PREDICTION OF ACOUSTIC AND SHOCK RESPONSES OF SPACECRAFTS OVER BROADBAND FREQUENCY RANGE

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ABSTRACT

Spacecrafts are submitted to high levels of vibrations during the launcher flight. Broadband frequency loads are induced by three major environmental flight events: the lift-off with severe acoustic pressure from the jet, the transonic phase with turbulent pressure load associated to sonic shock waves and the separation of last stage followed by spacecraft separation from pyrozip devices. Long before the first technological flight of new launch vehicle, margins of safety against previous vibroacoustic environment are predicted from combinations of numerical models and tests leading to more robust diagnosis and better qualification process of spacecraft equipment vibrations. Several examples of applied methodology are reviewed and discussed.

1 INTRODUCTION

Launch vehicle loads are unsteady, random or transient with frequency spectra extending to 100 kHz for shocks and to 8 kHz for acoustic loads. The spacecraft so-called payload is protected during the atmospheric phase by the fairing, the launcher nose. The fairing itself has to bear the external loads from previous events and is carefully designed for this mission. As flight events are difficult to simulate on ground, spacecraft is submitted to specific environmental testing expected to envelope the actual flight loads. On-ground qualification tests generate safety margins to flight operating conditions. Margins of only 4 dB are taken in acoustic qualification tests of full payloads and are generally performed in large high-performance reverberant chambers to insure high degree of diffusion in the acoustic sound field. Equipment components are tested on shakers with appropriate vibration levels derived from a chain of calculation and tests on launch vehicle subparts.

For shock events, specific separation tests are performed between the spacecraft and its last-stage adaptor or the last stage itself. At component level, equipment is tested on shock machines based on load specifications written in term of Shock Response Spectrum (SRS). Transonic phase is generally qualified by acoustic test when proven by numerical simulation.

As testing environment differs from flight, evaluation of the actual effective safety margins may conveniently be estimated from numerical modeling. When confident, theoretical modeling is easier and cheaper to handle than full-scale tests. The confidence in calculated outputs is nevertheless a long term approach. First, knowledge has to be collected on the rocket environment for generating inputs to the calculation. Second, calculation methods have to be entirely controlled and approved. Selected calculation methods for acoustic environment at lift-off are mesh-based Boundary Element Method (BEM) for the low frequency range and Statistical Energy Analysis (SEA) for the high frequency range. For shock response simulation, time history simulation is required for predicting SRS outputs. Prediction methodology is nevertheless very similar: Finite-Element structural analysis for low frequency and SEA specific solver for managing fast transient events in high frequency range. For mid-frequency, methods may be hybridized in various ways.

In next paragraphs, highlight on applied methodologies is put through series of examples taken from the development program of Ariane European launch vehicle family.

2 VIBROACOUSTIC PREDICTIONS AT LIFT-OFF

2.1 Ariane Fairing and Internal Payload volume random responses

Figure 1 (left) shows the European launch vehicle Ariane 5. The fairing is the top external shell protecting the payload during the atmospheric part of the flight. The fairing is jettisoned as soon as the launcher leaves the earth atmosphere as shown in Figure 1 (right). During the atmospheric phase of the flight, two major events are dimensioning the payload random-vibration environment.

First, at lift-off, the rocket engines generate high Sound Pressure Level (SPL), increased by ground reflections and jet impact on launch table. For the fairing, this noise field is viewed as set of traveling acoustic waves exciting its structure and penetrating inside the payload volume inducing strong vibrations with frequency content up to 5 kHz. Around the launch vehicle, during a few seconds after ignition, acoustic pressure levels are rising between 180 dB near the engines down to 150 dB in the vicinity of the fairing and are quickly vanishing with altitude as soon as the vehicle is far enough from ground reflections. This fall is emphasized by the downward orientation of the directivity lobe of emission of the jet plume as its deflection decreases further and further from ground.

Second, when the launcher crosses the sound wall (transonic phase), the fairing is again strongly excited by shock wave attached to nozzle and by accompanying turbulence. To predict these two major events in term of acoustic pressure level around payload, the source (i.e. the external wall pressure applied to the fairing) has to be known. These levels are determined all along the development program through series of ground testing and numerical simulations. Lift-off acoustic loads are experimentally determined using motorized-scaled model of rocket engine (1/20th scale for Ariane 4 and 5-cf. Figure 4) and measurements on launch facilities for first flights of the new rocket. Wind tunnel tests are performed for transonic loads.

They are followed by numerical simulations based on measured data as extrapolations are required for predicting full-scaled results. The spatial and time correlations of the acoustic field have also to be investigated as the sound field is unsteady with fast changing frequency content.

Figure 1. Left: Ariane 5 lift-off (Flight V209); right Fairing separation from Ariane 5 last stage when leaving earth atmosphere.

2.2 Prediction of Ariane 4 vibroacoustic environment

For predicting lift-off internal acoustic environment around the payload, the actual surrounding acoustic field may be idealized as an equivalent steady-state diffuse random noise. A diffuse sound acoustic field is made of traveling waves impacting the structure in all possible directions. Diffuse field is convenient as an input to vibroacoustic calculation for covering all possible ways an acoustic wave may enter the fairing volume. Assuming diffusion of acoustic and vibration fields at lift-off makes possible to predict responses using SEA energy-based method.

SEA prediction method was initiated by R. H. Lyon and G. Maidanik in 1962. It is typically applicable to the calculation of equipment responses of payload panels within a reverberant chamber or for estimating in-flight rocket vibrations. SEA assumes conservation of vibrational energy between the various parts of the rocket under dynamic loads. SEA is a valid method for the high frequencies because the power flow exchange relationships are assuming dynamic weak coupling between the "subsystems", a natural evolution of the coupling when frequency increases. Reversely SEA is losing accuracy and validity when applied in too low frequency domain. Because fairing loads are random with broadband frequency content, deterministic numerical simulations are at least difficult and in practice not possible for covering the required frequency range and SEA was at beginning of 80ths the only method able to deliver consistent predictions for this type of application.

