SHOCK PROPAGATION IN SPACECRAFT STRUCTURE

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OVERVIEW

During launch and deployment operations, a spacecraft is exposed to shocks that may be dimensioning for some pieces of equipment or subsystems. Shock specifications have to be issued even at early phase of programmes. Defining rules able to derive a shock specification at the source to shock specification for equipments with simple hypotheses is thus very valuable. This is the primary objective of this study co-funded by Astrium Satellites and CNES.

A method based a simple description of the structure and on several parameters such as location, local loading and proximity with interfaces proved to be inadequate. As a consequence it has been decided to simplify the approach and to define shock environments on spacecraft main substructures, defined by global geometrical zoning. The aim was to define global attenuation rules for generic substructure such as external walls, lower floors,… This has been done for different shock sources and different types of spacecraft with a final harmonisation to be as generic as possible with the main constraint of remaining conservative. A systematic evaluation of margins reached by such a method has also been conducted.

The difference between attenuation rules in Structural Model and Flight model has been tackled: Structural Model of generic spacecraft has proved to have a lower attenuation than Flight Model due to lack of cabling and lack of representativeness of generic payload.

Finally internal shock problematic has been treated separately as such shock levels have mainly a local impact. The concept of shock propagation path is hence simple and objective allowing the single parameter of distance to be directly used. In this frame, shock test at system level results have been compared with generic propagation rules such as NASA rules.

1. 1ST METHOD: ATTENUATION DRIVEN BY PHYSICAL PARAMETERS

1.1. Objectives

The idea was to build a shock prediction tool for early phase specification based on a simple description of the structure.

A detailed study of shock propagation in a Telecommunication spacecraft structure with more than 300 measurements distributed among four shock tests (Clampband release, Shogun, Ariane 5 Fairing separation and Ariane 5 VEB separation) has allowed to define several macroscopic parameters potentially useful to evaluate shock level for a given equipment:

- global zone on the structure (zoning);
- precise location on the substructure (sub-zoning);
- local loading of the supporting structure (non-loaded zone, local loading < 10 kg, local loading > 10 kg);
- proximity with interfaces.

The mean value (in term of SRS) was then calculated to affect a single shock environment to a single set of parameters. Attenuation was finally computed by SRS ratio over the frequency band 100-10000 Hz.

1.2. Limitations

Such a method proved to be inadequate for two main reasons:

- Despite a huge amount of data, is was not possible to determine the effect of a single parameter variation, either by lack of data or because contradictory phenomena were observed.
- Such a kind of parameters, though they are macroscopic, may be unavailable at early stage of a satellite programme as layout may not be frozen.

An example of dispersion for a set of accelerometer in a very small area and corresponding to a single set or parameters is given in FIG 1: the difference between those measurements reaches a factor 4 at some frequencies.

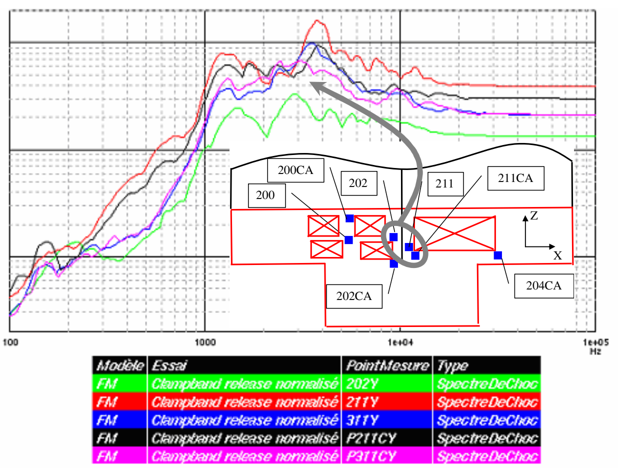


FIG 1. Shock levels dispersion for a single set of macroscopic parameters

Another observation that prevents from establishing some propagation rules with macroscopic parameters is given in FIG 2. In this case the propagative behaviour depends on frequency:

- Below 1 kHz the behaviour is the same on two symmetric measurements independently for the two shock tests.
- Above 1 kHz the behaviour differs between the two symmetric measurements but is very similar for a given location between the two shock tests (Shogun and Clampband release).

