Proceedings of the Institute of Acoustics

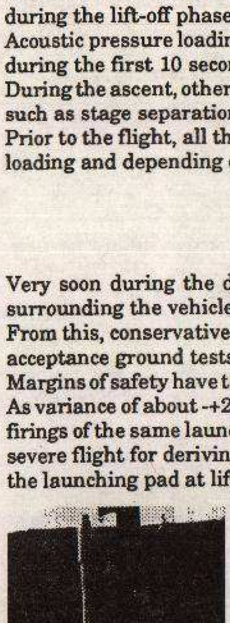
USE OF VIBRO-ACOUSTIC PREDICTIVE TECHNIQUES FOR SPACE VEHICLE DEVELOPMENT

G. Borello Consultant, 1 impasse des Hirondelles, l'Union (near Toulouse), 31240 France

A launch vehicle and its passengers are enduring severe vibrations due to Acoustic loads from the engine, during the lift-off phase.
Acoustic pressure loading is so high (140-150 dB) that damages and failures can occur in the equipment during the first 10 seconds of the lift-off phase. It is the main broadband random source of excitation. During the ascent, other broadband sollicitations are taking place but they have transient characteristics such as stage separations.
Prior to the flight, all the equipment has to be qualified by specific ground tests to the acoustic random loading and depending on their location on the launcher to shocks.

Predicting the external acoustic loading

Very soon during the development phase of the launch vehicle, the expected external acoustic field surrounding the vehicle at lift-off and the related launch vehicle vibrational response are predicted .
From this, conservative data entries are derived and imposed as a specification for the qualifcation and acceptance ground tests of the different components which are sensitive to vibrations.
Margins of safety have to be as narrow as possible, for not leading to heavier components when designing. As variance of about -+2dB is observed on the OASPL (OverAll Sound Pressure Level) between different firings of the same launch vehicle configuration, a margin of 2 to 4 extra dB is taken referred to the most severe flight for deriving a qualification level. These data are coming from SPL measurements around the launching pad at lift-off or from the in-board data acquisition system of the launch vehicle where a set of accelerometers and microphones are located.



Picture 1 1/20th scaled model of Ariane44 L for external acoustic prediction

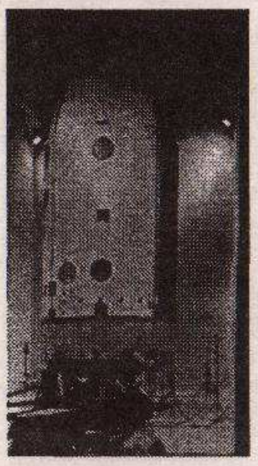
For a new launch vehicle under development, these data are not avalaible and they can only be derived from ground tests. From the firing of an engine in its test bed, the measurement of SPL gives some data. But the extrapolation to the actual planned flight configuration is not so easy as the acoustic power generated by the propulsion system is strongly dependant of the launch pad configuration . Depending on the engine being fired in a ground test facility or in a real flight, variance of as much as 6 dB can occur on the SPLs between the two configurations. This is not acceptable for specifying qualification levels within a 2 to 4 dB variance range.
Predicting the external sound pressure level at lift-off, is generally better performed using a scaled model of the launch vehicle on its launching pad, with miniaturized engines. The scaled mini jet is interacting the same way the full scaled one does, allowing for a more accurate external SPL prediction (within 3 dB).

Firing of an Ariane 4 1/20th scaled models in le Fauga (Research Center of ONERA) is shown on picture 1 .

USE OF VIBRO-ACOUSTIC PREDICTIVE TECHNIQUES

Predicting the acoustic load around a payload

When a good mapping has been done of the expected external SPL all around the launch vehicle, one must predict the expected vibrational environment on the launch vehicle itself.
This can be done by testing : direct measurements of accelerations are performed on a part of the launch vehicle excited by an acoustic field. On the picture 2, one can see the top part of Arane 4 in a reverberant room for acoustic testing.
The top part is here made of
-the fairing, a light weighted carbon fiber honeycomb sandwich to protect the payload during the atmospheric ascent,
-the equipment bay below , which contains all the equipment for guidance and control of the launch vehicle.
This specimen is 15 m high and 4 m diameter and test facilities in Europe don't accept much bigger ones.