The author joined the Ariane 4 European development program in 1984. The program was already well-advanced. Ariane 4 introduced series of innovations in term of design of the upper part (Figure 2-Left): a lighter structure with sandwich cross section made of two orthotropic carbon-fiber skins separated by an aluminum honeycomb sandwich. There were two separate payload compartments (fairing on top and SPELDA below) for two-satellite launch and easier payload integration in launch pad facilities. Equipment bay was an external platform located below SPELDA. The Fairing was made by two half-shells attached by a clampband and jettisoned after atmospheric flight (Figures 1 and 2). Bending stiffness of the fairing in circumferential direction was three times lower than in axial direction. First breathing dynamic mode of half a shell was set at low enough frequency to avoid impacting payload after separation due to amplitude of breathing vibration motion.

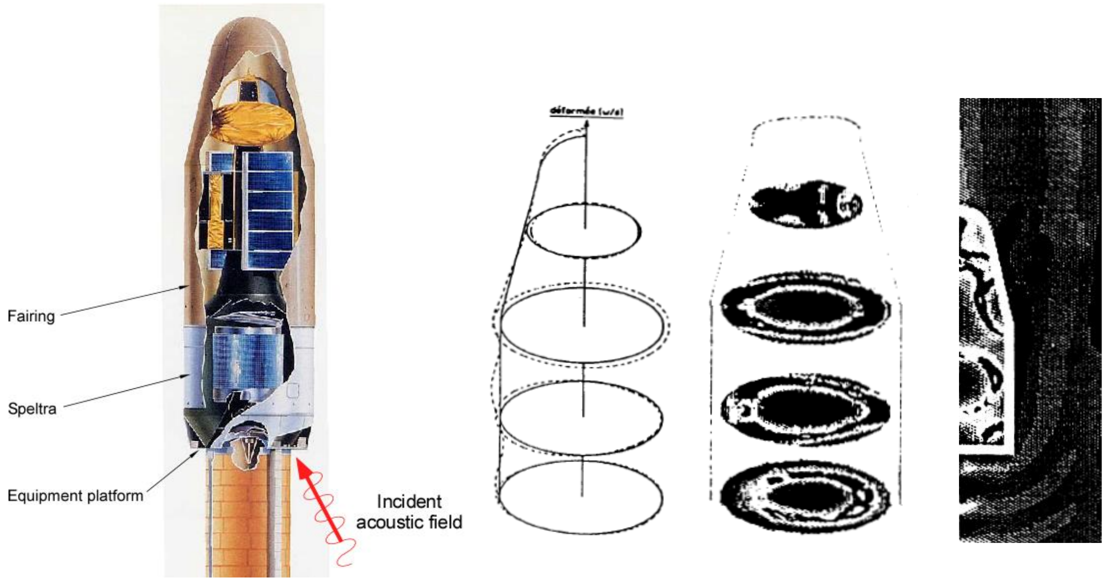


Figure 2. Left: Ariane 4 upper part. Right: First benchmark on fairing sound transmission using RAYON BEM software in 1985.

The new design, if mechanically very efficient, proved to depredate the acoustic environment of the upper part. After scaled-model tests were performed, expected external SPL's were known around the upper part within some margin of safety. From this, first SEA predictions run by Aerospatiale, the Ariane 4 architect, were showing a general increase of the vibroacoustic environment compared to previous Ariane launchers. It showed a potential increase of launcher equipment random vibration levels of about 10 to 20 dB as well as noise increase around payloads, exceeding environmental specifications used to qualify launcher and payload components. Due to novelty of fairing construction, there was no available published references throughout the world to confirm the SEA diagnosis and get some trust in predicted numbers. Research studies were then engaged to understand the physical causes of this noise increase and for finding any possible counter measures if the diagnosis would be confirmed.

The origin of the noise increase was quickly identified and was due to the conjunction of several factors: solid propellant boosters, added to the first stage of Ariane 4, were generating noisier environment than previous Ariane versions. Maximum noise levels were lying in the range 200-500 Hz.

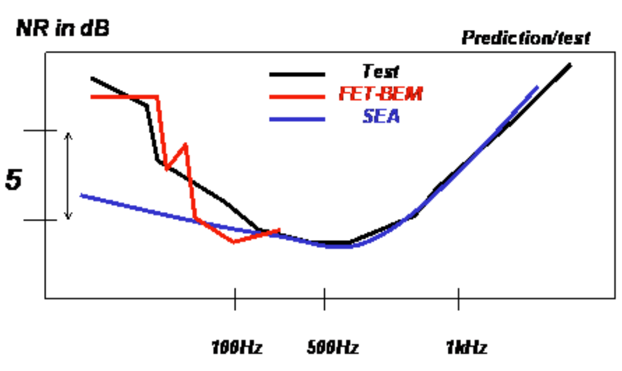
Unfortunately, the new sandwich fairing structure, stiffer and lighter than the classical Ariane 3 ribbed-aluminum structure, was showing acoustic critical frequencies just falling in this range. It led to very poor noise reduction in related frequency bands. As sketched in Figure 2 (Left), the equipment platform was also cantilevered with respect to the third stage, creating a corner in which impinging sound waves at lift-off from were badly scattered. This was generating an increase of about 10 dB of external pressure loading the equipment platform.

Emphasis was put on numerical acoustic prediction and engineering studies for :

- evaluating the various contributions to external noise level,
- mastering causes of uncertainty in the predictions
- improving the risk analysis knowledge.

There is a natural variability of the acoustic loads at lift-off due to the unsteady behavior of the engine noise, the type of boosters, the size of the payload inside the fairing. For qualifying equipment to random acoustic, a margin of + 4 dB is used for all frequency bands between the nominal expected level on launch pad and the specification which drives ground test level.