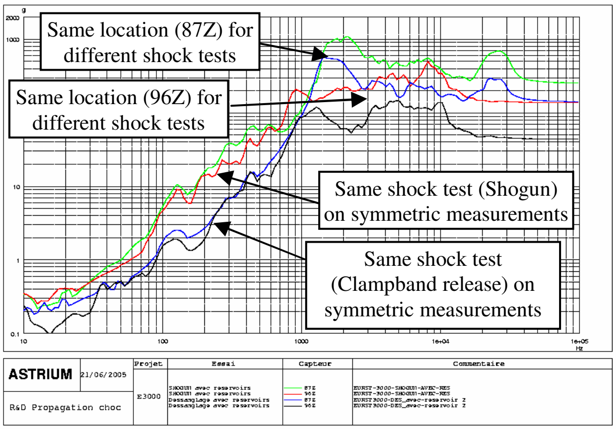


FIG 2. Difference in propagative behaviour wrt. frequency

Such dependence of propagative behaviour with frequency is not precisely understood and hence not taken into account in the definition of the macroscopic parameters that should enable an evaluation of shock levels using a global description of the structure.

These examples show that such an attempt to define a propagation rules from the source to equipment foot by defining macroscopic parameters is unsuccessful. As a consequence another method needs to be defined.

2. 2ND METHOD: ATENUATION BY MAIN SUBSTRUCTURES

2.1. General methodology

Following the evidence of difficulty in defining shock propagation by macroscopic parameters, it has been decided to simplify the approach. The objective is to define attenuation through a zoning of the structure as generic as possible.

For instance the question is whether it is possible or not to define a generic attenuation for an external wall or a lower floor of a spacecraft.

2.2. Attenuation computation

Attenuation are computed by means of SRS ratio between response and S/C interface. S/C interface levels are considered as the mean value of measurements with two different assumptions, leading to two sets of shock attenuation:

- taking into account both longitudinal and lateral levels leading to the following attenuation:

(Eq1) $$Att_{AllDir} = \frac{\gamma^{eqpt}}{Mean\left(\gamma^{I/F}_{Longi}, \gamma^{I/F}_{Lat}\right)}$$

- taking into account only longitudinal levels as it has been seen previously that this could partially take into account the particular case of Clampband Relaease for which lateral levels are fast vanishing; this leads to the following attenuation:

(Eq2) $$Att_{LongiForAll} = \frac{\gamma^{eqpt}}{Mean\left(\gamma^{I/F}_{Longi}\right)}$$

All attenuation have been computed using these two references. However all results presented in this paper are using the first reference (mean levels of both longitudinal and lateral levels) as it is the most common one.

All attenuation are then simplified to avoid sharp evolution and keep only the global variation. A specific algorithm has been developed to reach this objective. An example of such a simplification is given in FIG 3.

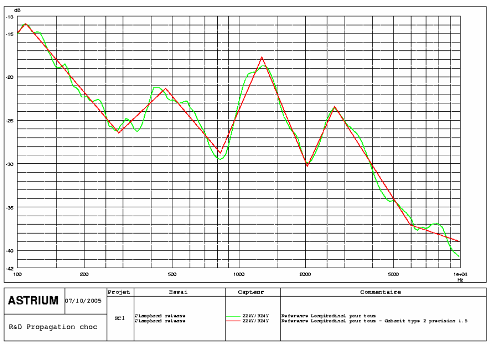


FIG 3. Simplification of attenuation vs. frequency functions

2.3. Validation principle

All attenuation rules have been evaluated in the same manner to establish the intrinsic margin resulting from the method.

This validation consists in comparing for each measurement the original SRS to its reconstruction resulting from the product of the associated attenuation function by the input levels at S/C interface :

(Eq3) $\gamma_{Source}^{eqpt} = Att_{Source}^{Ss-Structure}(AllDir) \times \gamma_{Source}^{I/F}(AllDir)$

(Eq4) $\gamma_{Source}^{eqpt} = Att_{Source}^{Ss-Structure}(LongiForAl) \times \gamma_{Source}^{I/F}(LongiForAl)$

Margins are calculated between the reconstructed levels and the enveloppe of the considered measurements.

The principle of this validation in explained in FIG 4.

