ARIANE 5 SOLID ROCKET BOOSTER (MPS) DYNAMIC BEHAVIOUR WITH RESPECT TO PRESSURE OSCILLATIONS

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Abstract

This article describes numerical simulations performed to simulate the dynamic behaviour of the Ariane 5 Solid Rocket Booster (Moteur à Propergol Solide – MPS) excited by internal pressure oscillations. These pressure oscillations have sliding frequencies close to acoustic natural frequencies and changing amplitudes. Because the modal behaviour of the booster is also continually changing during the flight due to propellant burning, predictions with FE modelling (modal analyses, harmonic and transient responses) are necessary to predict and understand the dynamic behaviour of the booster.

1. Introduction to the problematic of MPS pressure oscillations

1.1 The pressure oscillations phenomenon

In Solid Rocket Boosters (SRB), pressure oscillations result of instabilities characterized by the presence of vortexes in the flow. Some configurations of the combustion chamber are favourable to the development of these instabilities:

- the combustion surface of the propellant: the longer the segments are, the stronger the vortexes are,
- the inhibitors located on the top surface of each propellant surface: these rubber inhibitors represent an obstacle to the upstream flow and induce a shear layer between two different gas flows,
- the geometry of the propellant loading: angles between burning surfaces also generate shear layers in the flow.

Efforts can be done to reduce pressure oscillations, but it is not possible to remove them because conditions that generate instabilities cannot disappear.

MPS pressure oscillations occur mainly during the second half of the combustion, in specific ranges of frequencies: some instabilities are continuously generated at any frequency, but the only ones which can be observed and which are critical have a frequency close to the chamber acoustic natural frequencies (otherwise the phenomenon cannot be amplified and sustained). Because the geometry of the chamber is modified during the combustion, both frequencies and amplitudes of pressure oscillations are evolutionary, as shown on the Figure 1. Pressure oscillations are organized in a succession of blasts, linked together as frequency waterfalls around either the first or the second acoustic frequency of the cavity:

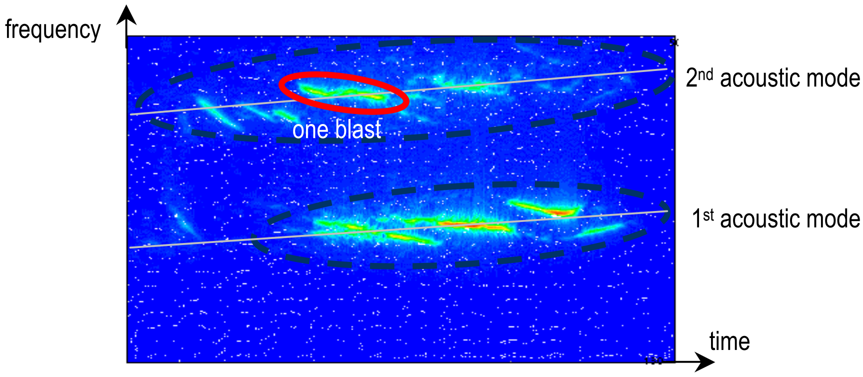


Figure 1: Sliding spectrum on MPS pressure measurement

Some measurement treatments allow to restore both frequency and amplitude evolutions for the different blasts of 1st or 2nd acoustic mode pressure oscillations (frequency evolution shown on Figure 2).

1.2 MPS modal behaviour and resonance risks

The structural eigenmodes of the MPS are depending on both mass and stiffness (including boundary conditions) of the booster. Assuming that the stiffness of the booster does not change during combustion (stiffness of the case not modified), natural frequencies are logically increasing, due to the propellant mass loss. Frequencies of first structural eigenmodes are in the same range than the 1st and 2nd acoustic frequencies, which may produce a high dynamic amplification of the pressure excitation in case of resonance. Most of these excitable eigenmodes are bending modes, mainly in the yaw plane because of the symmetry conditions.

The following Figure 2 presents the evolution of frequencies of pressure oscillations (1st and 2nd acoustic modes) and of structural eigenmodes (bending and longitudinal elongation). It clearly appears that MPS dynamic conditions of the response to pressure oscillations are changing according to combustion time and excitation frequency. It can be even noted that some resonance conditions exist in the bench configuration between 70% and 80% of effective combustion time (t_{cu}) on different blasts of the 1st and 2nd acoustic modes:

- around 77% and 82%, concerning the 2nd and 3rd blasts of the 1st acoustic mode ("B2" and "B3") and the structural mode n°3: the SRB is excited in almost resonance conditions,
- around 69%, concerning the 2nd blast of the 2nd acoustic mode ("B2") and the structural mode n°5: the SRB is excited in pure resonance conditions.