It was a very small margin in the currently faced situation. Predicting low and mid frequency content of internal fairing noise was investigated jointly with M.A. Hamdi [5][8][9][11][12], professor at UTC. He had developed during his thesis [2] a numerical kernel based on a new variational boundary element formulation (BEM) that was less subject to numerical drawback. His code called RAYON incorporated axisymmetrical formulation for coupling the lined-mesh structural FEM (Finite Element Method) model of the fairing with internal cavity. In place of solving the full 3D fairing-fluid cavity coupled problem, we could solve series of smaller 2D problems as CPU and memory was quite an issue in the eighties. 3D-dynamic behavior was retrieved by synthesizing series of 2D harmonics responses, for reaching higher frequency range. J. P Morand [16] and B. Chemoul from CNES provided the model of the orthotropic fairing structure. It was coupled with internal fairing volume and external sound field in RAYON by Hamdi & Co. Figure 2 (right) shows the first computation benchmark performed in 1985 with RAYON on a simplified model of the fairing. Original plots were in color and of better quality than current copy. It was the first time we could see at same time the motion of the structure and the wave patterns of exterior and interior sound pressure. This work was extended by developing a more industrial model of the Ariane 4 fairing/equipment bay for predicting the interior noise of the empty fairing surrounded by diffuse acoustic. This was a simulation of the acoustic fairing test inside reverberant chamber performed in the test facilities of Intespace company in Toulouse, cf. Figure 3 (right), after the delivery of the first fairing prototype by Contraves Corp., a Switzerland company.



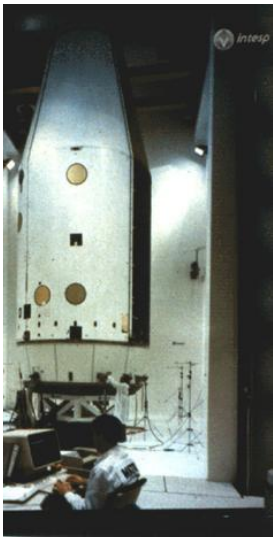


Figure 3. Combined BEM/SEA prediction (left) of the noise reduction of Ariane 4 fairing tested in reverberant chamber (right).

The author introduced the method of splitting the calculation of the random response into a set of deterministic BEM calculations under fixed grazing plane wave incidences in order to cover all incidences seen in the test chamber and to quadratically sum-up incident-response to recover the random response. Under this source specification, model construction and calculations were undertaken by Hamdi & Co. In parallel, high frequency SEA prediction from Aerospatiale and CNES completed the frequency range of interest. Agreement between predicted and measured noise reduction was excellent over the whole frequency range as seen in Figure 3 (left). The prediction model was further improved in 1987 to simulate the environment of the first Ariane 4 flight [11], which was fired the same year.

The source model was built from a set of acoustic monopoles along the jet line of the Viking and booster engines of which power was estimated with the standard NASA jet model [14]. This source representation was entered as inputs in a Ray-tracing acoustic model of the ELA2 launch pad [7] and SPL outputs were correlated with measured data provided by the 1/20th motorized mockup of Ariane 4 (Figure 4). Main expected incidences on the fairing were then retained as inputs to new BEM model of Ariane 4 upper part. As this model was intended to be correlated with first flight data, payload presence under the fairing was simulated by their rigid body shapes. Figure 5 provides the resulting predicted/measured SPL at the two microphones position installed in the fairing and SPELDA volume of Ariane 4 V401.

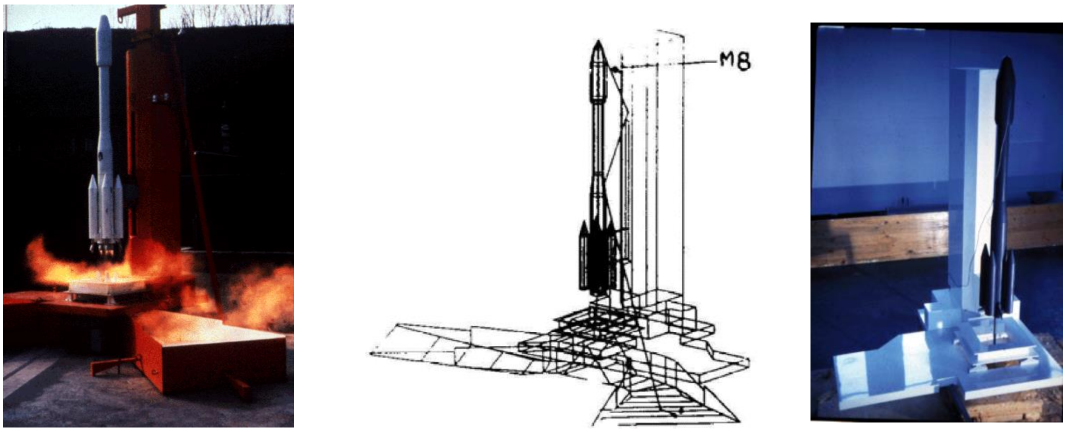


Figure 4 : On left, Motorized scaled-model acoustic test at Le Fauga (ONERA) and on right Ray-tracing acoustic model for jet radaited noise description with related scaled-acoustic model for measuring scattered field from ultrasonic sources (CSTB). M8 was the measured pressure reference on the launch pad to calibrate the source model.

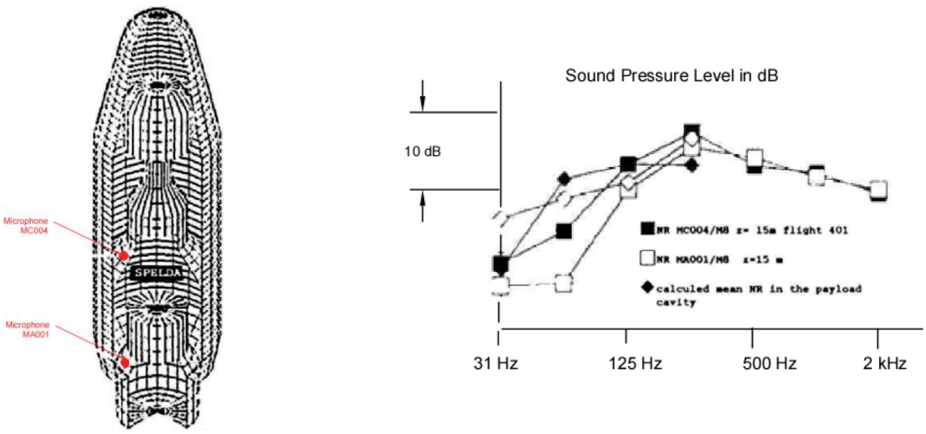


Figure 5. BEM/FEM coupled model and prediction against measured levels of flight acoustic levels in fairing and SPELDA compartments at the two in-flight microphone positions combining results of BEM/SEA models.

