NON-LINEAR DYNAMICS ON SPACE STRUCTURES AT LOW FREQUENCIES

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OVERVIEW

Due to continuous improvement and speed up of spacecraft structure design and tests, analyses have to be more and more accurate to facilitate the global development process. Thus, to provide sharp results in shorter time, complex issues like non-linear phenomena have to be treated at spacecraft level in order to use less numerous and more complete analyses. Non-linearities may be due to unintentional phenomena such as gaps between mechanical elements or intentional ones such as dampers for instance.

In the frame of the DYNOLI R&T co funded by CNES, EADS Astrium Satellites performs a study aiming at determining a method to treat mechanical non-linearities at spacecraft level.

After a global trade-off performed on different market software tools, a method has been selected then adjusted by testing it on more and more complex cases. Current results show that in spite of numerical difficulties, a global non-linearity treatment at full-size spacecraft scale is possible.

1. CONTEXT

Because of always sharper results requests in every kind of mechanical analyses, non-linearities have become a breaking point in the global mechanical process.

1.1. Current methods to deal with non-linearities

Today, two main methods are used to deal with non-linearities. The first one consists in an accurate local study. Traditionally performed with non-linear dedicated software tools, these analyses request time and energy to convert, refine and adapt local models for specific software needs. Once this first step is done, a link has to be achieved between data available at spacecraft level in the default software tool and data coming from local non-linear complex model. The second method consists in dealing with the non-linearity directly at the spacecraft level, which means with the linear software program. Obviously, this last method is faster than the first one but also much less accurate. There are different variant forms of this method. This goes from the simplest one, which consists in a brutal linearization of the non-linearity, to the most sophisticated one, which consists in iterating to find the adapted [Force-Displacement] couple at each frequency step. Anyway, none of these methods is fully satisfying. They have been developed to overcome software and hardware limitations. But both have achieved clear improvements these last few years and these limits might be no more up to date.

1.2. Different kinds of non-linearities

Some non-linearity kinds have always been present in spacecraft hardware; these are the not wanted ones. For instance, this may be due to gaps between mechanical pieces On the contrary, other kinds of non-linearities are wanted for different purpose. Typically in space structures, this is the case for dampers which aims at minimising disturbances coming form vibrations or shocks by using non-linear properties.

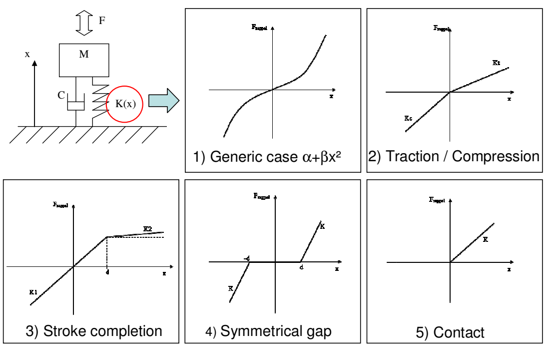

FIG 1. Elementary test cases

In the frame of the current study, a few representative elementary non-linear cases are selected in order to be used while testing different available software. These simple cases consist in elementary mass-spring-damper systems in which parameters are chosen to be representative of real spacecraft cases. In those ones, non-linearities are introduced in the dependence between force and displacement.

2. METHOD SELECTION

The first step of the method selection process consists in evaluating the different available software with their different used methods.

2.1. Software programs evaluation

Four different software tools are tested: MSC NASTRAN, MSC MARC, ABAQUS and SAMCEF. These ones use three different computing methods: explicit, implicit and harmonic ones. Each one presents its own advantages and drawbacks.

The explicit method may be rather fast but its stability widely depends on initial conditions and used parameters.

The harmonic method is based on Fourier analyses so that computing in transient domain is no more necessary. Thus, the harmonic method is the fastest one. However, it may present convergence difficulties at frequencies where non-linearities are particularly strong. Besides, SAMCEF, which is today the only program that owns a harmonic module, presents some important limitations. Thus, even if harmonics may be calculated until order 5, only the fundamental is available in final results. Finally, the second main limitation is that SAMCEF does not treat unsymmetrical non-linearities. It modifies this kind of non-linearity so that it becomes symmetrical, which lead to wrong results.

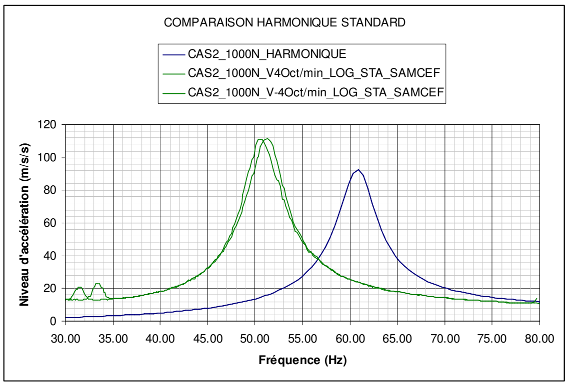

FIG 2. Comparison between harmonic and implicit method on unsymmetrical non-linearity

The implicit method is the more spread one. Even if implicit computation requires slower iterations, it is stable without conditions. Tests performed on the 4 programs presenting an implicit algorithm (Marc, Nastran, Samcef, Abaqus) show very close results, namely due to very close algorithm versions.