Picture 2 Top part of Ariane 4 in the acoustic test chamber of Intespace

In this, experimental vibrational predictions are limited to specific parts of the vehicle. These data have also to be fitted to the actual flight configuration as the test condition is never a simulation of the flight : in the previous fairing example, the test excitation is a diffuse sound field. It is an incident sound field at lift-off, introducing an extra variance that needs to be predicted by other means. The fairing is empty in this test and the vibrational effect of installing a particular payload in it, has to be estimated, and so on for some others parameters.

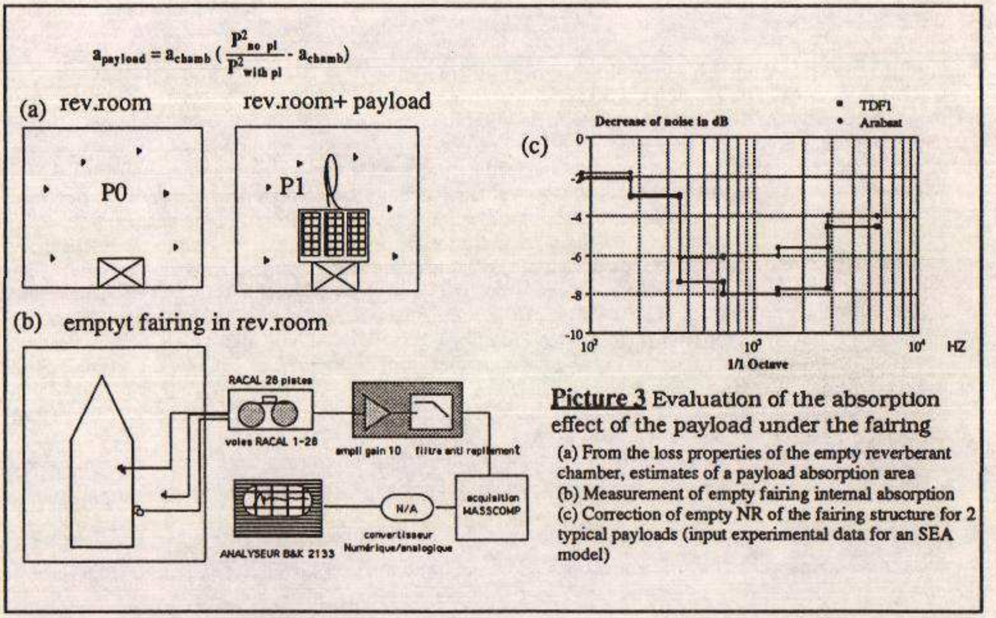
In this, theoretical predictive techniques such as Statistical Energy and Finite Element Analysis are a good complement of the experimental predictional process. Now they have become essential keys for the quality of the prediction in space programs.

They allows for parametric changes around a typical test situation and they spare the number of required test configurations .

On the Ariane 4 fairing, predictions have been conducted using SEA and Finite Element Techniques for estimates of the noise reduction variance due to parameters such as the payload size (picture 3) , the acoustic incidence at lift-off (picture 4) or the space distribution of the sound field inside the acoustic cavity. The quality of the further in-flight data analysis is naturally improve as only few in-flight measurements are authorized for the survey of a specific problem (picture 5).

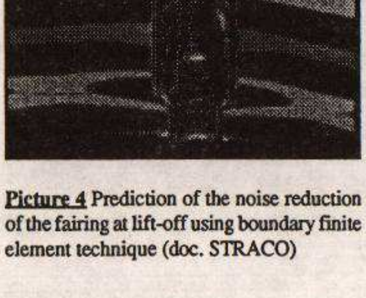
For the Ariane 4 programme, the vibroacoustic prediction process was vital in insuring the final success of the launcher. SEA predicted very soon the main trends of the vibro-acoustic levels. Compared to the data of the previous versions of Ariane, the trends were a general increase of vibration and internal acoustic levels, one part being due to an increase in the external sound field and the main part to the use of new structural materials such as carbon fibers sandwiches.
When the analysis came, there was enough time left to take corrective actions without compromising the development. In 1988 the first Ariane 4 was launched and the in-flight measuments (microphones and accelerometers) confirmed the predictive diagnosis.