In parallel, the author investigated numerically the response of the equipment bay as the guidance platform was very sensitive to acoustic levels. Calculation was performed using FEM structural model of the equipment bay to which was applied estimated blocked random wall-pressure to simulate the acoustic loads [3]. Results from SEA modeling driven by Aerospatiale and FEM results were in good agreement up to 200 Hz, covering the equipment sensitivity range due to internal resonance of the guidance platform. These predictions were confirmed by joint work with ONERA supervised by R. Ohayon, [3][16], using a more sophisticated elastoacoustic model of the equipment bay coupled to internal cavity (including acoustic internal modes).

The critical aspect of acoustic vibrations at lift-off was thus confirmed before the first flight. After the first demonstration flight, June 15, 1988, criticality of vibroacoustic environment was verified. The guidance platform vibration was found at only -2dB from failure level observed in test and conformed to predicted values. Extrapolation of future second flight showed negative margins of safety due to a noisier booster configuration. A set of counter measures were immediately undertaken such as modifying the launch pad to minimize lift-off acoustics, over-qualifying some of the equipment and changing the guidance platform to another technology less sensitive to vibrations. Despite or because of this troubleshooting, Ariane 4 has been one of the safest launch vehicle with a long carrier.

2.3 Ariane 5 vibroacoustic environment improvement from design stage

On the new on-going Ariane 5 program starting in 1985, Project team was now well aware of acoustic problems arising as soon as these loads are underestimated in specifications.

Research was then performed for optimizing Ariane 5 noise environment, undertaking noise reduction solutions from design stage, acting on both for exterior noise and fairing interior comfort for payload passengers, [6][10][12].

Thanks to cooperation with ISVR and ESA, acoustic tests were performed on 1/5th scaled model of the fairing to investigate orthotropic effect on noise transmission. Pr. F. Fahy developed a specific theory for quickly predicting noise transmission for this type of system. The related software called PROXMODE was further used by Dornier company, responsible for the development of the SPELTRA structure of Ariane 5, located below the fairing and containing a third payload. From this work, Dornier developed a specific acoustic treatment to attenuate low frequencies in the fairing by means of Helmholtz's resonators spread on internal face of the fairing to increase internal absorption.

Fairing Bending stiffness was also tuned in the circumferential direction to gain a few dB. BEM/FEM modeling's were also more and more useful to calculate exotic noise reduction solutions like Helium purge of the internal fairing volume that in theory could reduce interior noise level from 10 dB as shown in Figure 6. SEA and dedicated analytical predictive models were complemented the frequency range [6] [12].

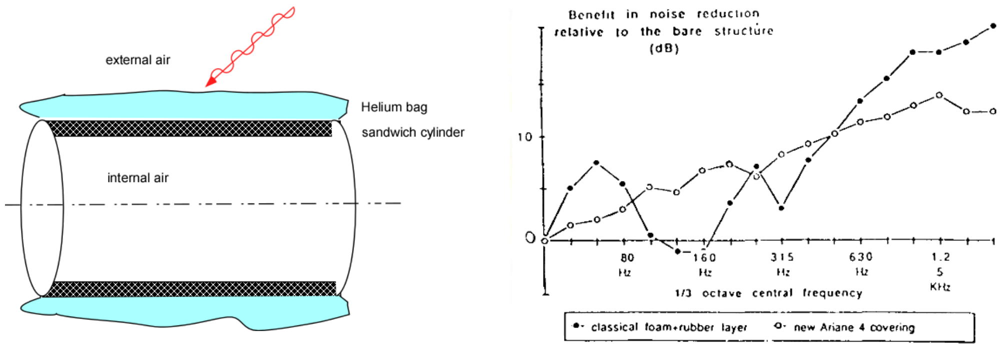


Figure 6. Helium bag to reducing noise inside fairing.

Nowadays BEM predictions are a standard method to design some of the equipment as large payload antennas. Capabilities of numerical BEM techniques have also improved in both model size and accuracy as shown in Figure 7.

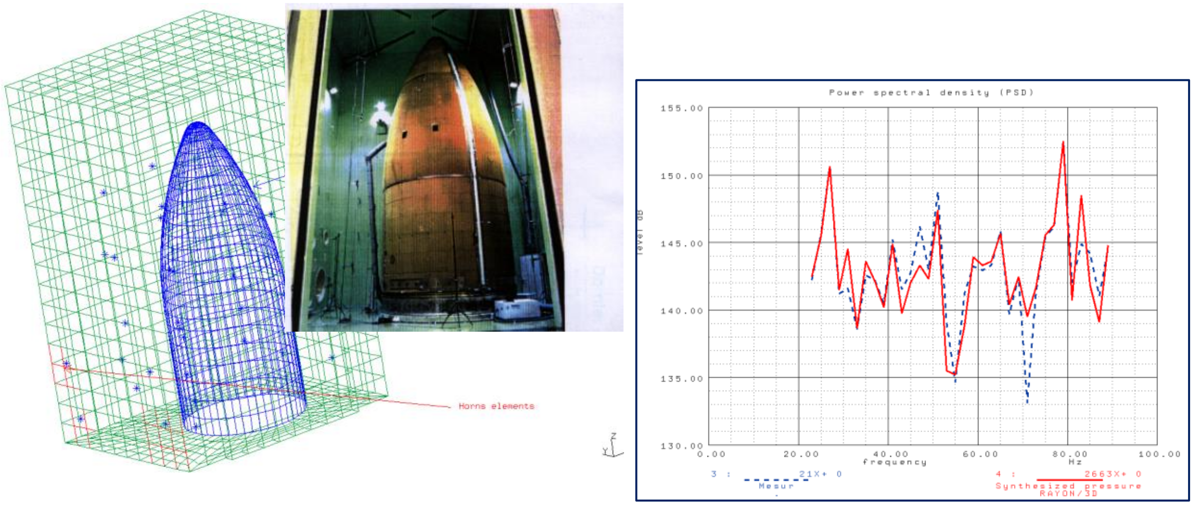


Figure 7 BEM analysis coupling FEM model of the Ariane 5 to both internal volume and to test acoustic chamber and correlation with test (Straco analysis for ESTEC).

