Systematic Investigations into the Numerical Response Prediction of a Solar Array Stack under Acoustic Excitation

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1 Abstract

Satellites and payloads launched with large launch vehicles equipped with solid rocket boosters, e.g. ARIANE-5 and NSTS, will be subject to high noise levels during lift-off and atmospheric flight. Particularly sub-systems that have a large surface area and low mass can be very sensitive to acoustic excitation. Examples of such sub-systems are antenna reflectors and solar arrays.

This paper presents the main results of a study that follows a systematic approach to investigate the numerical response prediction of a solar array stack, i.e. a solar array in stowed configuration, subject to acoustic excitation. The study has been carried out by Fokker Space (NL) and Metravib R.D.S. (F) under an ESA research and development contract.

The hardware selected for the study has been the ARAFOM 5-panel wing. In the frame of the study, the wing has undergone a sequence of mechanical tests, namely a

- modal survey test in air and in helium
- shaker test with harmonic base excitation (sine test)
- acoustic plane wave test
- acoustic noise test

Results of the modal survey and the sine test, particularly of the modal survey under helium providing a quasi-vacuum environment, have been used to correlate and update the initial mathematical finite element model of the wing. The target of this first step has been to establish a finite element model of the wing that represents as best as possible the dynamic characteristics of the the wing under vacuum conditions.

The effects of the air on the dynamic response of the wing have then been modelled by a boundary element approach. This can accurately represent the fluid pressure and radiation impedance loads on the structure. A particular difficulty has been the modelling of the thin air gaps in between the individual panels of the wing.

Responses of the wing to acoustic plane wave excitation have been computed and have been correlated with the responses measured from the acoustic plane wave test.

Responses have been evaluated in terms of structural accelerations and stresses, but also in terms of acoustic pressures in the inter panel gaps and the surrounding fluid.

Eventually, the response of the wing to acoustic noise excitation has been numerically simulated using a superposition of plane acoustic waves, and the results have been correlated with the responses from the acoustic noise test.

2 Description of the Test Hardware

One of the major requirements for the potential test item to be used within the frame of the study, was its full representativeness in terms of actual flight hardware. The selected ARAFOM 5-panel wing is fully compliant with this requirement. Figure 1 presents a sketch of the mathematical model of the wing.

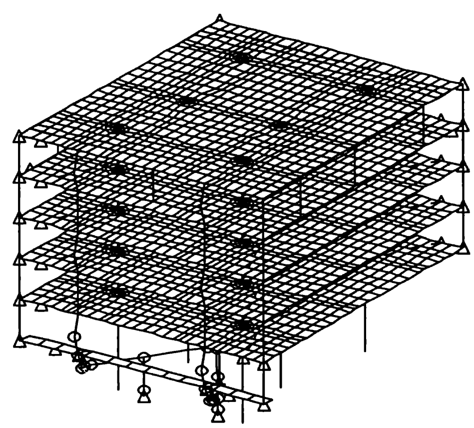

Figure 1 *ARAFOM 5 Panel Wing - Overall View*

The complete wing consists of 5 individual panels that are, in deployed configuration, linked by hinges.

During launch and early stages of launcher ascent however, where the satellite and its appendages experience the highest acoustic loads, the wing is in stowed configuration against the spacecraft sidewall.

In this configuration the panels are connected in addition via the 6 hold down stacks, which are tensioned by aramid cables. The positive z-axis depicted in Figure 1 points in the launch direction.

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The innermost panel (the one closest to the spacecraft sidewall) is referred to as panel-1, with panel-5 being the outmost panel.

During all tests the wing has been attached to a rigid test frame (1st eigenmode above 200 Hz) at the solar array drive mechanism and the 6 hold down points.

3 General Approach of the Study

The purpose of the study performed has been

- to assess the basic dynamic properties of the wing
- its coupling to the surrounding fluid in the different frequency ranges, and finally
- its response during a standard acoustic noise test.

In order to meet with these objectives, a unique, systematic approach combining test and analysis has been chosen, that includes the following sequence of tests.

(1) (a) Modal survey in helium.
(b) Modal survey in air.

(2) Acoustic plane wave test.

(3) Harmonic base excitation ("Sine test").

(4) Acoustic noise test.

All tests have been carried out using one single set of instrumentation, i.e. all transducers have been the same throughout the complete test campaign.

Responses from the tests have been measured in terms of the following:

(i) Structural accelerations on all panels, the yoke and the flex print panel.

(ii) Structural strains at a limited number of critical locations on the panels.

(iii) Fluid pressure in the gaps between the panels.

