FE Model Correlation & Mode Shape Updating using Qualification Test Data…A case study on the Olympus Satellite.

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1. ABSTRACT

Satellite equipment is subjected to shaker tests with various shaker levels to ensure their structural integrity and launch survivability. Traditionally 2 types of excitation signals are applied to the shaker table: random and swept sine. For large structures, this is sometimes complemented with a high-level acoustic qualification test. A fundamental problem in a shaker test is that it is difficult to control the load in the tested structure since the number of notching channels is hardware limited. A possible solution to this is to use a global measure of the shaker load, which can be easily obtained by the use of a multi-axial

Force Measurement Device (FMD) on the control channels in combination with a Signal Processing Unit (SPU) [1]. To have an idea of the maximum excitation a test specimen can accept during a shaker test, a mathematical model is used to generate transfer functions that show the maximal stress/displacement at critical locations in the model as function of the forces and moments that excite the structure at the base. These transfer functions can then be combined with the highest allowed stress/displacement levels to estimate the largest force load the satellite can accept during the test. As a consequence, the mathematical model needs to be of high quality, and thus be test-verified. This is only a first reason why it is of vital importance to dynamically correlate the FE model with experimental data and eventually to further fine-tune and update the model. A more important reason is that finite element models are used for the estimation of loads during the

launcher (rocket) flight. By combining the FE model with forces and moments, measured in-flight at the launcher/satellite interface, one can estimate the loads on the satellite at various locations. These calculated loads then determine which load levels need to be achieved during the vibration test as a minimum. The FMD is also used to verify that the desired loads are in fact achieved.

This paper illustrates the process of correlation and updating on the Olympus satellite. Instead of building another expensive and time-consuming classic modal survey test set-up, the measured data from the low-level, medium level and high level qualification test is used, processed and fed into a conventional modal analysis package in order to estimate the natural frequencies, the damping ratios and the mode shapes. Using this data as reference, the initial finite element model is correlated and fine-tuned towards resonance frequencies and MAC values.

The work related to the Force Measurement Device has been carried out under Contract 12014/96/NL/FG of the European Space Agency. The results and the pictures are provided as a courtesy from Ingemansson [2].

2. INTRODUCTION

During the process of the assessment of the structural integrity and the operability at launch of satellite structures, dynamic mathematical models are used for load prediction. Since it is crucial to have confidence in these analytical models, their dynamic behavior is verified by means of measured reference data on a prototype. This reference data is classically obtained via a modal survey test in the laboratory. Frequency response functions are measured and fed into a conventional modal analysis package in order to estimate the natural frequencies, the damping ratios and the mode shapes. In this paper however, the data from a qualification test is used. This normally is complicated by the fact that only response data are measurable whilst the actual loading conditions are unknown. The presence of the FMD however makes that the measured data can be processed and a classic modal analysis can be performed. These experimentally obtained mode shapes are then compared with results from the finite element analysis and several modal or response based assessment criteria can be used to validate the analytical model [7]. It is important to underline that it is good practice to use the finite element model to design the test in an optimal way [5]. By simulating the test during a pre-test analysis, the measurement locations can be selected such that spatial aliasing is suppressed as much as possible. Also, the best drive points can be identified such that all modes that contribute significantly to critical component responses are sufficiently excited. The outcome of the correlation analysis will decide if it is necessary to modify the analytical model such that it better describes the results observed from testing. Different model updating techniques exist. Parameter updating techniques, which try to obtain an improved analytical model by changing analytical model parameters, are favorable because they preserve the physical meaning of the model. Often, the difference between the measured and predicted resonance frequencies is minimized, by using the NASTRAN Sol200 solver in combination with LMS/Gateway as pre- and postprocessor [3]. In this paper, not only the resonance frequency difference is minimized, but also the mode shape correspondence is optimized, by using LMS/Optimus as optimizer and process manager, in combination with LMS/Gateway for the correlation analysis and MSC/NASTRAN.