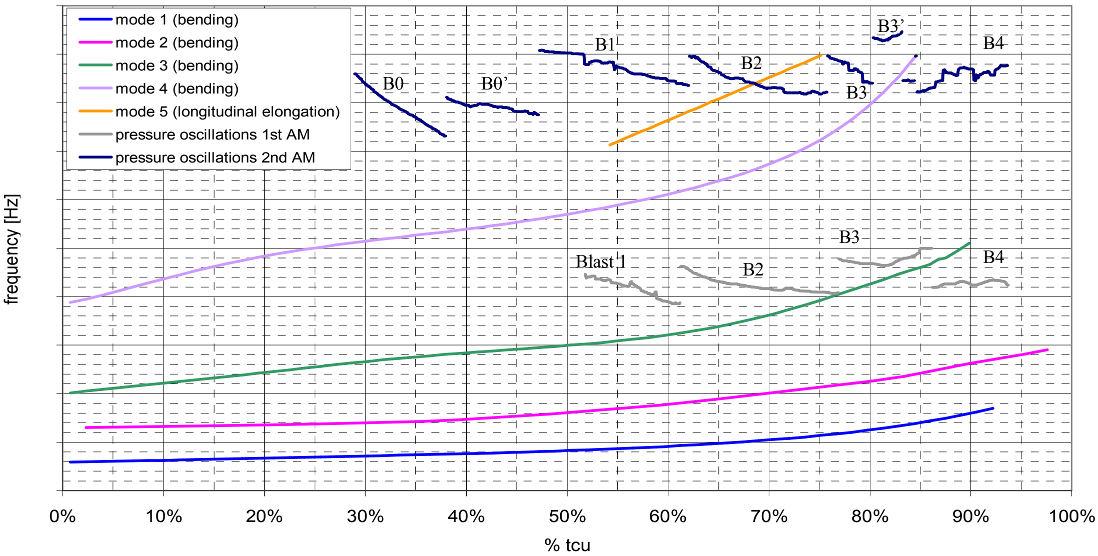


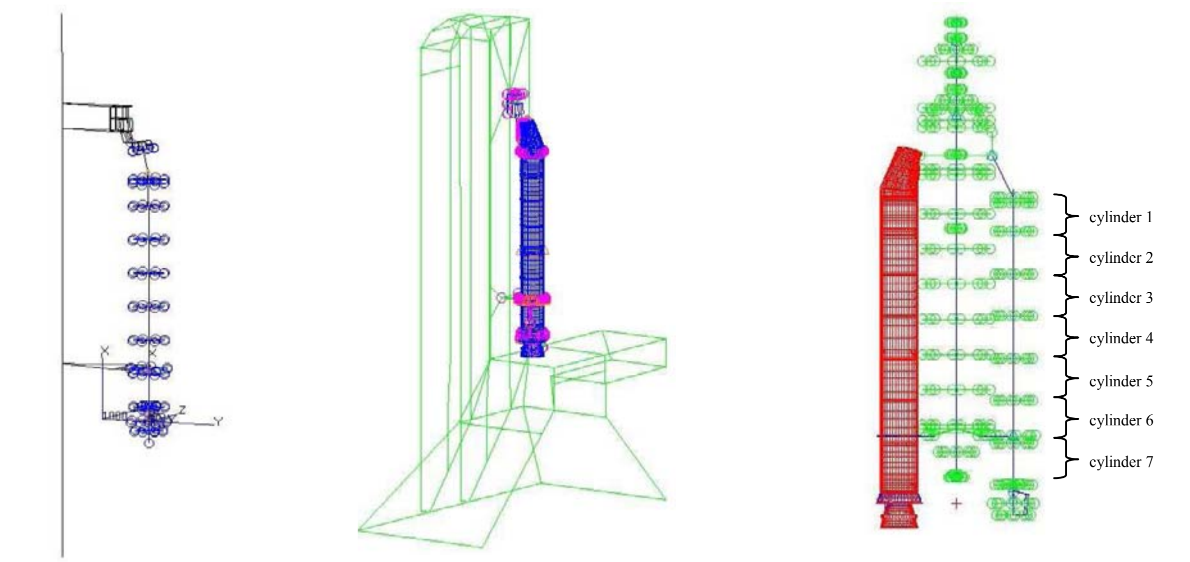
Figure 2: Structural natural frequencies (bench configuration) and pressure oscillations frequencies

These resonance conditions can be problematic for the MPS dynamic behaviour: it is necessary to simulate it finely, firstly to allow correct understanding of experimental observations and measurements and secondly to offer reliable predictions.