2.2. Implicit method development

Although harmonic method is too much limited and explicit method does not present any special interest for spacecraft analyses, the rather heavy implicit process needs all the same some developments to ensure that it can be used with large models. Indeed, it is nearly clear that a full size spacecraft model will not be supported by classical algorithms in terms of computation time and storage space, even taking into account potential ameliorations in both software and hardware fields. Therefore, a condensation way shall be used. First simulations performed on very simplified models show that the use of classical superelements is possible in non-linear transient solution in Nastran.

2.3. Method selection synthesis

Due to the global stability of implicit method and limits of harmonics one, the implicit method remains the most mature and interesting one to deal with non-linear issues. Moreover, the fact that Nastran is able to deal with non-linear transient analyses is a very important point in that this program is widely used in space industry, which means that all Finite Elements Models are already in the right format to be used in such a way. At last, the possibility to use superelements is a significant advantage that allows hoping to be able to treat wide models.

3. METHOD EVALUATION

In order to determine if the selected method can fulfil the initial requirements (to treat non-linear issues at spacecraft level), it has to be evaluated through cases with increasing complexity, from very simple cases to adjust parameters to full size models to ensure the method's credibility and reliability.

3.1. Damping issue

As in classical linear analyses, damping is necessary to match physically consistent results. However, contrary to what is usually used in linear context, non-linear analyses cannot support modal damping. Thus, only structural damping versions are available in non-linear analyses. The problem is that this kind of damping introduces dependence between damping and frequency whereas linear analyses usually use frequency-constant damping factor or user-controlled dependence vs. frequency.

Several ways are available in Nastran SOL 129 (non-linear transient algorithm) to introduce damping. Main ones are classical structural damping and Rayleigh damping. They are rather similar in the principle but the structural damping uses specific structural stiffness and damping matrices whereas Rayleigh damping uses general stiffness and mass matrices. While combining factors (A1 and A2) on those 2 last matrices, Rayleigh damping allows getting a nearly constant damping ratio on a specific frequency range.

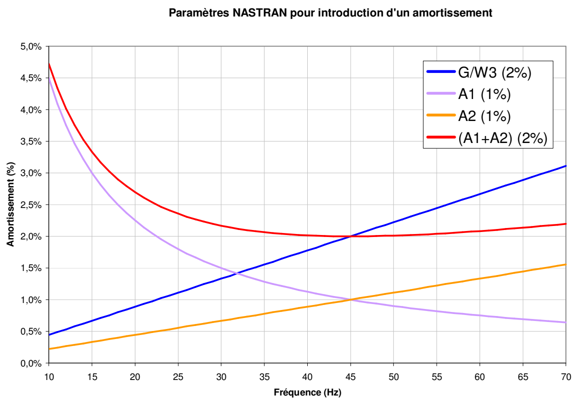

FIG 3. Damping factors combination

The combination of A1 and A2 factors will be used during further analyses since it is the closest way to model damping like linear modal damping.

3.2. Superelement condensation

It has been seen that superelement use in SOL 129 is possible. Anyway, a few questions have to be clarified before generalising the method, such as the method of condensation, the boundary conditions or the potential effects of modal truncation.

About the condensation way, 4 methods have been tested on a 2-subsystems system. They consisted in condensing only one subsystem, both ones independently, both ones in the same superelement without any link between them and both ones in the same superelement with a very light linear stiffness between them. The four methods give nearly exactly similar results.

About boundary conditions, a few extra simulations have been performed using realistic boundary conditions, all points at B-SET or all points at C-SET. Once again, all the three methods give nearly exactly the same results.

Finally, about modal truncation, the same superelement has been generated taking modes into account until 600, 200 or 100 Hz. Results show that there is no impact on fundamental but that, even if high order harmonics are always present, their amplitudes may decrease when the truncation is too short.

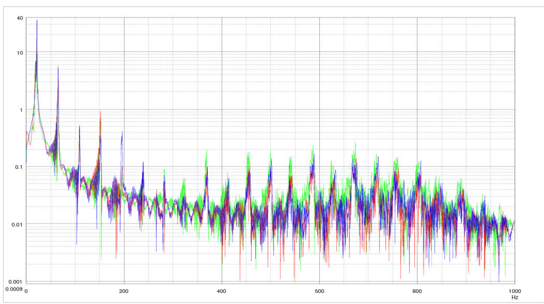

FIG 4. Modal truncation impcat (green=600 Hz, red=200 Hz, blue=100 Hz)

As a conclusion about superelement condensation, it can be said that it is very easy to be used for non-linear analyses with a very little impact of condensation parameters. The only thing to take care of is the modal truncation depending on the harmonics order that is wished to be present in final results.