(iv) Radiated fluid pressure in the external fluid domain of the solar array stack.

Results from the modal survey tests carried out under (1) have been used to correlate with the eigenfrequencies and modes obtained from the initial mathematical model termed **M1**. Following a sensitivity study, this model **M1** has been updated to achieve an improved correlation with the test data, resulting in the updated model termed **M2**.

The responses of the acoustic plane wave test performed under (2) have been correlated with numerical responses using model **M2**. These tests allowed the detailed assessment of the fluid-structure coupling phenomena with respect to individual well defined acoustic excitation cases, as opposed to a diffuse field test where the spatial correlation properties of the field are (especially in the low frequency range) not well known.

Sine test results have been used as an alternative means to identify the structural modes of the wing, which have also been correlated with the modes identified from the modal survey test in air as well as with numerical simulation using model **M2**.

Eventually, the acoustic noise test results obtained from (4) have been compared to a numerical simulation based on the model **M2**. The numerical simulation uses an (uncorrelated) superposition of 26 plane waves with an angular increment of 45° in azimuth and elevation.

3.1 Instrumentation

The total number of accelerometers mounted on the structure has been 158.

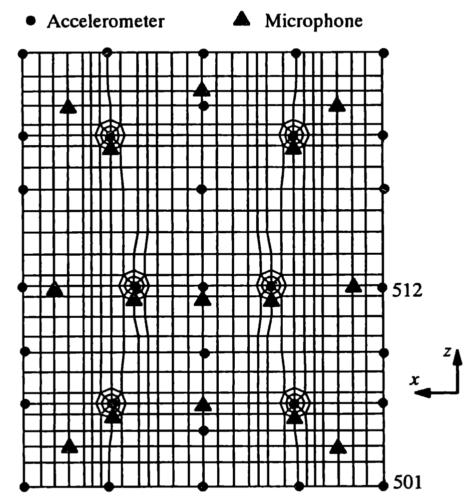

Figure 2 *Accelerometer Positions on Panel-5*

Figure 2 indicates the accelerometer positions on panel-5, and the microphone positions in the inter-panel gaps to pick up fluid pressures. A detailed instrumentation plan of the complete wing is presented in [1].

The accelerometer positions have been chosen such that they allow to properly identify all major modes in the frequency range up to at least 120 Hz.

In order to verify the selected accelerometer and pressure sensor positions in the air gaps, the initial mathematical model, which has been inherited from the ARAFOM project, has been used to compute the in-vacuum eigenfrequencies, eigenmodes and corresponding effective modal masses. The so called auto-orthogonality matrix A_{ij} has then been computed according to (eq. 1), whereby the structural mass matrix has been statically condensed to the selected measurement points, and the eigenmodes (which where computed from the full model) have been partitioned by the set of measurement points.

$$A_{ij} = \frac{\Phi_i^T M \Phi_j}{\sqrt{(\Phi_i^T M \Phi_i)(\Phi_j^T M \Phi_j)}} \qquad \text{(eq. 1)}$$

Here, Φ_i is the i-th structural eigenmode and M is the condensed structural mass matrix. In the ideal case where no condensation has taken place we will have $A_{ij} = \delta_{ij}$ (unity matrix) due to the orthogonality of the eigenmodes with respect to mass and stiffness matrix.
For a condensed set of measurement points, this will not be the case any more.

f [Hz]	43.4	46.1	47.1	50.9	53.4	56.9	57.9	66.3
43.4	1.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
46.1		1.00	0.00	0.00	0.00	0.00	0.01	0.00
47.1			1.00	0.00	0.00	0.00	0.02	0.00
50.9				1.00	0.01	0.00	0.00	0.00
53.4					1.00	0.00	0.00	0.00
56.9						1.00	0.00	0.02
57.9							1.00	0.01
66.3								1.00

Table 1 *Auto-Orthogonality Coefficients*

Results from Table 1 show that the auto-orthogonality of the main modes with respect to the selected accelerometer grid can be judged sufficient: Diagonal values are all equal to 1, off-diagonal values are smaller than 0.03, for the modes listed above.

Strain gauges have been installed on panel-1 and near the hold down areas, where significant stress levels have been expected.

Finally, a rectangular grid of microphone positions exterior to the stack has been defined, in order to be able to measure the radiated pressure due to the vibrations of the panels, and to have the possibility of identifying major radiating zones of the stack.

This external microphone grid has however been used only during the modal survey test in air: usage during the helium modal survey was not possible for safety reasons, and measurements during acoustic plane wave, sine and acoustic noise test where not expected to yield any valid results.