2. Finite Element simulations

2.1 Available Finite Element models

In the frame of MPS development, Snecma Propulsion Solide (Safran Group) has developed models of this motor for the account of Europropulsion and CNES. This long lasting study was intended to analyse the thrust oscillation levels measured during the development and qualification phase (from 1993 to 1996), to characterize their expected maximum level and to prepare for the assessment of their impact on the launcher during flight.
Different Finite Element (FE) models have been built with various precision levels. Since the end of the development, these FE models have been used either for flight or test bench exploitation or for further analyses, such as explanation of unexpected behaviour (anomalies) or dynamic predictions in new configurations.



a. MPS beam model in bench (beam model) test configuration

b. MPS 3D volumic model in bench (3D super-element model) test configuration

c. MPS beam and 3D volumic models in flight configuration (beam model for central rocket body)

Figure 3: MPS FE models in bench and flight configurations

Two MPS models exist and can be used either in flight configuration or in test bench configuration:

- the first one is constituted of beam elements ("beam model", see Figure 3.a): this modelling is quite simple (around 300 degrees of freedom) but nevertheless representative in terms of mass and stiffness. The different constitutive elements of the MPS are meshed separately (domes, segments, cylinders, nozzle …), in order to be easily adjustable to structural modifications like for instance the grain overloading of the front segment. The pressure excitation is applied as nodal forces on domes.
- the second one is constituted with shell, beam and hexahedral elements ("3D volumic model", around 120000 degrees of freedom at ignition). This model is much finer than the beam model but logically less simple to be used and modified. The pressure inside the channel is directly applied on all the free surfaces. As a consequence, it is possible to apply a static pressure combined with a "half-sine" pressure wave (1st acoustic mode) or a "sine" pressure wave (2nd acoustic mode) along the channel, like shown on the following figure:

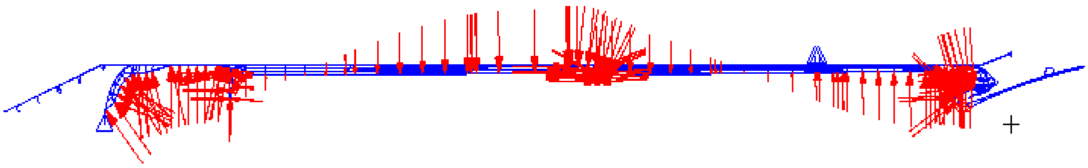


Figure 4: 2nd acoustic pressure field inside the combustion chamber (3D volumic model)

2.2 Simple FE simulations with beam model

Most of the dynamic response simulations are performed with the MPS beam model, either in flight or in test bench configuration. The range of accuracy of this kind of simulation is well known: these simulations, modal analyses and harmonic responses, are only reliable when global dynamic behaviour is expected and when no resonance occurs.
The beam model is used for all the flight exploitations and allows to rebuild with an inverse method the 1st acoustic mode thrust oscillations. All the modal analyses are also performed with this model : because of the simplicity to modify it associated with the reliability of the results, the FE beam model is a very useful and efficient tool.

2.3 Accurate FE simulations with 3D volumic model

However, the MPS beam model is sometimes not accurate enough to simulate specific behaviours such as resonance or local behaviours. In that case, the MPS 3D volumic model is used, because it offers high reliability, even in conditions like resonance where very accurate representativity is required.
Indeed, during one recent test bench firing, very high vibration levels were measured on the case (such high levels had never been registered before), although the exciting pressure levels were quite low. First investigations lead to suspect resonance conditions, which needed to be confirmed by measurements analyses and FE simulations with the 3D volumic model. All the FE model evolutions and the performed simulations allowed on the one hand to validate the model in test bench configuration and on the other hand to explain and to confirm an expected occurrence of resonance phenomenon: the motor has been excited by pressure oscillations practically on its 3rd yaw-bending eigenmode.

2.3.1 Modal behaviour

Many eigenmodes can be tracked by measurement analysis. Some of them can be easily tracked just by computing sliding spectra on vibration signals (Figure 5); for the others it is necessary to use a more complicated method which allows to catch at different times the frequency of the maximal transfer function between vibratory response and pressure excitation, even inside of the time range and frequency range of pressure oscillations (Figure 6).