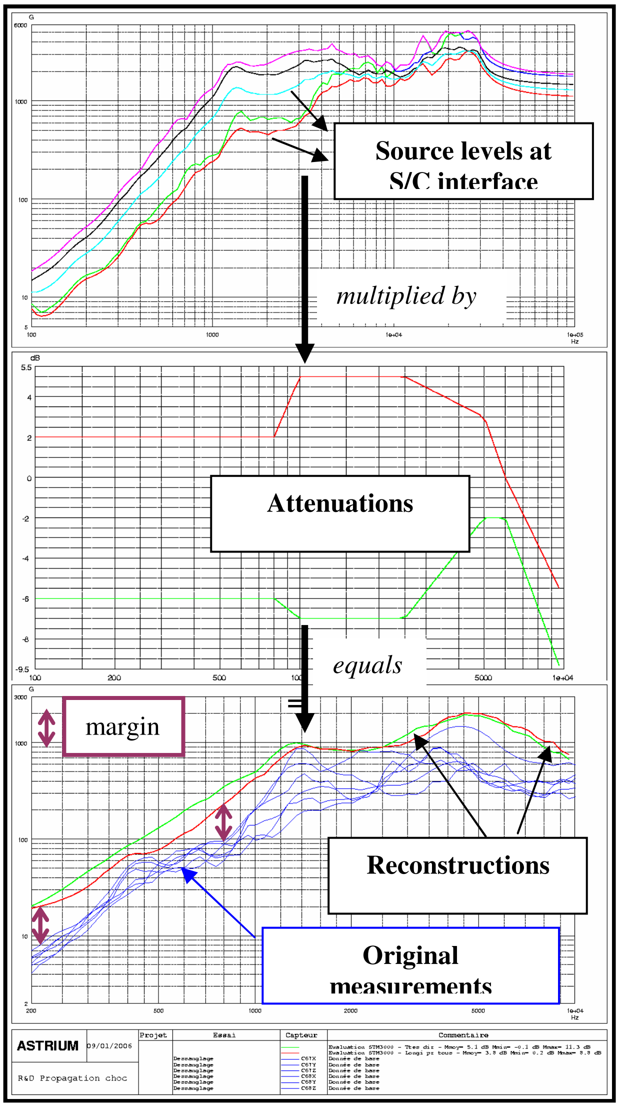


FIG 4. Method validation principle and margin calculation

2.4. Particular case of internal shocks

Internal shocks are generated mainly by release mechanisms. They have to be treated in a different way than shock coming from spacecraft interface for two main reasons :

- The source is rather punctual and induce in a more concentrated zone.
- The shock usually presents a main direction collinear to the release direction. This anisotropy is a specificity compared to shock coming from spacecraft interface.

This part of the study has focused on propagation laws based on distance as the zone of interest is usually limited to the substructure supporting the release mechanism. A first analysis has compared the test results with already established laws such as Nasa rule (coming from Lockheed-Marietta database) :

(Eq5) $$\boxed{att = \exp\left[\left(-8.10^{-4}.f^{\left(2,4.f^{-0,105}\right)}\right)d\right]}$$

A second step has consisted in evaluating the attenuation by ranges of distance between the source and the measurement point. This approach by distance ranges is interesting because it is compatible with the few information available at early phase of a programme. Two different ways to compute attenuation have been used:

- The first one consists in evaluating the mean attenuation over the available data.
- The second one consists in evaluating the attenuation producing the highest environment to get the dimensioning shock level.

3. ATTENUATION RESULTS

3.1. Treated data

3.1.1. External shocks

For external shocks, a very high number of test data have been treated to cover all the following aspects:

- different types of shock sources : Clampband release, Shogun, launcher induced shock, ASAP5 separation shock (for microsatellites) ;
- different types of bus : big telecomunication spacecraft, Spot-like observation spacecraft, microsatellites.
- for a given structure, different spacecrafts with same architecture and their generic structural model.

These data have been treated separately with the process explained above for attenuation calculations and simplification. This zoning procedure based on test data has then been adapted to be as generic as possible wrt. to the previously described criteria: studying these test data as a whole data package, similarities between attenuation levels and frequency dependence have been looked for to determine generic attenuation rules.