USE OF VIBRO-ACOUSTIC PREDICTIVE TECHNIQUES

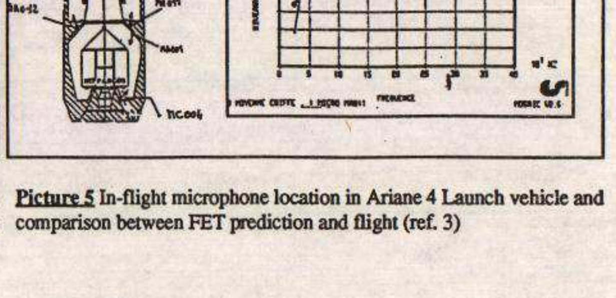


Picture 3 Evaluation of the absorption effect of the payload under the fairing

(a) From the loss properties of the empty reverberant chamber, estimates of a payload absorption area
(b) Measurement of empty fairing internal absorption
(c) Correction of empty NR of the fairing structure for 2 typical payloads (input experimental data for an SEA model)



Picture 4 Prediction of the noise reduction of the fairing at lift-off using boundary finite element technique (doc. STRACO)



Picture 5 In-flight microphone location in Ariane 4 Launch vehicle and comparison between FET prediction and flight (ref. 3)

Investigating the dynamical rocket engine response to external acoustics

The new generation of European launch Vehicles (Ariane 5 family) will lift-off in 1995. Ariane 5 is still in its development phase.

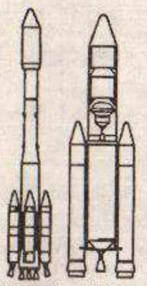
Despite its name, this is a completly new launch vehicle, powered by two solid propellant boosters (EAP), each of us having 250 tons of thrust. The central stage (see picture 6) is powered by a cryogenic rocket engine called VULCAIN with 100 tons of thrust.

The Ariane 5 development has taken benefit of the Ariane 4 experience especially for the acoustic design of the 5.6 m diameter fairing.

But it brings a set of new problems for the acoustics : the VULCAIN is surrounded by the EAPs generating 10 dB more noise than its self noise and this configuration is difficult to simulate when firing the VULCAIN alone.

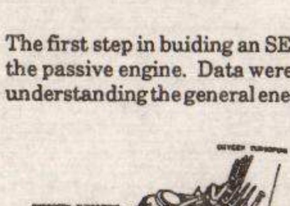
The behaviour of the nozzle is here under concern as predicted external levels which add up to the self noise, will produce additional fatigue.

A SEA model of the VULCAIN has been built to predict the broadband frequency response of the different components when submitted to the noise of the EAP. From the SEA prediction, one can then produce a first diagnosis and derive specifications levels for the qualification of individual components.

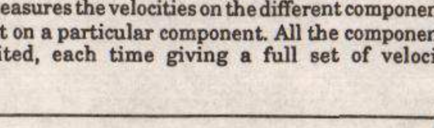


Picture 6
Ariane 44L vs Ariane 5

The first step in buiding an SEA model was to investigate the dynamical broadband behaviour by testing the passive engine. Data were acquired using **reverse SEA** in order to generate a reliable data base for understanding the general energy transfers. Here one measures the velocities on the different components for a given power input on a particular component. All the components are sequentially excited, each time giving a full set of velocity measurements collected on the whole engine. The vibrational energy of a particular component (for a particular input power) is obtained by averaging the relevant velocities,



Picture7 Vulcain engine



Energy flow model for the VULCAIN engine

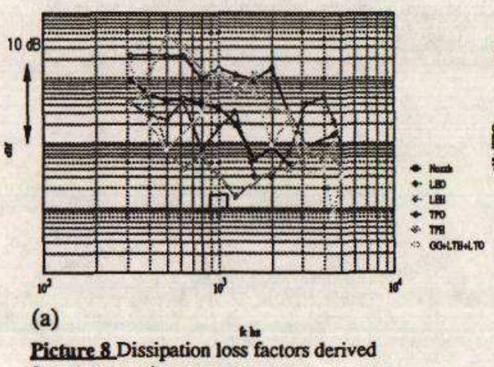
USE OF VIBRO-ACOUSTIC PREDICTIVE TECHNIQUES

ponderated by a mass factor and scaled by the autospectrum of the force input.
If N components are excited, N different sets of N energy balance equations can be written between the N coupled components.