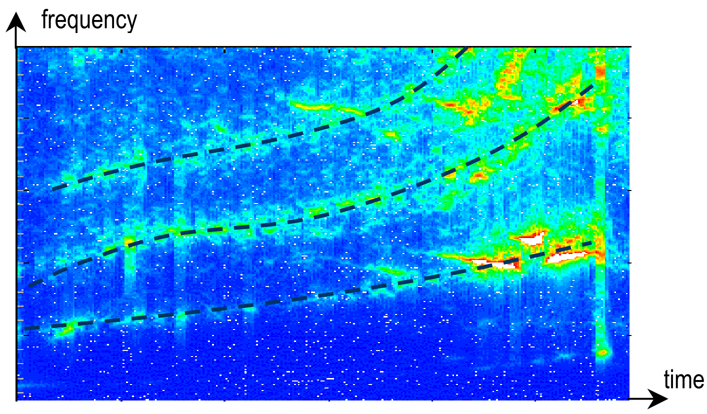


Figure 5: Mode tracking by measurement treatment: sliding spectrum

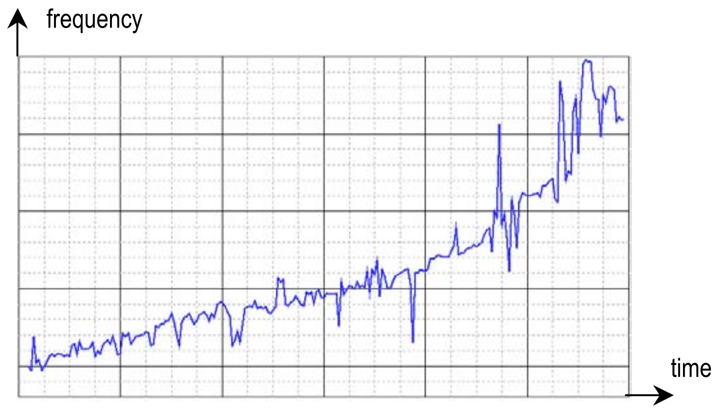


Figure 6: Mode tracking by measurement treatment: sliding maximal transfer function

Thanks to the treatment of vibrations measurements, it is possible to get the modal behaviour of all excitable eigenmodes of the booster.
Concurrently, the modal computation on the FE models (beam or 3D volumic) allows to track the numerical natural frequencies for all the modes at different times of combustion.
Since comparison between experimental mode tracking and numerical computation provides excellent results, the FE 3D volumic model in bench configuration can be considered valid with respect to its modal behaviour:

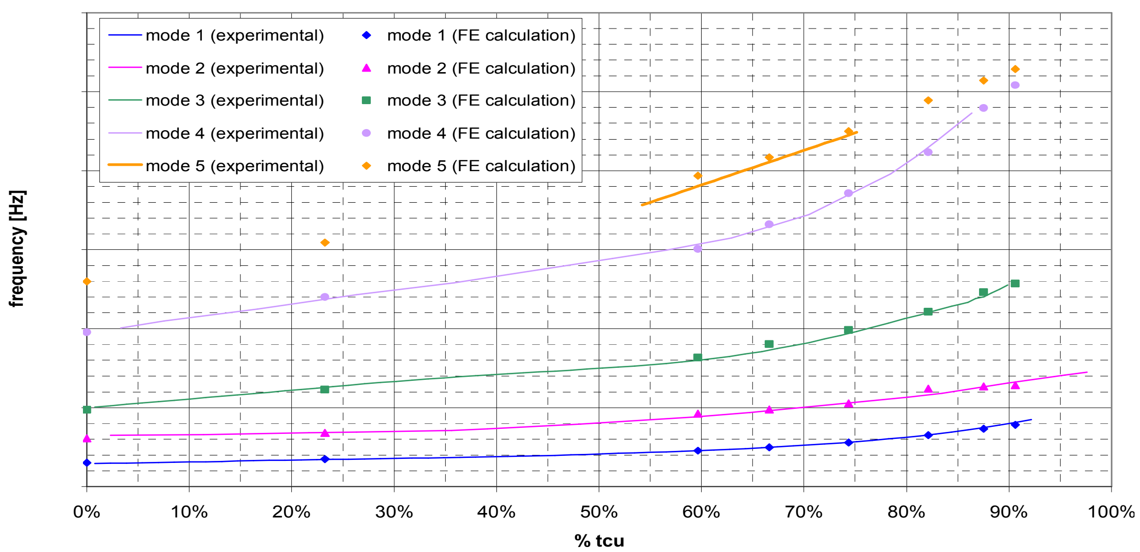


Figure 7: Experimental natural frequencies tracking vs. FE 3D volumic modal computations

2.3.2 Harmonic responses

2.3.2.1 Description

Even if the pressure oscillations frequency is continuously shifting (Figure 2), the evolution is quite slow (around 0.1 Hz/s) compared to the phenomenon frequency. Thus, pressure oscillations excitation can be considered harmonic.
The harmonic response simulation is very interesting when the 3D volumic model is used, because this FE model can be loaded by physical pressure fields on internal free surfaces (Figure 4). To be representative of real pressure oscillations, the pressure field needs to have a good "shape" (meaning a good repartition along the channel) and the correct amplitude. Simulations have been performed on an already burned booster configuration in order to validate the model and the computation method (because many vibration measurements are available and can be used as reference for comparison). Moreover, the real amplitude of pressure oscillations measured at the front dome is used. Indeed, nowadays there is no fully reliable computational tool available to predict the amplitude of pressure oscillations.