3. QUALIFAICATION TESTING

The shaker tests were conducted by ESTEC at Noordwijk. Figure 3.1 shows a picture of the OLYMPUS satellite and the FMD in a vertical shaker test. Ingemansson developed the FMD and SPU in co-operation with ESTEC. The FMD consists of a number of tri-axial piezoelectric force transducers in precalibrated "force links". The force links are fitted between stiff interface plates or rings, which in turn are fixed between the test object and the vibration table. The output signals from the transducers are weighed and combined in a Signal Processing Unit (SPU) to give the total forces and moments at the interface at every instant in time. The shaker tests included excitation in the vertical direction and the horizontal directions and the tests were conducted at low, medium and high shaker levels. About 200 response channels were simultaneously measured in the shaker tests for frequencies in the range 5 to

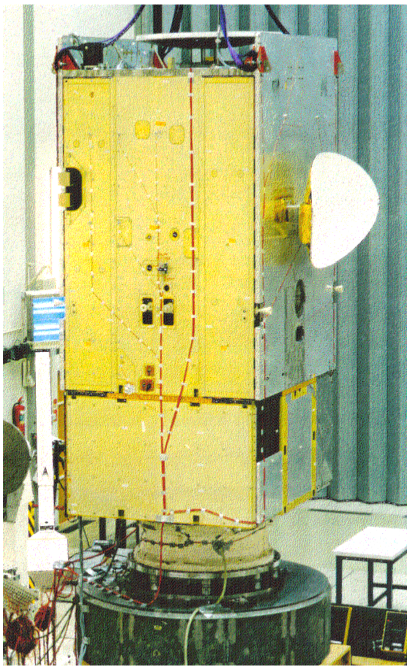


Figure 3.1: The OLYMPUS satellite with FMD under test. The clampband connects adapter to satellite

100Hz. The signals that were generated in this test were processed in order to perform an experimental modal analysis in LMS CADA-X. A total of 25 to 30 (properly scaled) modes were extracted per test. The ***repeatability*** and ***stability*** of the test was examined, by means of the Modal Assurance Criterion. The identification of perfect modal basis gives modes that are perfectly orthogonal. The MAC matrix of the perfect modal experimental basis should thus be a MAC matrix with diagonal elements of unity and zero-valued off-diagonal elements. Similarly, perfect repeatability in the structural modes from one test to another test would result in a cross MAC matrix with diagonal matrix elements of unity and off-diagonal elements that are zero. The orthogonality of the modal basis functions that are identified in the modal analysis can be checked by computation of the MAC values, see Figure 3.2 (results from the vertical shaker test, thus compression modes only). Figure 3.3 shows the MAC matrix between a low-level and a high-level amplitude vertical shaker test. Some of the modes change in eigenfrequency and mode shape when the shaker vibration amplitude is changed. This observation is also true if one simply takes the satellite of the shaker table and puts it back on again. The modes that have a high "effective weight" are the modes of primary concern in this work and they do not change with the vibration amplitude. It is thus futile to pursue a correlation for other modes. The reason for the lower repeatability of some of

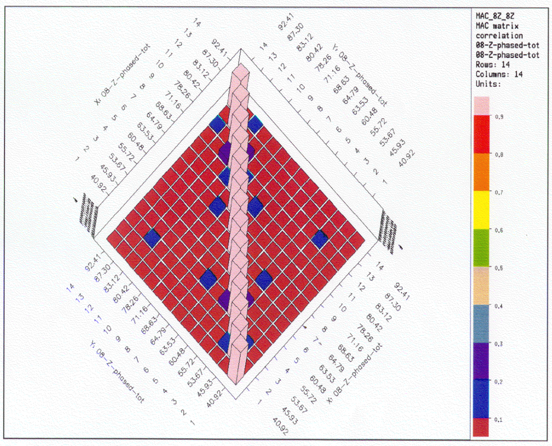


Figure 3.2: Test-Test MAC values from a low vibration amplitude test. ("Compression modes only")

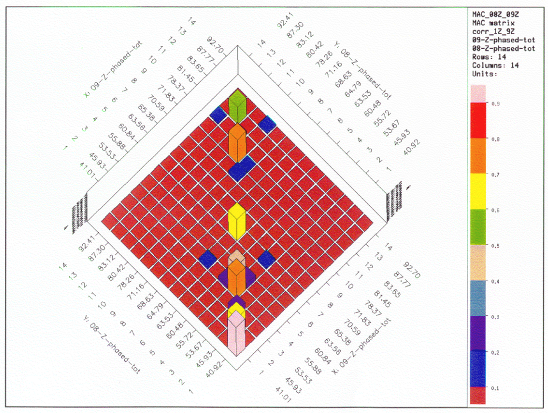


Figure 3.3: Test-Test cross MAC values for modes from a high and a low vibration amplitude test. ("Compression modes only")

the modes is probably due to local non-linearity in the structure from gaps and friction between parts. Some of the local modes change with vibration amplitude because parts across the satellite are better connected to each other when the vibration amplitude is sufficiently high to close the gap in the larger part of the vibration cycle and less connected when vibration is too small to close the gap.