4 Numerical Simulations and Test Correlation

This section gives an overview over the numerical simulations that have been performed for the various types of tests that have been listed in section 3.

The mathematical model of the stowed wing has been established in terms of a NASTRAN finite element model, that has been inherited from the ARAFOM 5-panel program.

All fluid effects have been modelled using the ASTRYD code. With this approach the structure itself is presented solely by its geometry and the in-vacuum modeshapes and eigenfrequencies that have been extracted from a NASTRAN computation. The fluid in the inter panel gaps as well as in the external domain have been modelled by the boundary element approach implemented in ASTRYD.

The unique approach implemented in ASTRYD is based on the direct computation of the response of the wing due to a mechanical or acoustical load in the time domain. Response spectra defined in the frequency domain are then derived from the time responses by means of a Fourier transform.

The advantage of this approach is that, given a

- sufficiently small integration time step size Δt and a
- sufficiently long total response time T

the response in the frequency domain can be obtained for the complete analysis frequency range in a single computation.

For the computations performed here a total response time of $T = 0.75\,s$ have been used. This leads to a frequency resolution of $\Delta f = 1.\overline{3}\,Hz$. The time step size is a direct function of the minimum distance between any two acoustic elements in the mesh and the speed of sound in the ambient fluid medium. It has been set to $\Delta t = 179\,\mu s$.

4.1 Modal Survey Test

For the purpose of the modal survey tests the solar array stack has been fixed to a seismic block (large mass).

The primary purpose of the modal survey tests in helium and in air has been to provide a structural modal basis. This modal basis has been used for correlation with the initial mathematical model **M1** of the wing.

Both modal survey tests (in helium and air) have been performed using small electro-dynamic shakers to excite the wing. Various different locations have been defined for the installation of the shakers. These locations have been selected based on a numerical simulation of the modal survey test, where the structure has been excited by a force impulse and the eigenmodes have been identified from the computed response time history using the Ibrahim time domain method implemented in the ASTRYD code.

The modal survey in helium has been carried out to simulate near vacuum conditions. With respect to an air environment the fluid density of helium is reduced by a factor of approximately 7, see Table 2.

	c [m/s]	ϱ [kg/m^3]
Air	343.0	1.23
Helium	1007.0	0.17

Table 2 *Fluid Parameters of Air & Helium (at 20 °C)*

Hence, the fluid-structure coupling effects (added mass and added damping) are expected to significantly decrease with respect to the air environment, allowing for a correlation of the results from the modal survey in helium with the bare structural mathematical model.

The helium environment has been realized by suspending a tent over the solar array wing and purging the tent with helium gas.
The modal survey test in air has been carried out for the same exciter locations that have been used for the helium test, thus allowing for a direct assessment of the effects of air as opposed to helium on the structural responses.

Figure 3 shows the frequency response of a corner node on panel-5 for the same excitation in air and helium environment.

The differences between the two curves are typical for most accelerometer locations on the wing and exhibit the following features:

- The air response shows additional modes in the 20 Hz range, which are not present in helium.
- The major response peaks in air are shifted to the left with respect to the helium response. This is due to the added mass effect of the air, which is most significant in the low frequency domain and decreases to zero for higher frequencies.
- The peak responses in air are lower than the ones in helium. This is due to the radiation damping effect of the air.

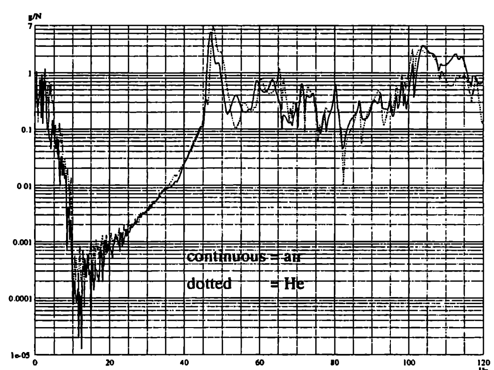

Figure 3 *Modal Survey Test Air/Helium - Point 501*

Modeshapes identified from the modal survey test in helium have been directly correlated with the in-vacuum eigenmodes computed from NASTRAN. Subsequently, the sensitivity of the eigenfrequencies/modes with respect to parameters modifications in the NASTRAN model has been assessed, and the initial model **M1** has been updated to achieve an improved correlation with the test modeshapes, yielding model **M2**.
The correlation of the eigenmodes between test and numerical simulation has been assessed using the cross-orthogonality coefficients C_{ij} according to (eq. 2).