The unknowns of these linear equations are the damping loss factors (DLF) and coupling loss factors (CLF), the matrix coefficients being the energies.
This leads to a N×N linear system. As there are N×N damping and coupling loss factors, the experimental determination of the loss terms is done by simply inverting the experimental energy matrices.
DLFs and CLFs are in fact computed separatly as the sum of all the dissipated energies must be equal to the total power input in the system (no dissipation allowed in the joints).

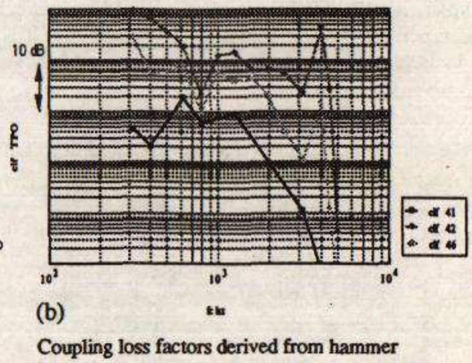
For practical purposes, the engine sub-systems were excited using hammer impacts. It is more convenient than a shaker but less accurate. 135 accelerometers were at disposal for data acquisition. The acquisition of the time histories was carried out by IABG in the test facilities in Ottobruhn, Germany.
These data were then post-processed in order to compute all the relevant DLFs and CLFs.
The measured CLFs were supposed to be representative of the energy transfers when exciting the VULCAIN by an external diffuse sound for simulating the noise of the EAPs.
Due to the signal/noise ration not all the CLF were identified :
The most satisfactory results were obtained with the energy model combining the main six components shown on previous picture.

On picture 8, it can be seen there are big differences in the DLFs on the differentcomponents. As expected the most damped ones are the oxygen and hydrogen turbopumps (TPO2 and TPH2), which dissipate energy through the bearings. One can also see the CLFs between the TPO2 and its connected components (nozzle, gas generator, oxygen exhaust line).



(a)

Picture 8 Dissipation loss factors derived from hammer impact tests



(b)

Coupling loss factors derived from hammer impact tests

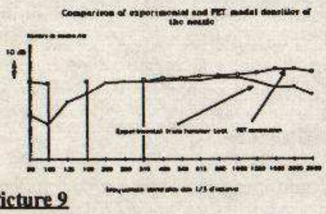
USE OF VIBRO-ACOUSTIC PREDICTIVE TECHNIQUES

Building a SEA theoretical model of the VULCAIN

The experimental analysis showed an effective weak coupling between components, a good condition for the development of a theoretical SEA model of the engine.

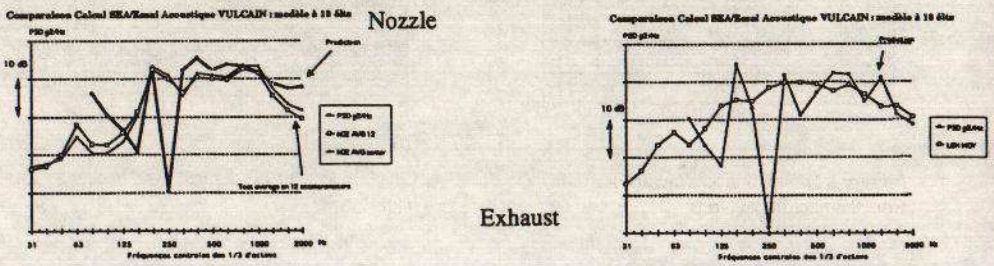
When the engine is excited by an external sound field, the main power input is applied to the nozzle. So specific modelling SEA techniques were applied to this structure to improve the accuracy ofthe prediction compared to available standard SEA procedures.