There are two different possibilities to define the pressure field of the harmonic pressure excitation. The easiest way is to assume that the pressure field has a perfect half-sine or complete sine shape (regarding the considered acoustic mode). But because the real channel geometry is not exactly a cylinder, this approach may not be completely representative in local cavities between the two main segments or concerning the amplitude ratio between aft dome and front dome. This is why a modal acoustic computation is performed using a finite element model of the cavity. It provides an acoustic field which is quite similar to the theoretical sine shape but which is supposed to be a bit more realistic (Figure 8). First a static uniform burning pressure is applied inside the whole channel. Then the acoustic pressure field at the border cavity/structure is applied as an excitation on the structure internal free surfaces after having been scaled to the front dome measured amplitude. Rigid boundaries are used for this computation, and the cavity mesh stops slightly upstream of the throat area (considering the acoustic impedance at the sonic throat). Some improvements of these simplifying hypotheses have been identified to increase the already satisfying accuracy of the computation.

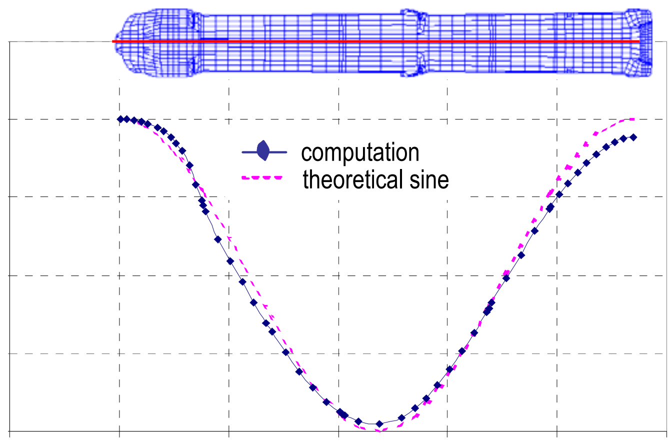


Figure 8: Normalized amplitude of acoustic pressure along the channel

Once the excitation has been defined and applied on the structure, the harmonic computation provides results for vibrations on the case, on the nozzle and associated to interfaces with the central rocket body, which are useful to define the load cases on the whole launcher.

2.3.2.2 Example of simulations

On Figure 2, superposition of pressure excitation blasts on structural natural frequencies reveals that the booster is excited in resonance conditions. Moreover, the analysis of vibratory levels on this booster in bench configuration shows that they are much higher than the ones measured during former test bench despite lower pressure excitation levels.
This typical resonance behaviour appeared due to the shift of natural frequencies in a new configuration of the booster. Indeed, the case cylinder junctions have been modified compared to former design, decreasing the mass and the damping of the case without any major effect on the stiffness. As a consequence, the booster structural natural frequencies have been increased:

- appearance of a resonance on 1st acoustic mode (at about 82 % t_{cu}),
- modification of some crossing conditions with pressure oscillations sliding frequencies and excitation amplitude at resonance (2nd acoustic mode at about 69 % t_{cu}).

These evolutions of the MPS dynamical behaviour can typically be explained and also predicted thanks to FE simulations.

The next paragraphs present the simulations performed on two particularly interesting blasts of 1st and 2nd acoustic modes compared to available measurements.

1st acoustic mode, around 82% t_{cu} (normalized time):

Figure 9 shows vibratory fields calculated with FE 3D model in comparison to experimental results at 82 % t_{cu} for the excitation frequency of pressure oscillations. Even in quasi resonance conditions, the computed vibration repartition along the case (labels of the cylinders available on Figure 3.c) is well representative of the real one. Such an harmonic FE simulation offers very good results, confirmed by the simulations of other blasts of 1st and 2nd acoustic mode.