$$C_{ij} = \frac{\Phi^T_{FE,i} M \Phi_{Test,j}}{\sqrt{\left(\Phi^T_{FE,i} M \Phi_{FE,i}\right)\left(\Phi^T_{Test,i} M \Phi_{Test,i}\right)}} \qquad \text{(eq. 2)}$$

The cross-orthogonality coefficients (diagonal values only) for the main identified modes of the wing from the modal survey in helium, using the updated mathematical model **M2**, are presented in Table 3.

f_{Model} [Hz]	f_{Test} [Hz]	C_{ij}
43.42	47.09	0.84
	47.15	0.84
46.06	45.86	0.75
	45.88	0.74
	47.72	0.78
	47.76	0.72
56.88	55.56	0.59
	55.58	0.71
57.91	60.21	0.75
	60.37	0.77
66.30	66.31	0.97

Table 3 *Cross-Orthogonality Coefficients - Helium*

In addition to the eigenfrequencies and modes, also the corresponding modal damping ratios have been identified from the modal survey in helium. These damping values have later on been used for the test simulation runs using the updated model **M2**.

Table 4 presents the cross-orthogonality coefficients in air.

f_{Model} [Hz]	f_{Test} [Hz]	C_{ij}
43.23	46.32	0.71
43.66	47.68	0.72
	49.08	0.71
44.96	39.11	0.71
45.88	46.87	0.83
53.05	53.80	0.87
57.43	59.02	0.83
65.56	63.47	0.91
69.26	69.98	0.73
	71.22	0.78
	72.04	0.81

Table 4 *Cross-Orthogonality Coefficients - Air*

The updated model **M2** has then been used to re-run the numerical simulation of the modal survey tests in helium as well as in air. Figure 4 and Figure 5 show the frequency response in helium and air, respectively, at sensor location 512 of the wing due to shaker excitation from test and analysis using model **M2**.

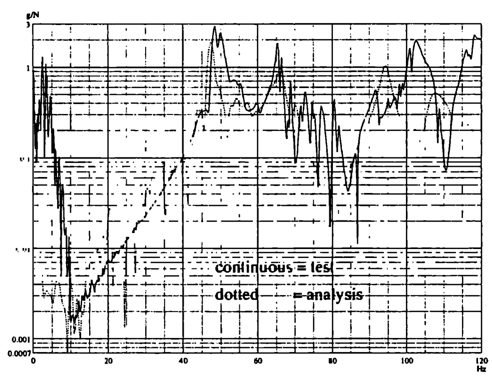

Figure 4 *Modal Survey He Test/Analysis - Point 512*

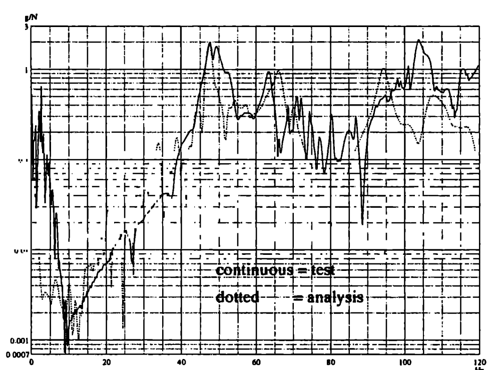

Figure 5 *Modal Survey Air Test/Analysis - Point 512*

4.2 Acoustic Plane Wave Test

During the acoustic plane wave test the wing and its test adaptor have suspended from the ceiling of the test room using nylon cables, where the wings long edge has been parallel to the ground.

The whole test set-up has been placed directly in front of the large external door of the test room. During the actual tests this door, positioned directly behind the array, has been opened to avoid reflections of the sound waves on the wall behind the suspended wing.

However, the creation of a proper plane wave field using the array of loudspeakers, remained one of the main difficulties during the test due to reflections from floor, walls and ceiling of the room.

The acoustic plane waves have been generated by a loudspeaker wall consisting of an arrangement of 3x3 individual speakers.

Acoustic plane waves have been generated under different angles of incidence for $\alpha = 90°/45°$, where α is the angle between the surface normal of the wing and the plane of the speaker array.

A schematic top view of the set-up is depicted in Figure 6.

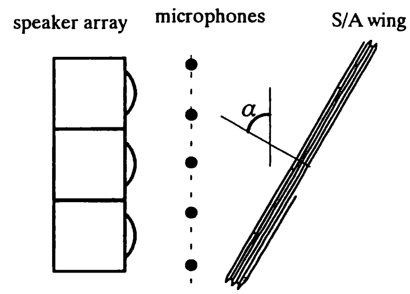

Figure 6 *Acoustic Plane Wave Test - Top View*

The quality of the plane wave acoustic field has been monitored by an array of microphones positioned in between the wing and the loudspeaker array. The field measurements have been assessed in terms of amplitude and phase of the individual microphone locations. The quality of the plane wave field has been found good in the low frequency range up to 100 Hz and for angles of incidence close to $\alpha = 90°$. In the higher frequency range and for smaller angles of incidence however, significant amplitude and phase differences appear due to reflections from the ground and the side walls of the test facility, such that the quality of the plane wave field is not good any more.