3 ACOUSTIC QUALIFICATION OF THE ARIANE 5 VULCAIN ROCKET ENGINE

3.1 VULCAIN Engine vibroacoustic environment

Vulcain is the cryogenic engine of the central stage of Ariane 5 launch vehicle. Vulcain is surrounded by two solid propellant boosters (the EAP's) and is submitted to their acoustic noise at lift-off.

SPL levels generated by the boosters are around 10 dB higher than the self-noise of Vulcain. Noise is also maximum at lift-off in the high frequency range around 2000 Hz. Compared to previous Ariane generation of launch vehicle, this new environmental configuration needed to be understood and qualified . Specified SPL could not be reached in available reverberant rooms and even so, the engine would have been passive not allowing qualification of the equipment.

Analysis started by developing a theoretical SEA model of the engine to get broadband response prediction of acoustic vibrations of the engine. This analysis was completed by experimental SEA tests under instrumented-impact hammer to derive damping loss factors and coupling loss factors of the major subsystems: nozzle, turbo-pumps, gas generator and exhausts.

These data were injected in the SEA model at low frequencies to compensate lack of accuracy of analytical calculation in the related frequency domain.

The coupling with the acoustic field was computed analytically from radiation efficiency with the dedicated SEA EARTH software, used by the SNECMA and developed by the author. EARTH predictions up to 4000 Hz were satisfactorily validated against test of the engine in reverberant chamber (Figure 8), [18].

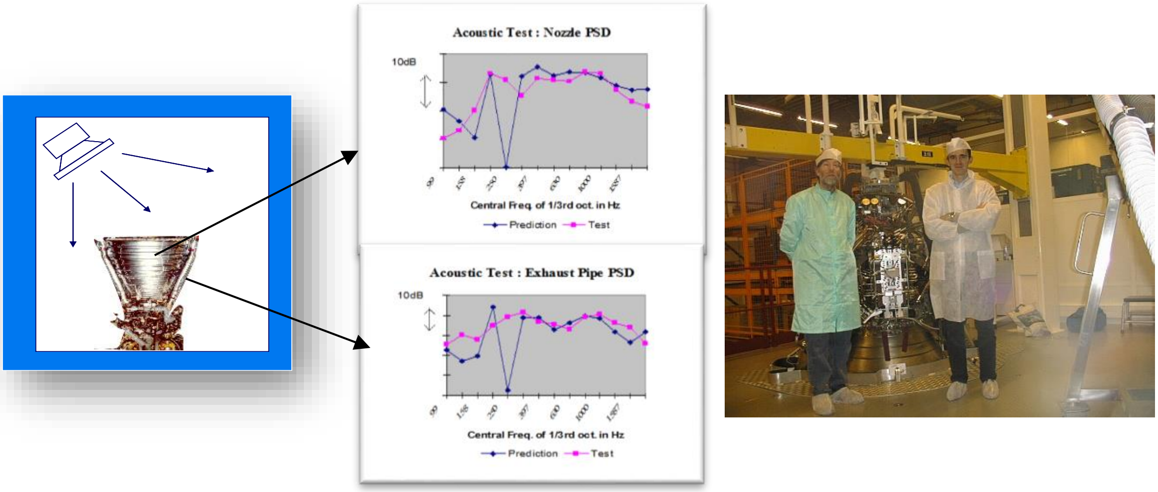


Figure 8. Test comparisons of VULCAIN SEA model Prediction of acoustic vibrations with SEA EARTH software.

3.2 VULCAIN Engine acoustic qualification process

Prior to undertake the Vulcain acoustic qualification process, a feasibility study started in 1993. Main idea was to concentrate the acoustic energy of the self-noise of the jet when fired in its test stand for increasing sound level on Vulcain nozzle. This increase of noise would simulate the noise of EAP's in the actual lift-off situation.

We had to prove enough energy could be trapped around the nozzle to reach the required qualification noise levels with the available radiated power by Vulcain. Radiated noise was predicted from [14].

The jet plume is split into slices along the flow line. Each slice has a global directivity diagram and a given spectrum of radiation efficiency computed from an experimental database of measurements on various kinds of engines. Abacuses of radiation of various engines contained in [14] were interpolated for covering the regime of cryogenic engines. Due to the scattering of sound wave on obstacles and to the presence of the jet guide, some corrections were necessary. As sketched in Figure 9, each slice of the plume is radiating in a given frequency band with given directivity. High frequencies are radiated by the nearest slices from the nozzle. Low frequencies are radiated by the furthest. The prediction of the sound pressure in the near field of Vulcain during a standard firing (Figure 10-left) was confirmed against measurement (Figure 9-right).

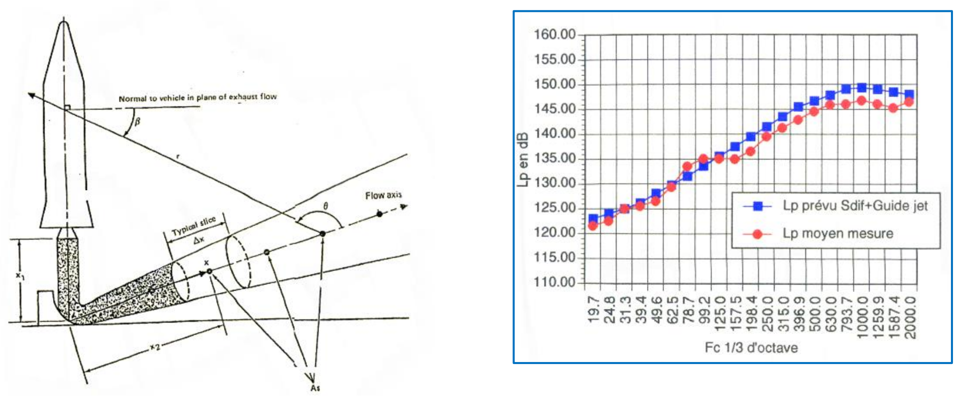


Figure 9. Prediction of Vulcain noise at test stand and related measured SPL.

From here, the first part of the jet was shown to be as appropriate source for delivering the required amount of diffuse SPL around the nozzle. A reflector structure was designed for confining the noise as shown in Figure 10-right.