An equivalent axisymetrical Finite Element Model (FEM) of the nozzle was first developed, after homogeneization of the 3-D stress-strain tensor. From this, it was then possible to extract from the FEM, high order modes of the nozzle. The modal density of the nozzle was then computed from the numerical resonance frequency set. The modal shape set was used to compute the CLF between the nozzle and the external sound pressure field. Here the mode per mode CLF is first calculated, then it is averaged by 1/3rd octave band for getting the average 1/3rd octave band acoustic CLF. The basic theory which is used to compute the mode per mode CLF is based on infinite wave radiation properties for cylinder liked structures. Each mode shape is decomposed into a set of infinite waves using a spatial FFT transform and the acoutic power is computed around the resonance frequency of the mode by integration of all the supersonic wave components. For a shell moreless conical, this kind of computation is only an approximation of the present physics. But it is much more accurate than standard procedures presently used in commercially avalaible SEA packages. In particular it leads to an exact solution when the structure is purely cylindrical. For computing the acousttic CLF of all the cylindrical structures within the engine (for example the exhaust pipes) the same kind of prodedure was applied except that modes were analytically generated. For the other components «classical» SEA modellings were performed using equivalent cylinder or plate to match the dynamical behaviour. The agreement between expermental modal density extracted from hammer test and FET modal density was found to be very good in the medium frequency range (see picture 9. Validation of SEA prediction levels were carried out on test data coming from acoustic tests of the VULCAIN in the reverberant chamber of IABG (picture 10). Test data were spaced and frequency averaged to give an estimate of the energy level of each component. The agreement is extremely good in the frequency range where the model is valid : 300-3000 hz. Below it can be seen the the variance is bigger, most of the components having no local mode in these bands.



Picture 9

Picture 10 Comparison of SEA prediction with acoustic test data

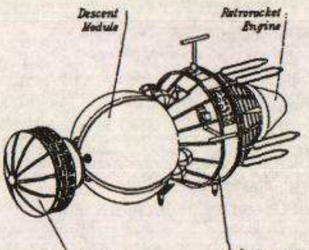


USE OF VIBRO-ACOUSTIC PREDICTIVE TECHNIQUES

Shocks problems on components

An other severe case of in-flight loading is produced by the separation of two stages. The separation process is generally produced by a pyrotechnical device which cuts the metal skin in a few milliseconds. Instantaneous acceleration levels near the cutting edges can reach levels up to a hundred thousand Gs, but are rapidly falling down with the distance.

For the user of a space vehicle, it means a set of specifications for testing. He need to prove to the launch vehicle authorities he can resist to the entire flight duration.

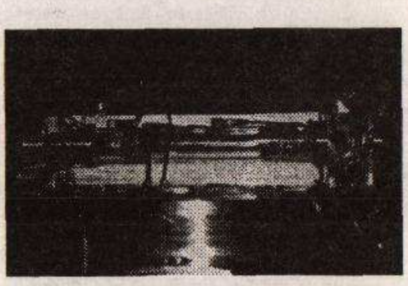


PROTON Spacecraft

The Gezon experiment is a small component designed to fly on a russian PHOTON spacecraft which is put into orbit by a PROTON launch vehicle. Gezon is a microgravity experiment designed by the CENG (Centre d'Ertudes Nucléaires de Grenoble) under the survey of the CNES (Centre national d'Etudes Spatiales) for studying the fusion of germanium . It must turn around the Earth, make some data acquisition and then return and land in the PHOTON descent module. Gezon has to survive not only to the flight duration but also to the landing.

The Gezon component is mainly made of a quartzt envelope inside which is a germanium bar. The envelope is hermetically closed, vaccuum being necessary for the experiment. The component itself is installed in a space oven with other components designed for other experiments.

Quartz is a brittle material with a low resistance to stress (fracture around 4 Hbars). Germanium has the same kind of behaviour and fracture can occur around 1 Hbar. Before any qualification testing, a predictional study was performed to check if specified levels could be dangerous for the component. At this stage the component was modelled as an equivalent beam in flexure vibrating on damped one degree of freedom oscillators, one at both end . The modal synthesis technique was used to built the required kinetic and potential energy expressions from which the equations of the dynamical equilibrium are derived by a variational approach.



