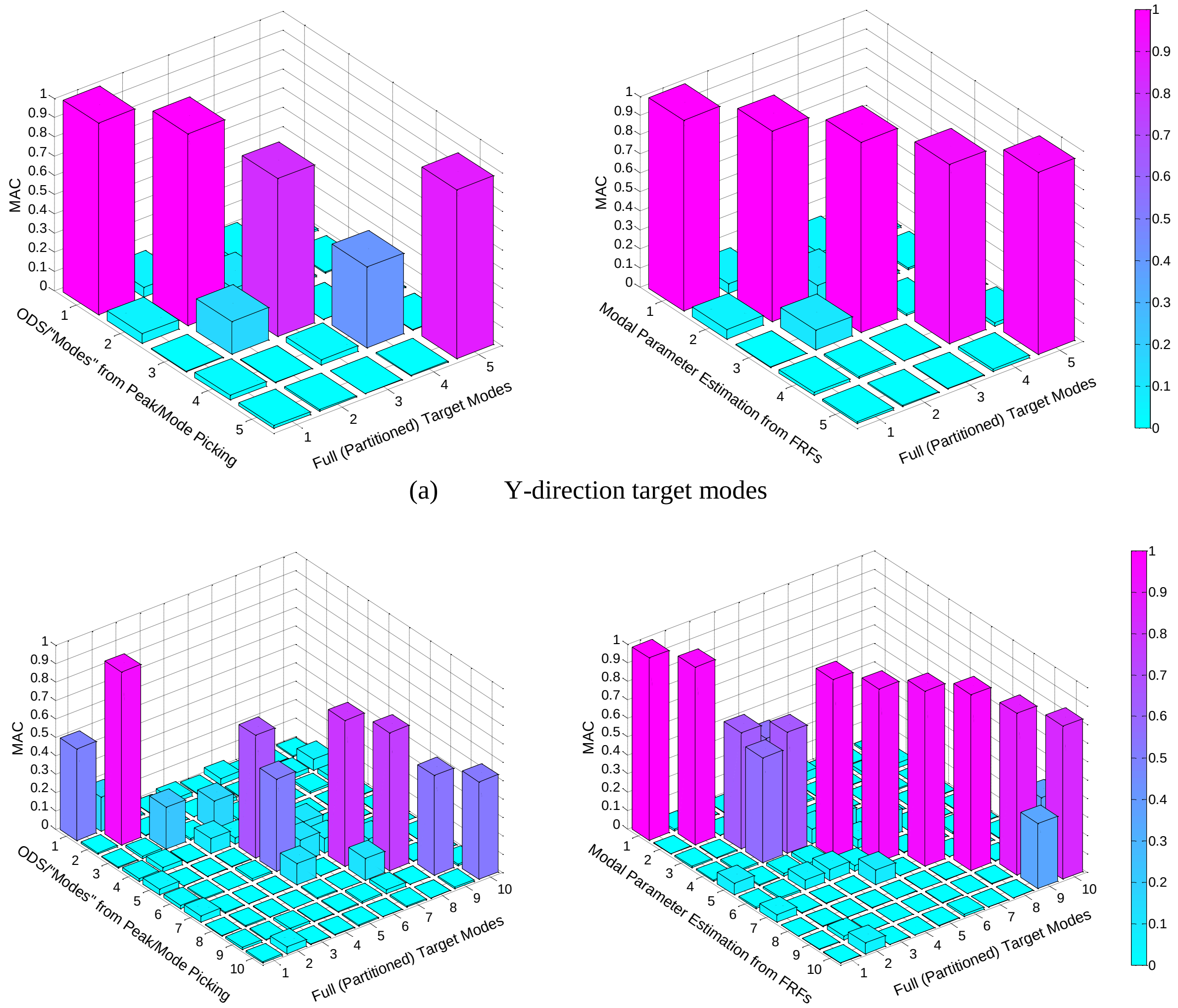


Figure 9. FEM ODS and eigen-mode matches for first 3 x-dominant target modes for 25 example DoFs

Figure 10 shows the MAC comparison of the BepiColombo Y- and Z-direction target FEM mode shapes (directly from FEM normal modal analysis) compared to their closest matching estimates from the FEM frequency response analysis (of the same baseline FEM); again with 'peak picking'/ODS results on the left and result from dedicated modal parameter estimation software, using a poly-reference LSCF method, on the right. Again there is a consistent improvement in the MAC result when the software is used to perform mode shape estimation rather than using simple 'peak picking' of modes equivalent to ODS'.