The resulting groups of attenuation were subdivided using the following criteria :

S/C class	Big spacecraft		Microsatellites
Substructures	Floors Shear Walls Central structure External walls		Lower floor External Walls Upper Floor Payload floor
Shock source	Clampband release	Shogun	S/C separation

TAB 1. Attenuation rules subdivisions

For big spacecraft, another subdivision stage has been added compared to TAB 1: each substructure subdivision was split to be able to better represent the attenuation variation over big spacecraft structure. The different categories resulting from this supplementary subdivision are presented in TAB 2, and further explained when necessary.

	Clampband release	Shogun
Floors	Floor in lower part, very close to launcher interface Floor at lower or intermediate height Particular case of a floor at lower or intermediate height with a direct tight mechanical link with launcher interface ring Floor in upper part	First floor from launcher interface Second floor from launcher interface Third floor from launcher interface
Shear Walls	*No subdivision*	*No subdivision*
Central structure	Lower part Upper part	Lower part Upper part
External walls	Walls located in S/C lower part Walls located in S/C upper part	Walls located in S/C lower part Walls located in S/C upper part

TAB 2. Second stage subdivisions for big spacecrafts attenuation rules

For floors in the case of a Clampband release source, these categories are:

- Floor in lower part, very close to launcher interface (called later PH-D-1). This is typically the case of a floor located at a dozen centimetres form the launcher interface. Clampband release levels, which drastically decrease when moving up in the structure show hardly any attenuation.
- Floor at lower or intermediate height (called later PH-D-2). These floors are globally located in the lower part of the S/C (not at its top). Levels show an important attenuation but still show important components in high frequency.
- Particular case of a floor at lower or intermediate height with a direct tight mechanical link with launcher interface ring (called later PH-D-3). This is typically the case of a floor linked to the central structure by struts arriving very close to the launcher interface. These struts facilitate the shock propagation in the longitudinal axis resulting in high response levels in this single axis. For in-plane response, previous case PH-D-2 should be used.
- Floor in upper part (called later PH-D-4) : these floors are located at the top of the spacecraft structure ; they present very attenuated levels especially at high frequency.

For central structure in both case of a Clampband release or a Shogun source, these categories are:

- Central structure lower part (called later TUB-D-1). The main point is to be located before (along the main propagation path) a floor that cuts the central strucutre. Thus a monolithic central structure is in this category whatever its dimension is.
- Central structure upper part (called later TUB-D-2). The main point is to be located beyond (along the main propagation path) a floor that cuts the central strucutre. Levels are there highly attenuated.

For external walls in both case of a Clampband release or a Shogun source, these categories are:

- Walls located in S/C lower part (called later MUR-D-1). This external wall is located below any horizontal floor.
- Walls located in S/C upper part (called later MUR-D-2). This external wall is located above the first horizontal floor.

3.1.2. Internal shocks

For internal shocks study, the used data were coming from five different flight models of telecommunication spacecrafts of different size and configuration. Several types of sources were considered, either pyrotechnic or not, used on different types of deployable subsystems (solar arrays, antenna reflectors). All considered measurements points were located on the panels supporting the shock source or on neighbouring panels.

The zoning has been made by distance ranges from the source.

3.2. Example of results

As it is not possible to present all the obtained attenuation rules in this paper, some examples are presented for each category to show an order of magnitude of what is achievable when trying to build generic attenuation rules.

3.2.1. Case of big spacecrafts

The attenuation obtained for horizontal panels (also called floors hereafter) in the case of a Clampband release shock are presented in FIG 5.

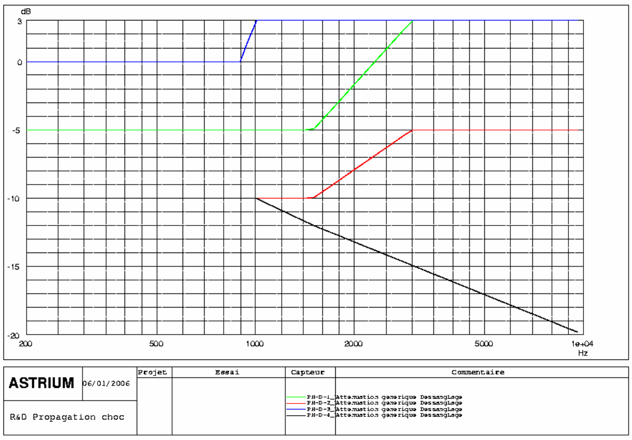


FIG 5. Attenuation for horizontal panels in the case of a Clampband release shock

The attenuation obtained for horizontal panels in the case of a Shogun shock, representative of launcher induced shocks, are presented in FIG 6.