Nevertheless, the reflector should have enough aperture for supporting the gas flow, enough stiffness for the resulting dynamic pressure and an optimized inclination for improving diffusivity and sound amplification. Its design was then performed thanks to 3D acoustic ray tracing model of the test stand to optimize its shape and its volume. There was also a risk of inducing local acoustic resonances in the fluid volume between reflector walls and nozzle.

Effect of the incidences on nozzle response was analyzed using EARTH software and the implemented reciprocal radiation integral that states the generalized applied acoustic force is reciprocal of its radiation efficiency in the direction of the incident wave.

Effect of depressurization due to jet aspiration was analyzed using a CFD model and the pressure outputs were used by EARTH SEA model to predict mean stress in the reflector panels.

Potential fluid resonances were analyzed using a BEM model with sources calculated from the jet model. The work was done in parallel by Acouphen company (ray-tracing optimization of the reflector structure), by Straco company and Pr. A. Hamdi for BEM risk analysis, by the Snecma (SEP division) for all CFD calculation, reflector construction and test realization and by the author for all SEA-based calculation, transducer calibration before the first qualification test and overall supervision of the study, [19].

The first qualification firing test lasted only 20 seconds and confirmed the prediction and the design choices as shown in Figure 11 (5 s past ignition) and Figure 12. The reflector was amplifying of about 8 to 10 dB the noise on the engine which was found acceptable despite achieved levels were 2dB below specification. The sound pressure measured during the lift-off of the 501 flight confirmed the correctness of the acoustic qualification process as shown in Figure 13.

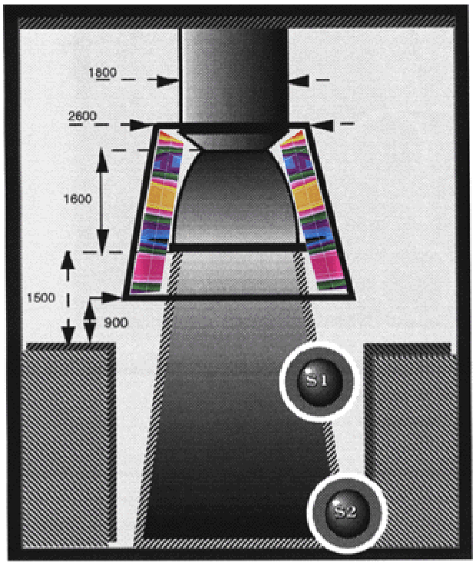


Figure 10. On left standard test stand configuration when firing the VULCAIN engine; on right acoustic qualification configuration with the acoustic reflector in position.

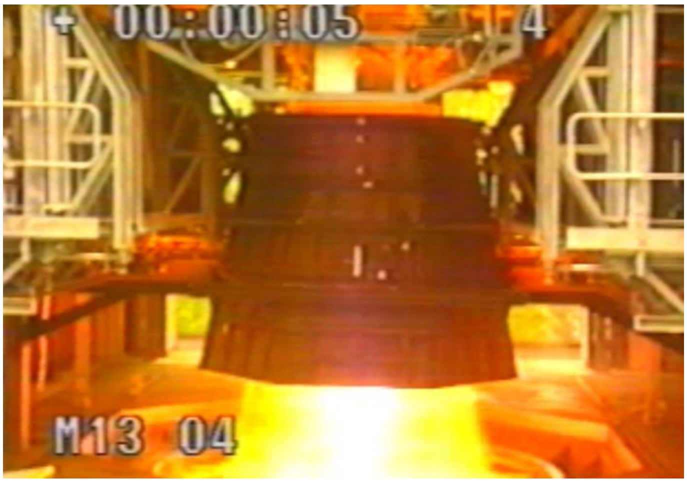


Figure 11. Firing the engine with acoustic reflector in position.

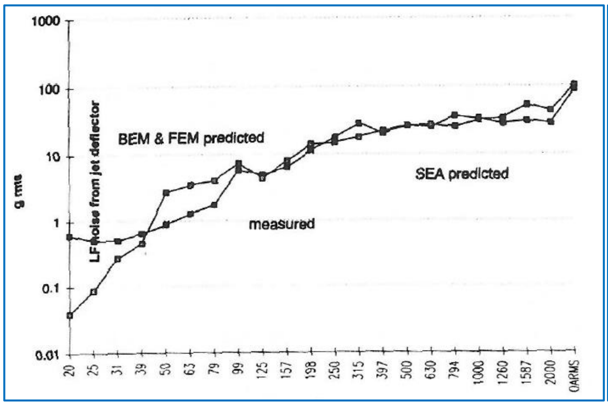


Figure 12. Reflector vibration: measured vs predicted.

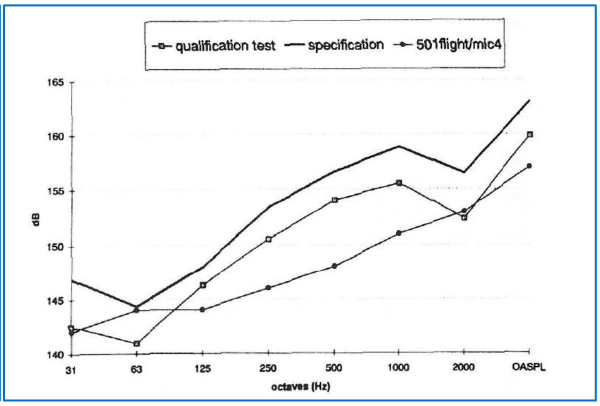


Figure 13. Comparing qualification test and flight 501 measurement.

4 SHOCK RESPONSE PREDICTIONS

During the rocket flight, inter-stage separation is commonly performed by pyro-zip devices. Payload separation may also involve pyro-zip cut or explosive bolts for final in-orbit injection.
The cut is highly energetic and fast due to propagation of initial crack at 7000 m/s. It leads to very impulsive vibration signals near the separation line with very broad frequency band (above 100 kHz) and instantaneous levels of several thousands of g's and more.

Shocks are inducing failures on equipment such rupture of welds, malfunctioning electronics…
The severity of the shock is measured by the Shock Response Spectrum or SRS. The SRS of a signal $s(t)$ corresponds at a given frequency to the maximal response of a test oscillator with given Q-factor having this resonance frequency and excited at base by $s(t)$.