Likewise, Figure 11 shows the MAC comparison of the Aeolus X-, Y- and Z-direction target FEM mode shapes (partitioned to the ≈300 DoFs from the test measurement point plan) compared to their closest matching estimates from the FEM frequency response analysis; again with 'peak picking'/ODS results on the left and result from dedicated modal parameter estimation software on the right. Here the target modes in each direction were reasonably well separated and so the 'peak picked' results appear to give a relatively close match to the target modes. Nevertheless, there is still a notable improvement in the MAC results when the Global MDoF mode shape estimation method is applied.

The actual BepiColombo test data, processed with 'peak picking' as described above, was then compared to both the FEM mode shapes (from direct FEA modal analysis) and the FEM ODS/modes (from 'peak picking'), with the resulting MAC comparisons given in Figure 12. This figure reveals that the test results generally give a better match to the FEM ODS than the FEM mode shapes, confirming that the ODS at resonance frequency is not necessarily representative of the corresponding pure mode shape. This could also be viewed as showing potential for there to be merit in the argument to compare FRF data directly. The right plot in Figure 12 is essentially a comparison of test and FEM ODS; in effect the same as applying the FDAC comparison method.



(a) Y-direction target modes

(b) Z-direction target modes

Figure 10. BepiColombo MAC results of FEM normal modes compared with:
Left - FEM ODS/modes from peak picking, Right - FEM modes from modal parameter estimator