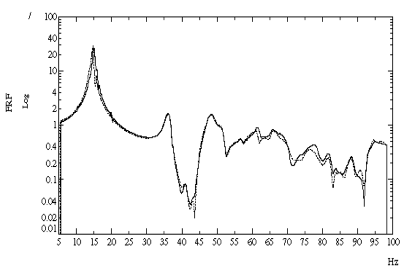
Summarizing one can say that the structurally important modes that are excited at rocket thrust and satellite separation are repeatable, and that some of the modes with small effective weight cannot be predicted with a single FE model for the simple reason that they change with the structural vibration amplitude. The further correlation/updating study is thus only done for the modes with “high effective weight”.

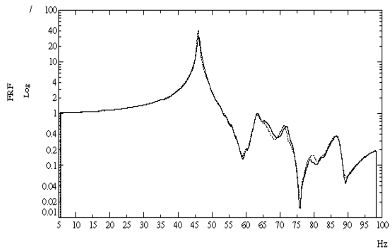
Based on these results, the influence of the FMD on the test results has been examined. Values for the eigenfrequency difference and the cross MAC values are used to study the influence of the FMD. It is found that the deviation in eigenfrequency that is indicated by the FE model is within the repeatability of the test, i.e. is within 0.1% for the vertical test direction and 0.7% for the lateral test direction. The frequency difference that is found between the tests is larger than what is found between the FE models because it contains errors from the frequency identification process as well. Therefore, one can say that the FMD device has negligible impact on the test results, see Table 3.1 and Figures 3.4 & 3.5.

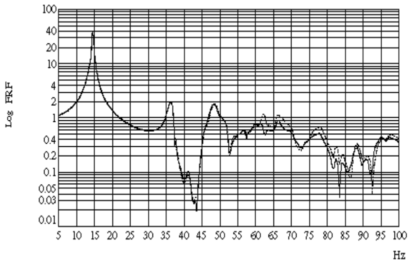
Test with FMD [Hz]	Test [Hz]	% diff. [-]	FE with FMD [Hz]	FE [Hz]	**% Diff.[-]**
-	-	-	14.35	14.45	**-0.7**
14.5	14.9	-2.9	14.72	14.83	**-0.7**
-	-	-	30.36	30.39	**-0.1**
45.9	46.1	-0.4	48.16	48.16	**0.0**

Mode	**MAC Test w FMD/Test [-]**	**MAC FE w FMD/FE [-]**
1st x-bending	-	0.998147
1st y-bending	0.959	0.999993
1st z-torsion	-	0.998826
1st z-compression	0.949	0.999865

Table 3.1: [Upper] The eigenfrequencies from the (updated) FE model and test. [Lower] The MAC between the test-test and the FE-FE mode shapes for the cases with and without the FMD.







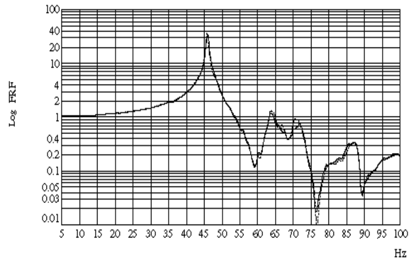


Figure 3.4: Transfer function between the dofs 20Y and 26Y. A) For the cases with and without FMD. B) Repeatability Test

Figure 3.5: Transfer function between the dofs 9Z and 16Z. A) For the cases with and without FMD. B) Repeatability Test

4. QUALITY CHECK OF THE INITIAL FE MODEL.

The correlation study starts with the calculation of the MAC values between Test and FE resulting in a 'pseudo orthogonality' test. The Test/FE modes can not (even in theory) be perfectly orthogonal for the simple reason that all points on the test object are not measured. Instead, the Test-FE MAC values show how close the resemblance is between two cases. MAC values above 0.7 to 0.8 are considered to show that the test case and the simulated case describe the same situation. MAC values above 0.9 are achieved for well-correlated modes. Due to the history of the OLYMPUS Structural Model (large number of tests, removal of parts, repair) it was not expected that the