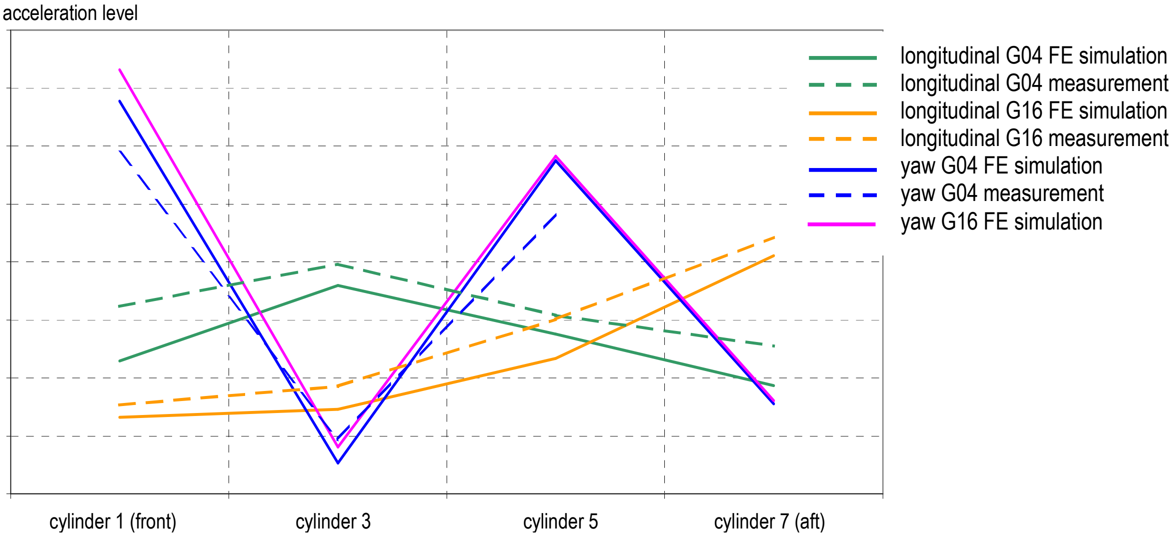


Figure 9: Measured and simulated vibrations in yaw and longitudinal directions (1st AM blast 3)

2nd acoustic mode, around 69% t_{cu} (normalized time):

Because of the modification of crossing conditions between pressure excitation and MPS longitudinal eigenmode (due to the case design evolution), the resonance on the 2nd blast, 2nd acoustic mode has become stronger and more severe. Pure resonance occurs earlier than with the former heavier design of the case (due to the shift of structural natural frequency), at a time with higher induced pressure amplitude (Figure 10). As a logical consequence, maximal vibratory levels are higher.

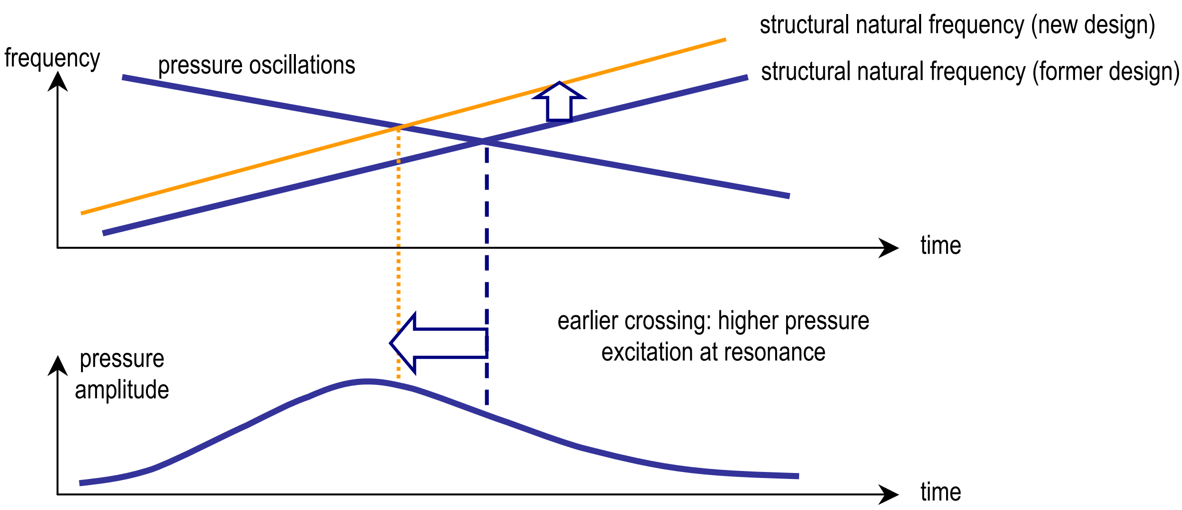


Figure 10: Resonance condition during 2nd AM around 69%t_{cu}

3D simulations are performed for the two case designs (former one and new lightened one) at the measured pressure frequencies in test bench configuration. Modal analysis first confirms the frequency shift due to mass loss. Then the harmonic response to acoustic excitation allows to simulate correctly the dynamic behaviour of the MPS excited by pressure oscillations at resonance: calculated vibratory fields of the MPS case excited by 2nd acoustic mode pressure oscillations are similar to measured ones.