In general, the time history is required to perform SRS prediction in order to know the severity class in which the equipment is falling. Depending on equipment location on the launch vehicle, the specified SRS is different depending on distance to expected shock source. The payload has to be qualified to shocks and the resulting specified qualification SRS is an envelope of various shock events.

Pyrozip shock tests are known to be difficult to predict as the source itself is difficult to measure and calibrate. Specifying an SRS does not provide the deterministic signal to use in the qualification test as the SRS transform is not reversible. Due to the high frequency content of shocks and the general variance in input description, a statistical approach appears as quite natural to predict response. Inside research program driven by the CNES, the author has demonstrated the validity of SEA method to predict fast transients generated by shocks. This may look like a paradox as SEA is predicting steady-state random vibration responses from forces and modal behavior.

This is only appearance. Near the source, the propagation is non-modal and response may be considered as constrained forced motion. The vibration level of the separation ring is considered as the effective source term. Away for the ring, frequency transfer functions on the various panels and equipment are close to SEA calculated transfers. Experimental work using shock sources shows SEA is given very good trends is term of transfer as soon as the force spectrum is known.

Nevertheless, SEA transfer has no phase. It is a real-valued transfer, not invertible for retrieving time domain response.

For this, a time history signal profile is allocated to the source: it may be a pre-defined simple-shaped force term like a triangle an impulse or half-sine pulse with given amplitude and duration. The force term is closely related to the separation process. Pyrozip cuts are delivering nearly perfect $\delta-$ Dirac's force profile but force has to be converted into injected power in the structure. For this a dedicated model to make this conversion is required.

For a fixed-position $\delta-$ Dirac, the conversion factor is known: $P_{in} = Y\left(x_i, f\right)F^2(x_i, f)$ where Y is the real part of the driving -point mobility at point x_i and F^2 is the square modulus of the autospectrum of applied force at x_i. In a pyrozip cut, the applied force moves along with the crack failure and this propagation speed has a strong influence on injected power in the structure. In a separation system using a clampband like in the Ariane 4 fairing, the clampband is first cut at both ends by explosive bolts creating a relaxation force moving at speed of sound in the clampband material, followed by internal potential energy liberation of the underlying compressed structure that was maintained by the clampband. Using Fourier's-based simple modeling of the injected power process due to propagating on edge of a continuous system leads to very good predictive model as shown in [24]. These models are also appropriate to predict measured responses near the source if force is scaled from tests. In example given in Figure 14, SEA-Shock method, as found in SEA+ software, is applied to the prediction of a pyrozip separation test of the Ariane 5 upper part. The time reconstruction is performed by the LMPR algorithm (Local Modal Phase Reconstruction) that develops the response in the receiver over its local analytical modes of vibration and scales it to expected real-value transfer function between the source and the receiver provided by the SEA model of the various coupled subsystems. The propagation force model for computing injected power was tested for the first time in this example study. Second similar example is given in Figure 15 and was part of benchmark test of SEA-Shock for the European Space Agency. Further details may be found in references [20] to [25], especially the application to shock responses of the payload. Recent developments implement shock prediction directly using specified SRS as the input to simplify the modeling work for launch vehicle passengers that do not know the underlying shock source at the origin of the specification.

5 CONCLUDING REMARKS

Various examples of usefulness of vibroacoustic calculation methods taken in the Ariane launch vehicle program have been presented in a way to put emphasis on the calculation scheme. The latter improves both risk analysis and engineering knowledge through easier interpretation of measured data and extrapolation to unmeasured configurations. BEM and SEA are complementary techniques for covering the full spectral domain of investigated process. SEA method provides a very powerful insight into the random vibration behavior of such complex machines even for fast transient like separation shocks. This article is complemented by a bibliography related to the treated examples where readers will find related theoretical developments that are not presented here.

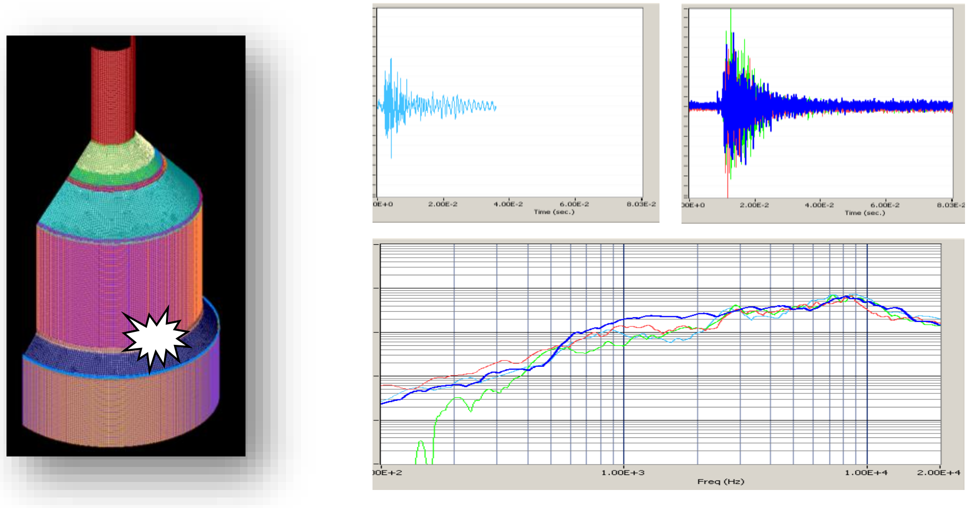


Figure 14. SEA-Shock prediction of Ariane 5 separation test of the upper part (top synthesized and measured time history on the payload, bottom SRS for predicted time signal (blue) compared to SRS from measurements.