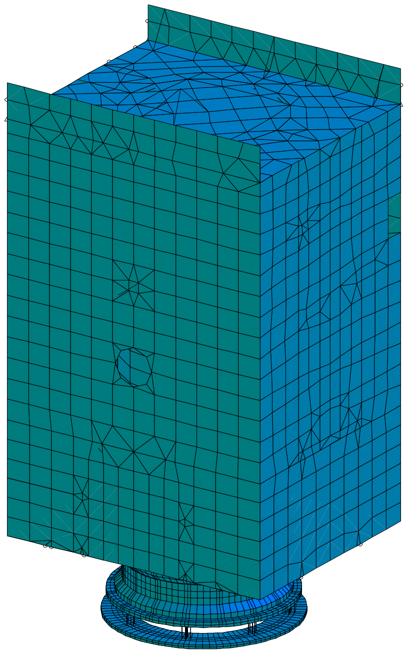


Figure 4.1: Initial FE model of OLYMPUS-adapter-FMD system used in the shaker test

mathematical model, based on the original structure, under consideration of the removed items, would directly provide good correlation.

The OLYMPUS-FMD finite element model contains 12657 nodes and 11365 elements, see Figure 4.1. The finite element model contains the clampband, the adapter and the FMD [4]. The FE model was originally prepared by ESTEC and adapted by Ingemansson to fit the finer mesh of the adapter and the FMD. Since the FE model does not include any information on material damping and/or the distribution of damping in the satellite, the EIGRL Nastran solver was used to extract the first 30 real modes even though the experimental data suggests that energy propagates within the modes. The first step in a Test-FE correlation is a geometric correlation to identify the points in the test model that are the closest to the nodes in the FE model. This can be done in a semi-automatic way in LMS/Gateway by clicking at least three well-chosen node pairs in both geometries. The result of this study is a node pair table and a common geometry on which both measured and predicted mode shapes can be visualized, see Figure 4.2. A second step was to convert the complex test modes into real modes and to project the measured results onto the FE coordinate system. The correlation module in LMS/Gateway completed this conversion step.

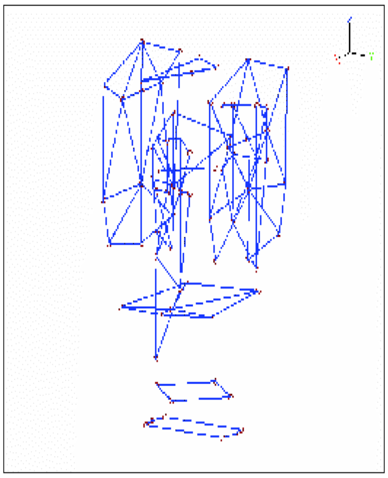


Figure 4.2: The correlated geometry

The Test-FE comparison includes the 4 ‘global’ modes: first lateral bending modes in the x- and -y directions; the first torsion mode around the z-axis; and the first compression mode. The initial correlation result between the Test modes and the FE modes is shown in Figure 4.3.

The computed mode shapes and eigenfrequencies are satisfactory for the lateral-bending modes. The correlation is poorer for the torsion mode, partly because it was poorly excited in the shaker tests that excite translation motion only. The torsion mode is not the most important mode for the satellite model because it is weakly excited during operation. The results are therefore acceptable for the model. The MAC values show that the first

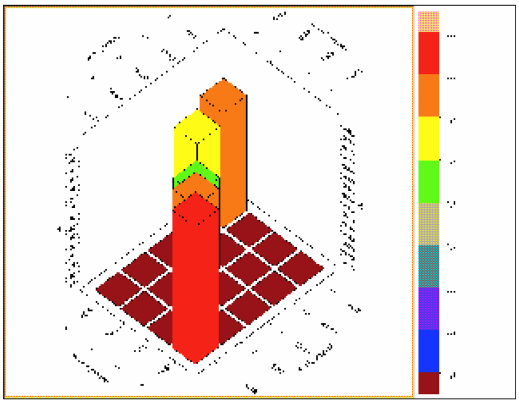


Figure 4.3: Test-FE pseudo MAC values.