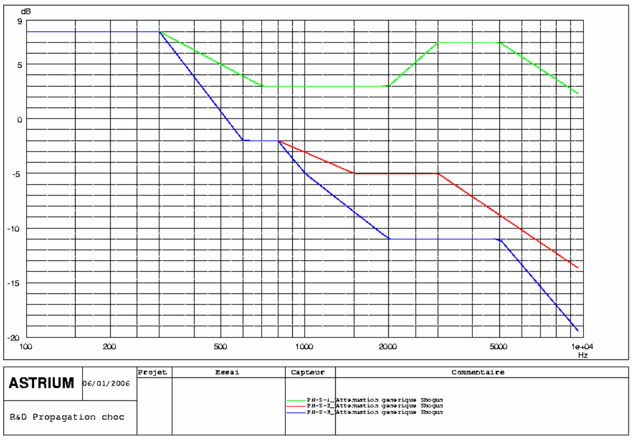


FIG 6. Attenuation for horizontal panels in the case of a Shogun/launcher induced shock

These two examples show that the distinction between the two kind of shock sources is absolutely necessary.

The validation process presented in 2.3 has allowed to compute margins resulting from this global attenuation rules. These margins are given between the reconstructed levels using the proposed attenuation rules and the **envelope** of the considered measurements. This means that this margin is a minimum margin wrt. possible shock levels on the considered area.

The margin associated with the example of the horizontal panels (floors) presented above are given in TAB 3. Mean margin is the mean margin over the considered frequency band (100 Hz – 100 kHz). The maximum (resp. minimum) margin is the maximum (resp. minimum) margin measured at a single frequency over the considered frequency band.

		Telecom S/C	Observation S/C
1st floor	Mean margin (dB)	7.2	4.5
	Maximum margin (dB)	14.0	8.6
	Minimum margin (dB)	-0.4	0.6
2nd floor	Mean margin (dB)	5.8	3.2
	Maximum margin (dB)	10.7	8.8
	Minimum margin (dB)	-0.2	-2.2
3rd floor	Mean margin (dB)	NA	2.8
	Maximum margin (dB)		6.4
	Minimum margin (dB)		-1.1

TAB 3. Margins between reconstructed levels and measurements envelope for horizontal panels in the case of a Shogun/launcher induced shock

The reconstructed environment and the associated margins may be seen in FIG 7 in the case of 1st and 2nd floors for a Shogun input.