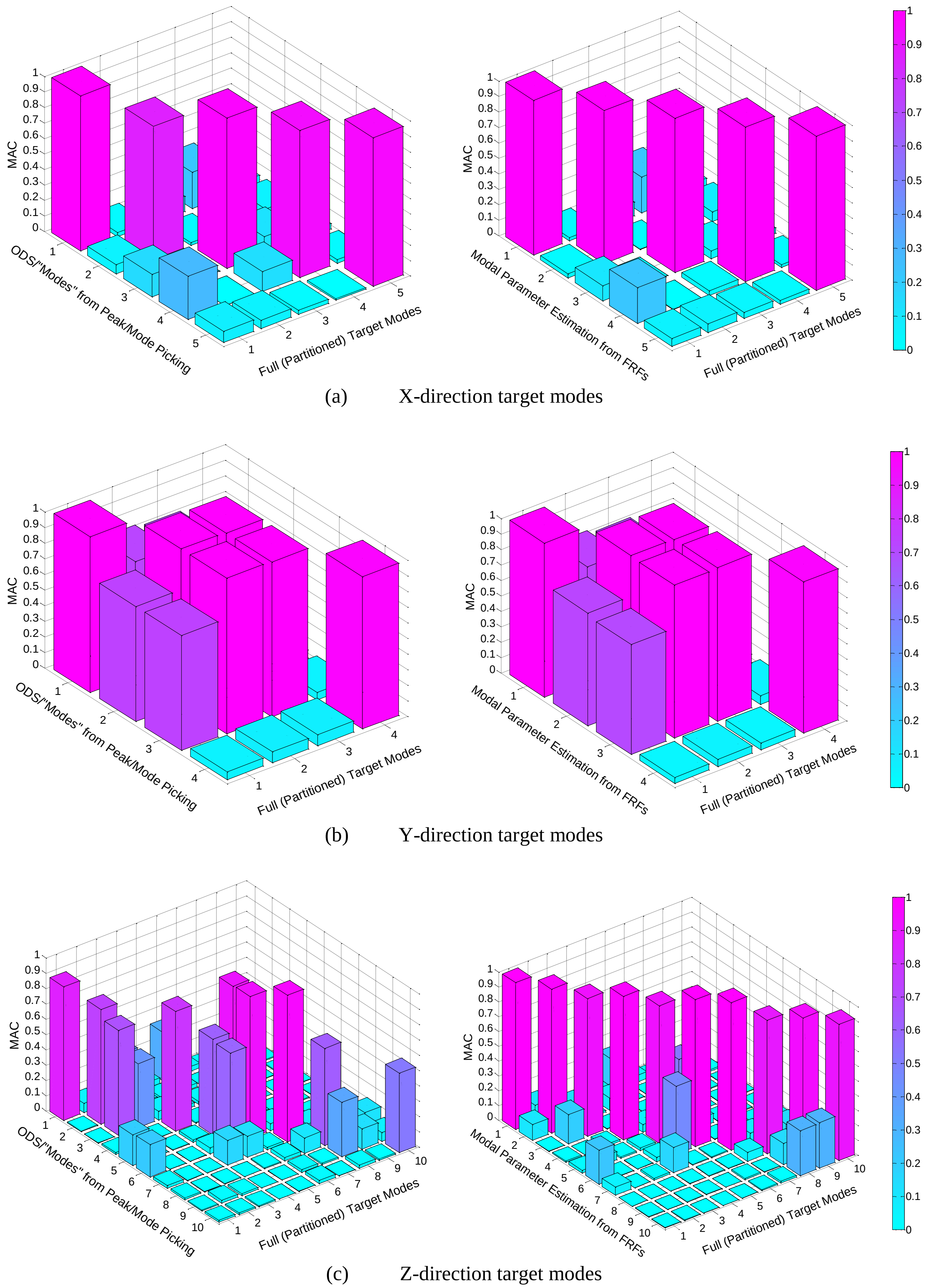


Figure 11. Aeolus MAC results of FEM X-direction normal modes compared with:
Left - FEM ODS/modes from peak picking, Right - FEM modes from modal parameter estimator

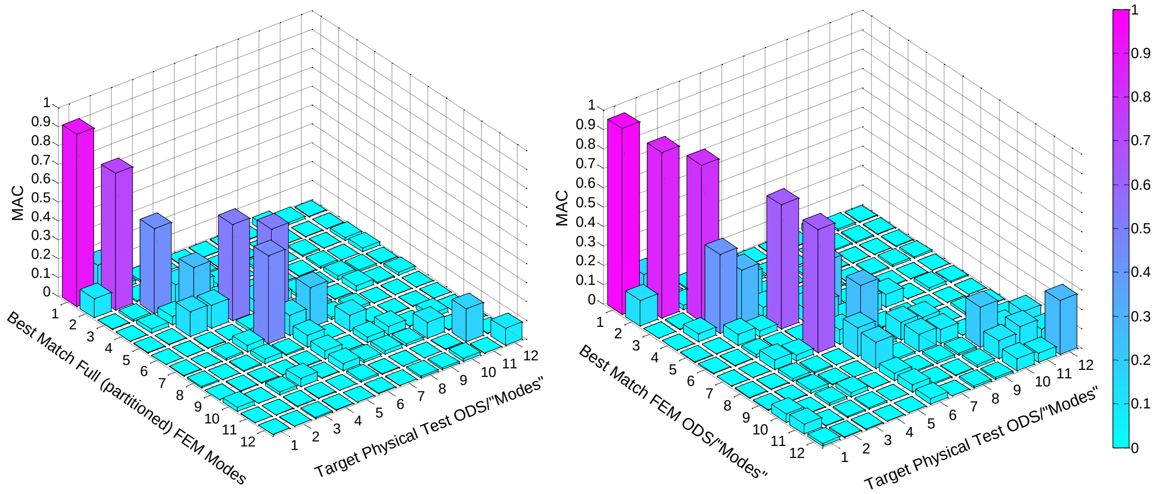


Figure 12. BepiColombo MAC of test ODS vs. FEM modes (left). MAC of test ODS vs. FEM ODS (right)

5 CONCLUSIONS

It has been shown that the modal parameter estimation method must be selected as appropriate to the problem under consideration. Here it has been demonstrated that, although sufficiently accurate under certain conditions, the simple single degree of freedom 'peak picking' method is not appropriate to large, complex spacecraft applications where modes are heavily coupled. Under such circumstances it is observed that more sophisticated methods, such as the poly-reference least squares frequency domain approach, can give a more accurate representation of the mode shapes of the system. This is an important point to note if mode shapes, estimated from test measured imaginary frequency response functions, are used as targets in FEM correlation. If these estimated mode shapes are not an accurate representation of the modes of the system, correlation based on subsequent comparison with analytical mode shapes is undermined.

An alternative which avoids the issue of modal parameter estimation is correlation based directly on frequency response functions. This has been demonstrated by the direct comparison of test ODS with FEM ODS. The potential to avoid both the effort of modal parameter investigation and, more importantly, the introduction of associated errors through the use of frequency domain merits further investigation and has the potential to be the subject of future work.

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