global mode in the vertical direction is highly correlated with two of the analytical modes. The mode with the lower eigenfrequency is a local mode in which the propulsion tank vibrates. This eigenmode occurs at almost the same eigenfrequency as the global vertical mode and has a shape that visually resembles the global vertical mode. The propulsion tank mode has its largest motion at the propulsion tank, i.e. at a position without measurement points that could be used in the correlation. Therefore, one reason for the high cross-correlation with the two analytical modes is because of spatial aliasing, i.e. that the measurement points are too few and/or that the measurement points are not positioned at strategic points that generate good 'orthogonality' when the Test and the FE modes are compared. It is a good practice to use the LMS/Pre-Test module before the actual tests are initiated [5]. Effects from spatial analysis can be suppressed by the use of Pre-Test where the test is simulated and planned by the use of the FE model. The most beneficial measurement points are chosen from the pre-test analysis. The best drive points are identified in the analysis as well. The chosen drive and response points are used to create the CADA-X model geometry automatically. Some of the error localization techniques available in LMS/Gateway were used to improve the correlation. The MacCo routine is very useful at pinpointing localized modeling mistakes that show in the measured responses. The MacCo routine pinpointed that a set of the measurement points on the satellite significantly lowered the model correlation. Ingemansson examined the quality of the responses at these points in co-operation with ESTEC. The inspection revealed that some of the points had been positioned with unknown accuracy since they were complicated to reach physically. The worst contributor turned out to be the measurement point at which an accelerometer was positioned on the thin wall of the propulsion tank. The transducer mass and the flexibility of the wall caused a high local reaction at this point only. The propulsion tank is modeled as a lumped mass. In other words, there was nothing wrong in the measurement of the accelerometer signals or in the positioning of the transducer. However, the above mentioned measurement point was not representative for the gross propulsion tank motion and, thus not representative for the lumped mass motion in the FE model. In total, 6 points were removed from the correlation, something which improved the Test-FE MAC values. At this stage, no distinct modeling errors were pinpointed by the MacCo routine or by any of the other correlation tools in LMS/Gateway. An important observation during the correlation was that few of the measurement points on the propulsion tank could be used in the correlation. In other words, the measured data contained a 'blind data spot' in this area. The lack of distinct guidelines implied that the remaining modeling error either was due to a global error and/or was located in the vicinity of the 'blind data spot' at the propulsion tank. At this stage, Ingemansson resorted to manual model debugging [6]. Inspection of front/back animated measured and computed mode shapes identified that the FE model was overly stiff in the propulsion tank region. The propulsion tank is a sphere, which contains the fuel and is very stiff in the examined frequency range. Detailed drawings of the propulsion tank were requested from ESTEC, and these showed that the propulsion tank was linked to the satellite shell via a set of cleats that can provide flexibility in the vertical direction, see Figure 4.4. The lumped mass, representing the propulsion tank, was connected in the original FE model to the shell structure with several RBE2 elements that cause a very stiff connection in all dofs across the sides of the surrounding shell structure. A first modification consisted of the replacement of the RBE2 elements into RBE3 elements. This did not change the eigenfrequency of the vertical compression mode very much, but did slightly improve the discrimination between the propulsion tank (pt-) and the compression (c-) modes. Next, the modal strain energy of the vertical compression mode was inspected, and some erroneous RBE2 elements were found. This lowered the eigenfrequency of the compression mode by 1 Hz and did help resolve the discrimination between the pt- and c- modes. Finally, the propulsion tank was also suspended with zero length mass-less springs (CELAS2) in the vertical direction. Again, the model correlation was improved and the MAC values improved, but the frequency shift was not resolved.

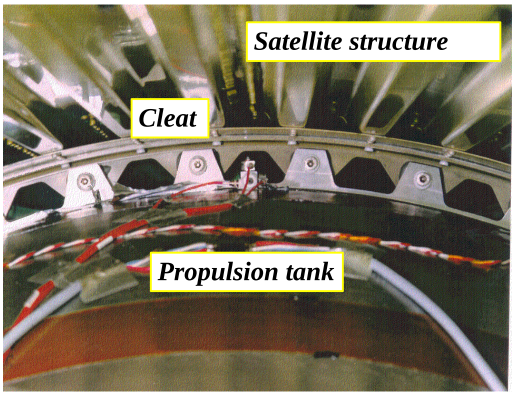


Figure 4.4: The propulsion tank. The cleats that stick out from the propulsion tank should provide some flexibility in the vertical direction.

5. MODEL UPDATING

At this point, the outcome of the initial correlation work was found to be sufficient and the further work was focused towards fine-tuning of the FE model. In a first attempt to tune the FE model, LMS/Gateway was used in combination with the MSC/NASTRAN SOL200 optimisation solver to tune the clampband stiffness and the propulsion tank stiffness [7]. The clampband stiffness is known to greatly affect the eigenfrequencies for the lateral bending modes and the vertical compression modes. The initial clampband stiffness estimate was supplied by ESTEC. LMS/Gateway produced an input deck for the NASTRAN Sol200 solver. The optimisation was successful in the sense that good match of eigenfrequencies was achieved, but the MAC value of the compression mode was completely lost. Indeed, by using the MSC/NASTRAN Sol200 solver, one does only minimize the difference between the test and FE resonance frequencies, but it is not possible to control the MAC values. Scrutiny of the results identified a 'magic frequency' at which the shape of the global compression mode was significantly changed when it started to couple with a mode which otherwise had a strong localized response only in the panels. This is maybe due to failure in “Mode Tracking” in MSC/NASTRAN.