2.3.3 FE model validation and further uses

On the one hand thanks to the modal validation and on the other hand thanks to the very reliable simulations of response to pressure oscillations (1st and 2nd acoustic modes), even in sharp resonance conditions, the 3D volumic FE model has been validated in test bench configuration and is considered as reference. All tasks performed as a follow-up effort to simulate the dynamic behaviour of the new lighter case design allowed to understand new resonance conditions (although the difference with former configuration is very small) and to validate the FE model. It is henceforth available for further accurate previsions of dynamic behaviour and enquiries in case of future potential anomalies in test bench configuration.

The validated FE 3D volumic model is very useful to improve the use of the simpler FE beam model and the understanding of simulations performed with it. Indeed, it can be used to identify and associate the deformed shapes of the eigenmodes calculated with both 3D and beam models and to compare them with the ones computed from experimental measurements.

In flight configuration, the MPS booster is linked to the central rocket body through the DIAS (discoupling device), which is much more flexible than the front bench attachment. For this reason, the dynamic behaviour of the MPS in this flight configuration is specific and different from test bench configuration. Confirmation of the 3D model validity for test bench configuration needs to be updated for the flight configuration.

3. Future prospects

3.1 Improvement of the acoustic harmonic excitation

Modal acoustic pressure fields are calculated in a rigid undeformed cavity. Because in real burning conditions the cavity is deformed due to internal combustion pressure and according to excited structural eigenmodes, it would be preferable to calculate the acoustic modes in a deformed cavity. This would imply to create a new mesh to take into account pressure effects and/or to calculate simultaneously structural eigenmodes and acoustic eigenmodes to evaluate the respective effect of these two parameters.

3.2 Validation of the FE model in flight configuration

Because of specific boundary conditions in flight configuration, the FE 3D volumic model cannot be directly used in the validated test bench configuration. Some improvements have been identified to make it more representative of the real booster, in particular concerning the discoupling device (DIAS) between the MPS and the central rocket body.
Once the FE model will have been modified, it will be necessary to validate it in flight configuration in the same way as it was done for the test bench configuration.
This flight-validated FE 3D volumic model could be used to evaluate the new dynamic behaviour induced by future design evolutions of the booster. It could be also used in the framework of anomalies: very accurate simulations could help understanding unexpected behaviour observed during booster flights (transient phenomena at ignition, pressure oscillations, etc.).
Moreover, predictions of global dynamic environment generated by the MPS combustion could be performed with this FE model for future design of the booster and then be used as an input for global system studies on the whole launcher.

3.3 Transient response simulations

There are many possibilities to define pressure loading in order to simulate the MPS behaviour excited by pressure oscillations. The 3D model is loaded by physical acoustic pressure fields and has been validated with this kind of solicitation in test bench configuration. Nevertheless, the performance of this excitation can be improved:

- acoustic pressure fields are calculated in the cavity, excluding the volume close to the throat and the volume of the nozzle,
- the static pressure which is applied in the channel is uniform,
- acoustic pressure fields are consistent with a simplified approach using a cylindrical geometry for the channel, but no data are available concerning the shape and the amplitude of the pressure field at the aft dome or in the middle-channel cavities to check the accuracy of applied pressure load,
- the harmonic approach with acoustic pressure fields needs to simulate separately 1st acoustic mode excitation and 2nd acoustic mode excitation.

An alternative approach to harmonic computations has been developed to avoid some of the bias listed above: a transient response simulation. The aim is to simulate the dynamic response of the booster excited by pressure oscillations (all acoustic modes merged), with an expected better reliability for the cavity pressure field. Such a simulation has been developed in a Research and Technologies study with a CNES contract. The selected configuration was a flight configuration, because of the reliability of the available computed instationery pressure field, despite the fact that the FE 3D volumic model had not yet been validated in that configuration.