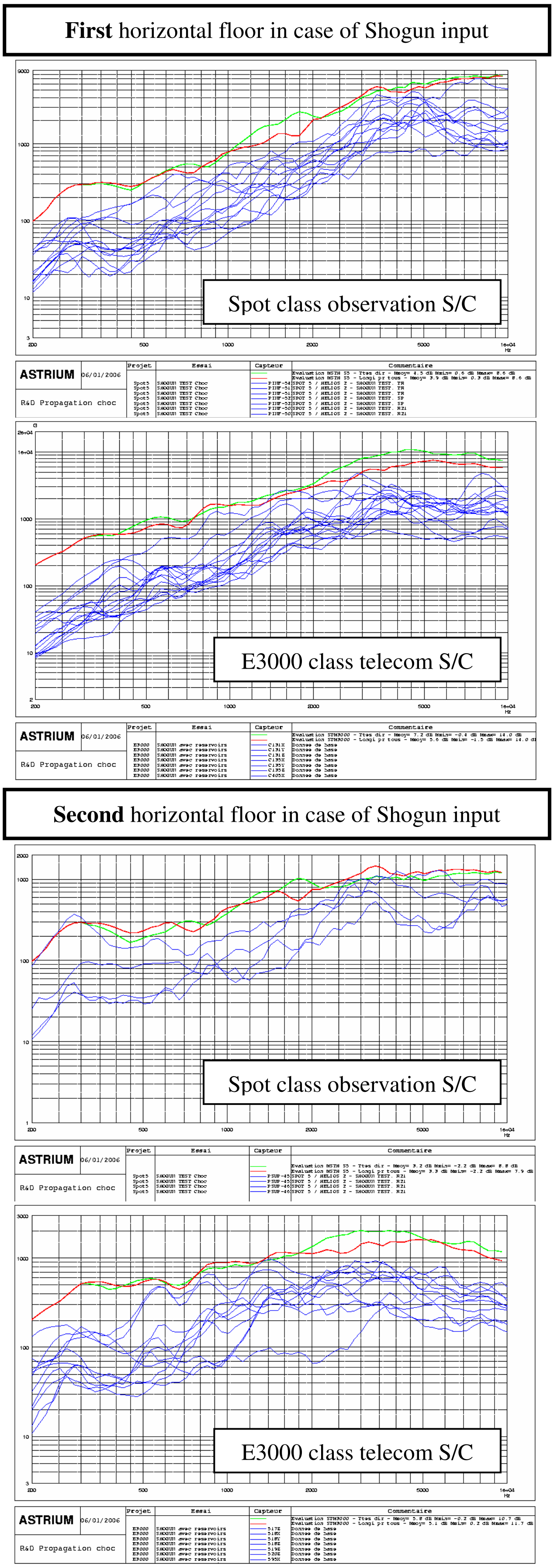


FIG 7. Attenuation rules validation for floors (Shogun)

The entire study has shown that this method has lead to the following margins with respect to maximum measured shock environment :

- mean margin about 6 dB
- maximum margin about 12 dB
- Minimum margins about -1 dB.

No margin policy has been applied here and these margins are inherent to the method which tries to derive generic attenuation. Thus such an order of magnitude in margin is the price to pay for having generic rules to derive shock by standards attenuation rules. Nevertheless these rules have been computed using a mean value at the launcher interface. Launcher specifications are usually based on envelope levels. This means that using these attenuation rules applied on a launcher specification will contain an additional hidden margin equals to the difference between the mean and maximum levels at launcher interface, which is evaluated at 1 to 3 dB. Thus no additional margin is really needed.

3.2.2. Case of microsatellites

The attenuation results for the external walls and for the upper floor and payload floor are presented in FIG 8 for both Flight Model and Structural Model.

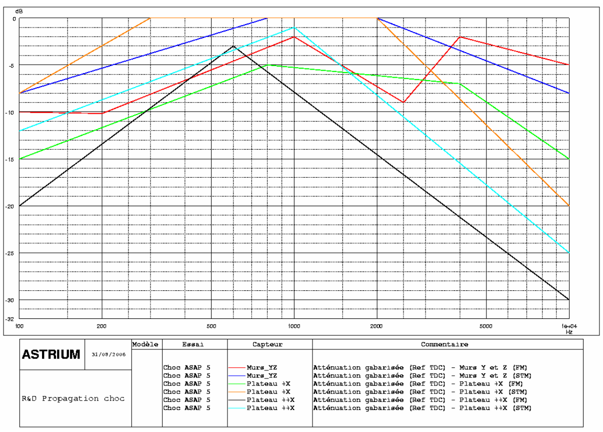


FIG 8. Attenuation rules for microsatellites substructure

The case of Lower Floor is not presented on this figure as it has shown no attenuation because of both the stiffness of the assembly spacecraft interface / lower floor and because its proximity with the shock source.

A high dispersion has been observed between the different external walls. As a matter of fact, the loading of these panel may differ in a wide extent. Moreover the effect of the loading by equipments is very sensitive on such a very small bus, as mass of equipment may be very important with respect to structure mass.

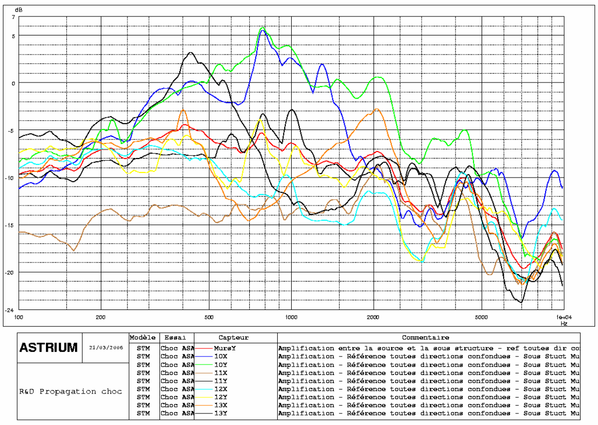
This dispersion is shown in FIG 9 which presents the SRS ratio between the measured data and the source levels on the STM external walls.