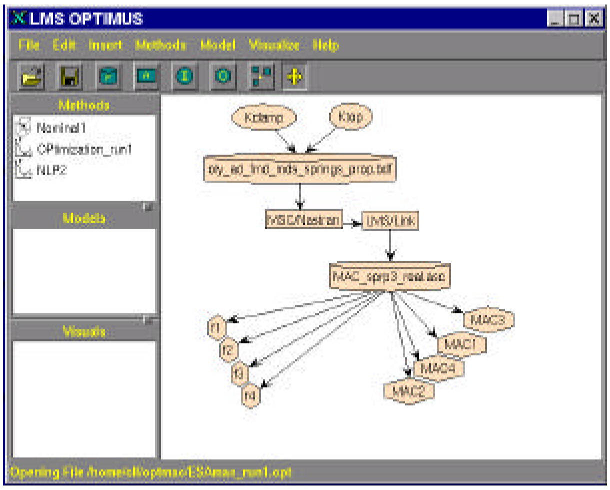


Figure 5.1: The LMS/Optimus work flow.

In a second attempt to tune the FE model, LMS/Optimus was used. LMS/Optimus has the advantage that the user can define and drive the complete optimisation sequence, that the targets can be user-defined and that LMS/Optimus contains not only local optimisation solvers but also global optimisation solvers. The workflow or analysis sequence is shown in Figure 5.1. The input variables for the optimisation loop are the clampband stiffness and the stiffness of the propulsion tank in the vertical direction. These two parameters are subject to change in the MSC/NASTRAN input deck, and MSC/NASTRAN was executed on a remote HP/C200 workstation because it was the faster machine. By means of session file, LMS/Gateway is then launched on a HP C100 workstation because the license resided on this machine, and the measured eigenfrequencies and MAC values of unity were selected as targets in the optimisation loop and provided with equally large target weights. This way of working provides the user a high flexibility. LMS/Optimus was used to optimize the correlation of two different tests: one case that included the satellite, adapter and FMD; and another case that included the satellite, adapter and the upper FDM ring. Both optimizations returned clampband and propulsion-tank-suspension stiffness values that matched closely. Cross-reference of the values did not show any change in the MAC values and differences in the computed eigenfrequencies in the third decimal. The optimisation run was therefore deemed to be stable and successful. An example of the optimized correlation is shown in Table 4.1. Note that LMS Optimus can correlate inhomogeneous models if needed, e.g. it would be possible to find the best average clampband stiffness by simultaneous Test/FE cases with the FMD and without the FMD, that refer to tests of different structural configurations and different FE models, respectively.

MAC1/f1 (Y) [-/HZ] 1/14.51	**MAC2/f2** (X) [-/HZ] -	**MAC3/f3** (RZ) [-/HZ] 1/30.94	**MAC4/f4** (Z) [-/HZ] 1/45.93
0.93/14.35	-	0.63/30.36	0.75/48.16

MAC1/f1 (Y) [-/HZ] 1/14.92	**MAC2/f2** (X) [-/HZ] 1/15.32	**MAC3/f3** (RZ) [-/HZ] -	**MAC4/f4** (Z) [-/HZ] 1/46.15
0.93/14.45	0.78/14.72	-	0.75/48.16

Table 5.1: The correlated and model updated FE model and the test modes. A) For the case with the FMD.
B) For the case without the FMD.

6. CONCLUSIONS

This paper illustrates the process of correlation and updating on the Olympus satellite. Instead of building another expensive and time-consuming classic modal survey test set-up, the measured data from the low-level, medium level and high level qualification test is used, processed and fed into a conventional modal analysis package in order to estimate the natural frequencies, the damping ratios and the mode shapes. Using this data as reference, the initial finite element model is correlated and fine-tuned towards resonance frequencies and MAC values. The use of LMS/Gateway for the correlation analysis together with LMS/Optimus provides a means to update the FE model, using both the measured resonance frequencies and the MAC values of unity as a reference.

7. ACKNOWLEDGEMENTS

The work related to the Force Measurement Device has been carried out under Contract 12014/96/NL/FG of the European Space Agency. The results and the pictures are provided as a courtesy from Ingemansson.

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