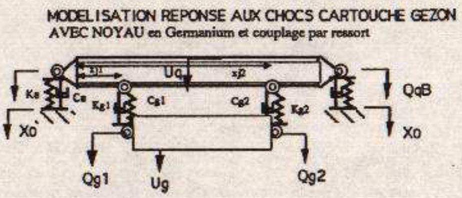
Gezon experiment in random test

From this model the stress level due to bending was found to be critical respectively in the random test (vibroacoustic specification) and in the shock test (shock spectrum spectrum of stage separation specification). During the qualification random test of a Gezon prototype, the envelope effectively broke down due to an accidental overloading of the test sample. The experimental stress level derived from a strain gauge measurement was found in good agreement with what was predicted from the model. The germanium bar was also damaged. The qualification test campaign then stopped.
A more complex model was so built to predict stress inside the germanium as pictured in fig. 12, and to derive instantaneous stress level predictions when applying the shock spectrum test.

USE OF VIBRO-ACOUSTIC PREDICTIVE TECHNIQUES

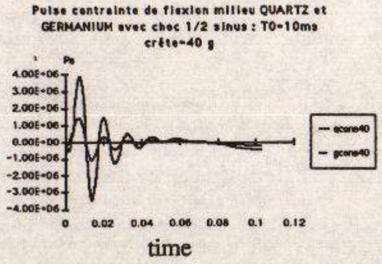
The procedure for such a prediction was conducted as follows :
-first of all, a vibration input time history was computed from the shock spectrum specification for exciting the model;
-then the complex frequency stress/acceleration transfer function between the middle of both the quartz envelope and the germanium bar and the excitation input points , were synthetized using the model of fig.12. Here both the quartz envelope and the germanium bar are modelled as beams in flexure;
-the stress time history is then obtained by inverse Fourier transform of the product of the complex spectra of the input and the transfer functions as shown on picture13 .

The effect of the space oven in the energy path from the excitation input point to the envelope supportages was also investigated in a simplified way by interposing a damped oscillator between the excitation point and the model of Gezon for simulating an oven resonance.
The oven was also modelled by an SEA techniques using the AutoSEA software and the attenuation computed by the SEA model and the previous simulation were compared. The two models lead to the same conclusion : when applying the excitation to the oven, no practical attenuation could be observed in the Gezon component.
In this case the theoretical prediction has helped the designers of Gezon for modifications of the test samples and for negociating qualification levels with the launch vehicle authorities, as these last were found too severe referred to the location of the Gezon experiment.



<u>Picture12</u> Theoretical model of Gezon for transient stress response estimates

<u>Picture 13</u>



Some conclusions

That was here an attempt to review different aspects of the use of predictional techniques in space progams. First the Launch Vehicle Authority point of view which is to give reliable and safety specifications to his Clients but which are necessarily general. Second, the point of view of the Industrialist in charge of the realization of a vital part of the vehicle. Third the point of view of the episodic client who must fly on a spacecraft and who discovers that there are flaws in his design when applying the general specifications. One aspect of the prediction will be here to insure that the specification is not too general, leading in his case to overload his component.

Many other examples could have been choosen, as bargaining on specifications is part of the space business life. But this is because here a one dB increase has not exactly the same meaning as in classical acoustic problems.

References

1. **G.Borello, Alliot, Kernilis**, «Identification of SEA coupling loss factors on a rocket engine», INTERNOISE 91, Sydney
2. **J.Ben Mariem, L.Mebarek, A.Ounadjela**, 1988, «Vibro-acoustic Analysis of Ariane 4 Launcher by a New Boundary Finite Element Method», INTERNOISE 88 pp391-394, STRACO SARL Compiegne
3. **H J P Morand & B Ritchie** "Etudes vibroacoustiques des lanceurs " Colloque prevision du bruit émis par les structures vibrantes CETIM senlis 26-28 mars 1991