On such a small structure the obtained margins are in the following order of magnitude:

- mean margin about 6 dB
- maximum margin about 15 dB
- Minimum margins about -0.5 dB.

They are comparable with those obtained on the big spacecrafts, even higher for the maximum margins, which means that the dispersion is not lower but even higher on small structure.

SRS ratio for the different measurement points located on external Y walls



SRS ratio for the different measurement points located on external Z walls

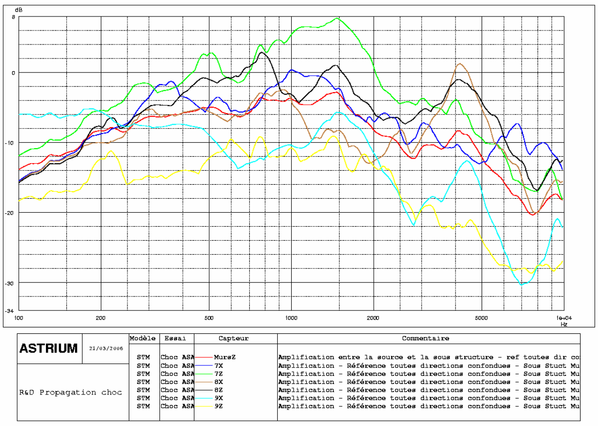


FIG 9. Dispersion in attenuation (SRS ratio) in microsatellite external walls

3.2.3. Case of internal shocks

The proposed attenuation rules are based on a zoning related to distance to the shock source, with discontinuous distance band compared to other rules using continuous definition of shock attenuation. The attenuation presented hereafter in FIG 10 may be used to define a maximum expected environment.

The following observations have been made:

- At very short distance (up to 20cm), attenuation is limited and does not really depend on the frequency No more than 2 to 3 dB in attenuation may be expected compared to the source levels.
- In a medium distance band (30-40 cm) attenuation is widely increasing over the entire frequency band. This increase is faster than what is predicted by NASA/ESTEC rules (see below).
- Finally attenuation is not monotonic wrt. distance which differs from what is said by NASA and ESTEC rules. Some frequency bands may show local reduction of the shock attenuation. In the case studied here such an decrease of attenuation was very often observed around 5 kHz.

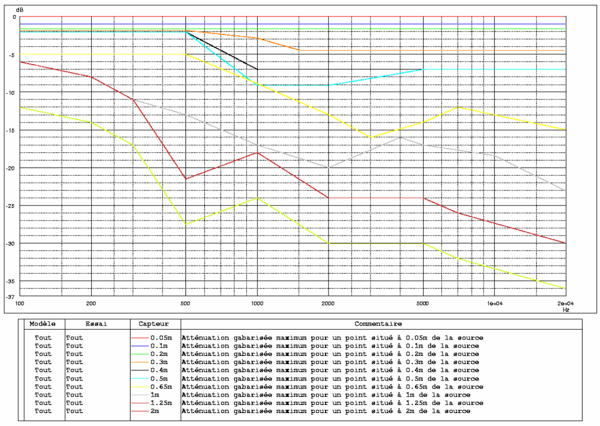


FIG 10. Attenuation rules by distance band for internal punctual shock source

The consistency with the already existing NASA or ESTEC rules using the distance criteria has been studied. FIG 11 presents the mean attenuation (i.e. the attenuation giving the mean measured level) over the entire studied dataset compared to NASA standard rule as given in 2.4 (Eq 5).

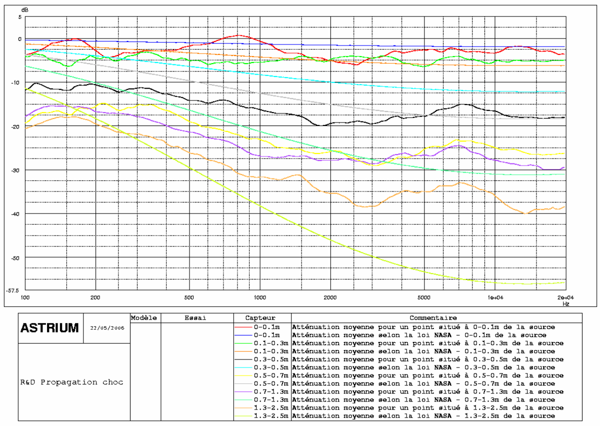


FIG 11. Comparison between mean attenuation on panels coming from spacecraft test data and NASA rule wrt. distance