Figure 7 presents the structural response at corner node 501 due to an acoustic plane wave incident under $\alpha = 90°$

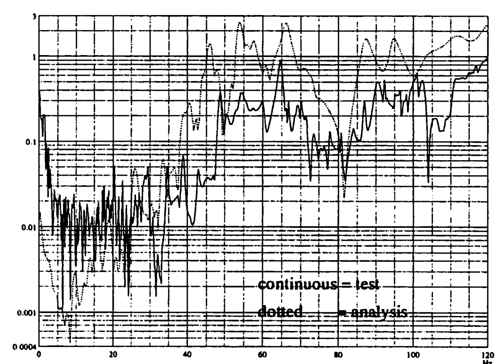

Figure 7 *90 ° Plane Wave Test/Analysis - Point 501*

4.3 Sine Test

The sine test has been carried out by using a standard set-up, with the wing mounted on an electro-dynamic shaker table.

Sine test runs have been performed in all 3 axes at different levels to verify linearity of the test object.

The measured responses in terms of structural accelerations have been used to directly identify the modeshapes using the DYNAWORKS package.

Due to a shortage of space, no detailed results from the sine test will be presented here.

4.4 Acoustic Noise Test

The acoustic noise test has been carried out with the wing mounted on the seismic block in the LEAF (Large European Acoustic Facility) at ESTEC.

Acoustic test runs have been carried out a different input levels to verify the linearity of the solar array wing.

The main purpose of the acoustic noise test has been to gather response data in terms of structural accelerations and strains as well as fluid pressure in the inter panel gaps, that can be correlated with the numerical simulations obtained from the updated model **M2**.

Response data has been recorded in the frequency range up to 2000 Hz.

The data in the low frequency range ($f < 150\,Hz$) is currently being correlated with the calculations performed with the boundary element code ASTRYD.

Data in the high frequency domain has been compared with output from statistical energy analysis. These results are however not presented here.

Figure 8 presents the measured acceleration power spectral density at sensor locations 501 and 512. Simulated responses for this test have not yet been available at this time.

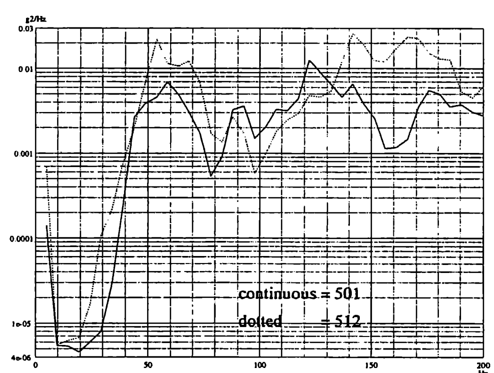

Figure 8 *Acoustic Noise Test - Points 501/512*

5 Conclusions

A systematic approach has been presented whereby an initial mathematical model of a solar array stack has been updated using a correlation with data extracted from a modal survey in helium.

Comparison of the responses from the modal survey in helium with the responses in air have shown clearly that the influence of the air on the modeshapes and eigenfrequencies is significant

Summarizing briefly the main outcomes of the study so far, the following can be said:

- Clearly both structure and fluid dominated modes have been identified.
- The tested structure behaves linear.
- The identified structural eigenfrequencies are lower in air than in helium.
- Modal bases identified from
  - modal survey (in air)
  - sine test
  - plane wave test

  correlate well both among each other and with the mathematical model.
- Fluid mode responses in the 20-30 Hz range are not significant.
- Accelerations measured during acoustic noise test are clearly higher on the outmost panels (1/5) than on the innermost panel (3).
- Fluid pressures measured in the inter-panel air gaps are higher in the innermost gaps (between panels 2/3 and 3/4) than in the outer gaps (between panels 1/2 and 4/5).

6 References

[1] D. Slootweg, *Instrumentation Plan for the ARAFOM QM Wing*, FS doc. ASTP-PR-008-FS

[2] B. Winter, *Test Results and Correlation*, FS doc. ASTP4-001-FS

[3] N. Trompette, *ASTP4 Vibroacoustics of Solar Arrays - Modal Survey/Plane Wave Test Report*, M-RDS doc. 101344/RES/018/A0