This transient simulation allows to use for the excitation a representative pressure field inside the channel (and no more uniform like in harmonic simulations), containing all the harmonic acoustic components. Vibratory fields on the case and at interfaces between MPS and central rocket body are computed with the FE 3D model. Results are available as transient signals and are compared to experimental data, after specific frequency treatments. The following Figure 11 presents spectra for the calculated vibratory signal and measurements for cylinder 5 at the time chosen for the simulation (around 69 % t_{cu}):

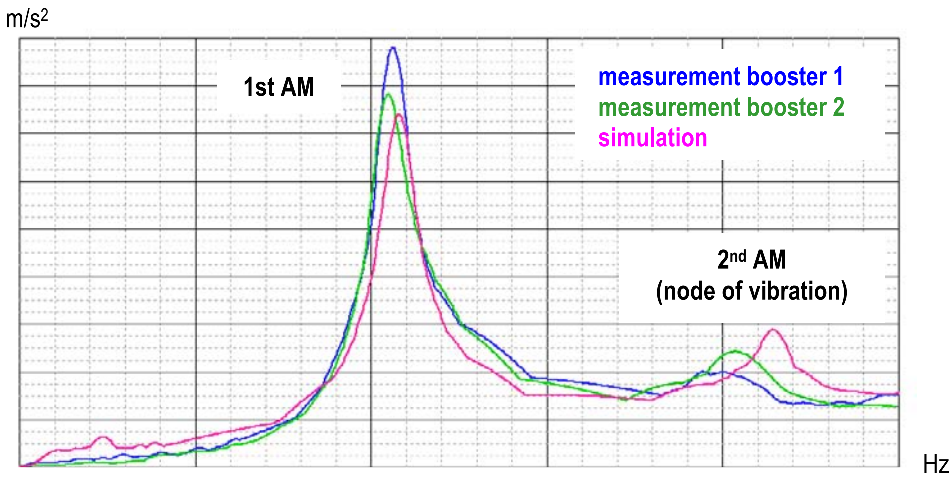


Figure 11: Spectrum of calculated and measured vibration signals

The performed transient simulations are very encouraging with this example: both vibration levels and peak frequencies (more or less for 2nd acoustic mode) are representative of the flight measurement. Nevertheless, some imperfections still exist in this kind of simulation and need to be improved:

- it is necessary to calculate completely the instationary flow inside the cavity for each time of combustion when pressure oscillations of any acoustic mode occur. Because these computations are very long, all blasts cannot be calculated.

- computed signals along the channel applied on internal free structure surfaces need to be very representative in terms of frequency, otherwise they could modify real resonance conditions: a shift of one Hertz on a 2nd acoustic mode frequency will dramatically reduce the reliability of dynamic simulations at resonance.
- nowadays, totally reliable predictions of pressure oscillations are not possible: the example here above was chosen because it was representative (for the 1st acoustic mode), but in many situations, existing simulations do not provide enough accuracy (for instance, the frequency is not accurate enough here on the 2nd acoustic mode).

3.4 A dynamical approach to balance the lack of reliability of the previsions of pressure excitation

Various methods have been developed and validated to simulate the dynamical behaviour of the MPS excited by pressure oscillations. In order to deal with the lack of reliability of pressure excitation previsions, it would be very useful to perform some sensitivity studies to identify the effect of occurrence time and frequency of pressure oscillations (amplitude is not necessary because the FE models are linear) on the MPS dynamic behaviour (transfer functions). Such analyses could indeed point out the critical excitation conditions in terms of dynamic behaviour, and calculate the associated most critical dynamic response for a normalized pressure amplitude. Nevertheless, amplitudes of pressure oscillations are necessary to quantitatively predict vibration levels.

4. Conclusions

Many tools and simulations methods have been developed by Snecma Propulsion Solide (Safran Group) for the account of Europropulsion and CNES in order to simulate correctly the dynamic behaviour of the MPS excited by internal pressure oscillations.
Different FE models are available depending on the accuracy required for analysis (beam model, 3D volumic model) in flight or test bench configuration. Some improvements of the finer 3D model need to be achieved to complete its validation in flight configuration, already acquired in test bench configuration.
Harmonic responses are performed after a modal acoustic pressure field computation, which is used afterwards as the excitation for the structural FE model. Even if all the identified improvements have not been implemented yet, this simulation is sensitive to slight evolutions of design and provides very good results, even in resonance conditions.
In order to improve the representativity of the pressure excitation, a transient method has been developed. The pressure field is obtained from an instationary flow computation: it should allow to have a more physical pressure repartition inside the cavity than with the acoustic computation. Moreover, excitation signals also contain all acoustic harmonic components. Results are very encouraging but are very sensitive to the precision of the pressure excitation.
Validated FE simulations (both harmonic and transient) of the MPS dynamic behaviour could be very useful in the framework of future dynamic studies on the whole launcher: the MPS dynamic behaviour would be simulated with the FE 3D model in the validated flight configuration (with the simplified central rocket body FE beam model), and the induced dynamic environment computed at interfaces with the central rocket body would be an input for global system studies on the whole launcher performed by the launcher architect.