This comparison has shown that:

- At short distance (from 0 to 0.8 m) NASA rules are rather conservative which means that attenuation is usually underestimated. However some local (in frequency) exceeding are often encountered.
- Beyond 80cm from the source attenuations given by NASA rules correspond to what is observed on the treated data at low frequency but are really overestimating the test data: up to 2.5m from the source, no more than a 40dB attenuation is measured compared to 65dB given by NASA rule.

3.2.4. Difference between flight models and structural models

This study has allowed to use test data from Structural Models and Flight Models. The comparison between these data has shown that the corresponding shock attenuation may differ in a wide extent, especially when the considered STM corresponds to a STM of a generic platform with low representativeness of payload layout.

The presented results are resulting from the comparison between the Structural Model of a telecommunication bus and some corresponding flight models. The data that have been treated in this frame only concern Clampband Release as this is the only test available for Flight Models.

For structure close to the shock source or directly linked to it (central structure, lower floor), no significant difference has been found out. However for structures far from the shock source such as external walls or upper floors the difference may be important. The attenuation calculated from the measured shock data are presented for this latter case in FIG 12.

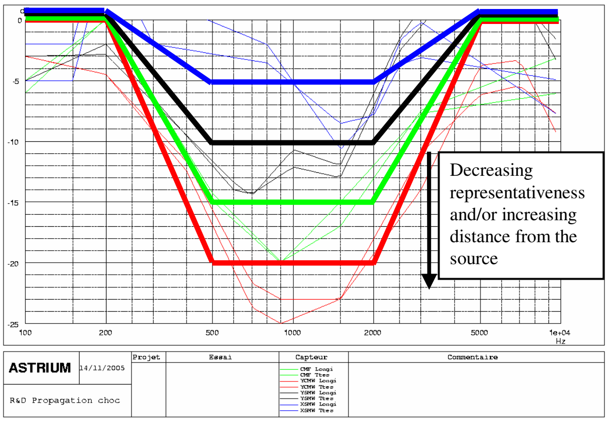


FIG 12. Ratio between the shock attenuation of a generic Structural Model and the shock attenuation of some associated Flight models

Attenuation is higher for Flight Models as such a generic Structural Model is not equipped with some elements that bring attenuation in the structure at high frequencies such as cabling. Moreover the bus and payload equipment are represented by big dummies not really representative of equipment footprints and stiffness.

The difference is shock attenuation between Structural Model and Flight models is low (and can be considered as not significant) in very low frequency (< 200 Hz) and in very high frequency (> 5 kHz). However in the frequency band 500-2000 Hz the influence may be high. The difference increases with on the lack of representativeness of the Structural model and/or with the distance of the source, reaching values up to 20dB.

For Structural Model of unique spacecraft its representativeness is usually really better and such differences in shock attenuation between Structural Model and Flight Model is expected to be really lower.

4. CONCLUSION

This study is based on exploitation of a very wide database of shock tests: telecommunication spacecrafts, observation spacecrafts, microsatellites, Structural Models, Flight Models, different types of shock sources,…

It has shown that defining shock levels through propagation rules based on a limited number of macroscopic parameters is very difficult: different behaviours always appear for a single set of parameters thus claiming new parameter and finally making each measurement a particular case. This way has be abandoned.

A simpler approach consisting in defining shock attenuation on main spacecraft substructures has been proposed. The objective is to produce attenuation bringing the maximum expected environment on a given substructure, as much applicable to different spacecrafts and platforms as possible. This approach leads to mean margins over the frequency band about 6 dB and maximum margin of at least 12 dB. Such a margin has been computed with respect to the maximum shock environment measured on the substructure, which means that these margins are minimum and that for many locations of the substructure it is in fact greater than these figures. This is the consequence of the high dispersion in shock levels over a given substructure.

As a conclusion defining a shock environment from scratch is still a very tough job bringing some high values of margin in order to be conservative. As a consequence using similarities with existing spacecraft should always be preferred to evaluate shock environments in a new platform.