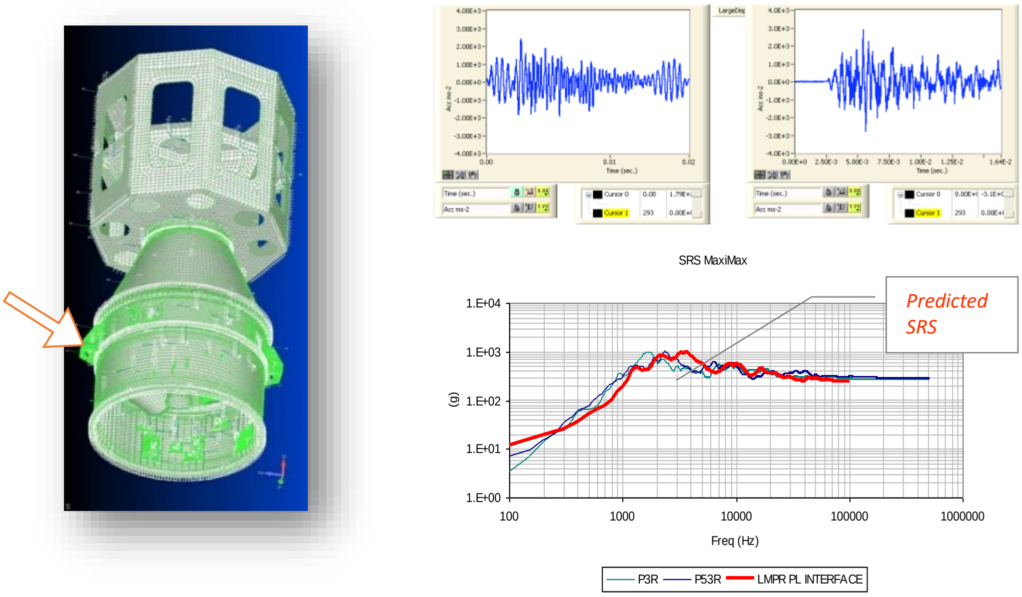


Figure 15. Prediction of Vega launch vehicle upper part: top left, predicted time history on payload interface and top right related measurement; bottom predicted vs measured SRS at same location.

REFERENCES

[1] H. Morand and R. Ohayon. Variational Formulation for the Elastoacoustic Vibration Problem: Finite Element Results. 2ème Symposium International sur les méthodes d'éléments finis dans les problèmes d'écoulements, Rapallo 1976.

[2] M. A. Hamdi. Formulation variationnelle par équations intégrales pour le calcul de champs acoustiques linéaires proches et lointains. Thèse UTC, 1982.

[3] G. Borello. Réponses basses fréquences de structures axisymétriques en bruit diffus. Spacecraft Structures Conference. (ESA SP-238, April 1986), 1986.

[4] G. Borello. Acoustic Intensity Techniques Applied to Parameter Identification of Noise under a Fairing through a SEA Mode. AIAA, Dynamic Specialists Conference, pp. 844-850, April 1987.

[5] G. Borello. Numerical Methods for the Prediction of Internal Vibroacoustic Environment of Space Vehicle. Inter-Noise 1987.

[6] G. Borello, A. Blaise, C. Lesueur, M. Gotteland and M. Barbe. Sound Transmission Studies of some Ariane Structures (Acoustic Optimization of Light-Weighted Aerospace Structures). Inter-Noise 1988.

[7] Van Maercke, D. Kapus and E. Roland. Etude du champ acoustique au voisinage de la coiffe d'Ariane par une méthode d'acoustique géométrique. CSTB Grenoble, GA/87-637/JR/BEA pour CNES/DLA.

[8] M. A. Hamdi. Recent Advances in Vibroacoustic Computation. Inter-Noise 1988.

[9] J. Ben Mariem, L. Mebarek and A. Ounadjela. Vibroacoustic Analysis of Ariane 4 Launcher by a New Boundary Finite Element Method. Inter-Noise 1988.

[10] G. Borello, N. Pinder and I. U. Borchers. Interior Noise Control of Spacecraft Launch Vehicles. IAF Congress, 1989.

[11] G. Borello. Low Frequency Noise Prediction of Internal Acoustic Environment of a Launch Vehicle at Lift-off. Inter-Noise 1989.

[12] G. Borello. Utilisation de l'hélium pour la protection acoustique des lanceurs. ASTE, 1990.

[13] G. Borello, Payload Configuration Influence of the Ariane 4 Launcher on the Internal Acoustic Environment at Lift-off. Inter-Noise 1990.

[14] Acoustic Loads Generated by the Propulsion System. NASA SP 8072. June 1971.

[15] G. Borello. Identification of SEA Coupling Loss Factors on a Liquid Rocket Engine. Inter-Noise 1991.

[16] H. J.-P. Morand and R. Ohayon. *Interactions fluides-structures*. Edition Masson 1992.

[17] G. Borello. Vibrational Energy Prediction of the response of the Vulcain Rocket Engine using a Mixed FET/SEA Analysis. Inter-Noise 1992.

[18] G. Borello, A.Kernilis, R. Gazave and P. Esparcieux. Ambiance Vibratoire des moteurs fusées. Colloque International Ambiance Acoustique et Vibratoire des Systèmes de Transport Spatial. 1994.

[19] A. Kernilis, F. Desnot, G. Borello and J. M. Mondot. Acoustic Qualification of Ariane 5 Vulcain Engine. ECSSMMT (ESEA SP-428, February 1999), 1998.

[20] G. Borello. Analysis of Wave Propagation in Pyrotechnical Shock Tests. 1er Colloque européen sur la Technologie des Lanceurs, Vibrations des Lanceurs, 1999.

[21] E. Bodin, B. Brevard, P. Wagstaff and G. Borello. Pyrotechnic Shock Response Predictions Combining Statistical Energy Analysis and Local Random Phase Reconstruction. *The Journal of the Acoustical Society of America*. Vol. 112, iss. no.1, pp 156-163, July 2002.

[22] G. Borello and V. Cipolla. Prediction of High Frequency Shock Response of a Satellite Using SEA. ECSSMMT 2002.

[23] G. Borello. Analyse statistique énergétique SEA & Applications industrielles de la SEA. *Techniques de l'ingénieur*, R 6 215 & R 6 216, 2006 et mis à jour R 6215 V2, 2012.

[24] G. Borello. J. Primus, R. Nguyen Van Lan and S. Kiryenko. Prediction of Payload Shock Response in the Mid and High Frequency Range. ECSSMMT, 2009.

[25] G. Borello. Acoustic Response of Spacecraft Equipment and Shock Response from SEA Prediction. ECSSMMT, 2016.