3.3. First test simulation

Before trying to simulate a real case, a very simple spacecraft dummy model is used to evaluate the possibility of modelling several non-linearities simultaneously.

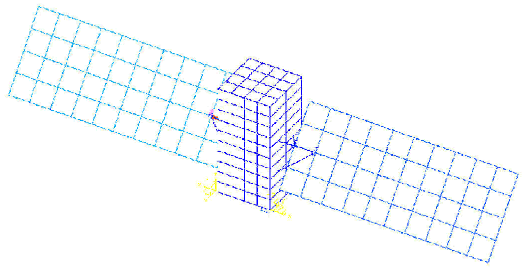

FIG 5. Dummy spacecraft model

Thanks to this simple FEM, convergence stability and time step adjustment could have been deeply studied. Finally, the method seems to be able to treat simultaneously different kinds of non-linearities but convergence difficulties appear when their number increases. Moreover, the non homogeneity of used non-linearity kinds increases the convergence difficulties. That means that it is better to treat simultaneously non-linearities of the same kind without mixing with other non-linear problems if possible.

3.4. Full-size test simulation

The final way to fully evaluate the selected method consists in comparing predictions using this method and tests results. For that purpose, a case has been selected. It consists in a sub-system linked to a plat-form through a non-linearity consisting in a symmetrical gap with a large increase of stiffness after 1.7 mm.

Available data refer to a dummy sub-system used on rigid boundary conditions.

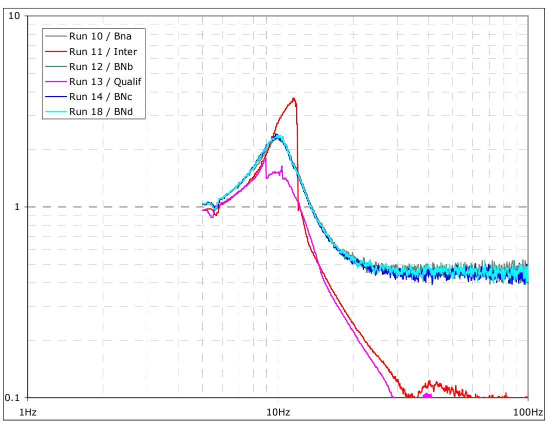

FIG 6. Test results

The blue curve corresponds to an excitation of 0.1 g. The resulting behaviour is linear. The red curve corresponds to an excitation of 1.0 g. The resulting behaviour show a clear non-linear jump around 12 Hz.

The dummy equipment has been modelled in Nastran with elements CBUSH1D for the non-linearity. After adjustments of time step, damping introduction and convergence parameters, analyses show rather interesting results.

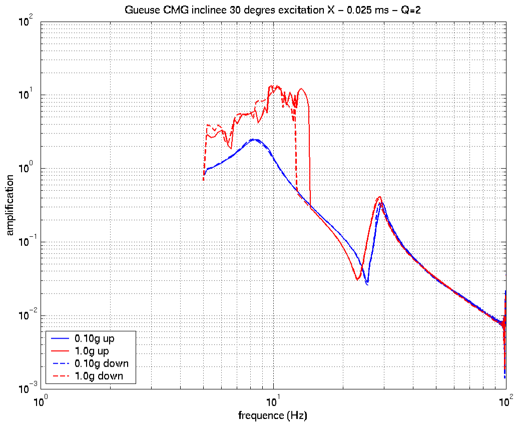

FIG 7. Analyses results with dummy model

Thus, up and down analyses for 0.1 g input level lead to a very linear behaviour whereas an input level of 1.0 g leads to a clear hysteresis with a typical non-linear frequency jump around 12 Hz. The amplitude of the peak remains difficult to predict because of the use of rubber in the sub-system interface.

Once the dummy sub-system FEM is replaced by the physical FEM one, results remain consistent.

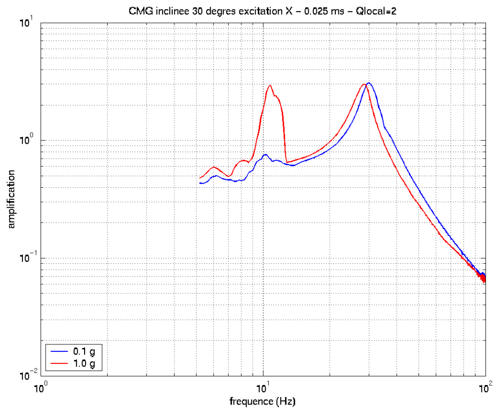

FIG 8. Analyses results with real model

On the above figure, the presence of the non-linarity is even clearer with the peak around 10 Hz which is reduced to minimum in the case of a low input level at 0.1 g. This phenomenon can be understood on studying the displacement curve which corresponds to the local relative length variation of the non-linear element.

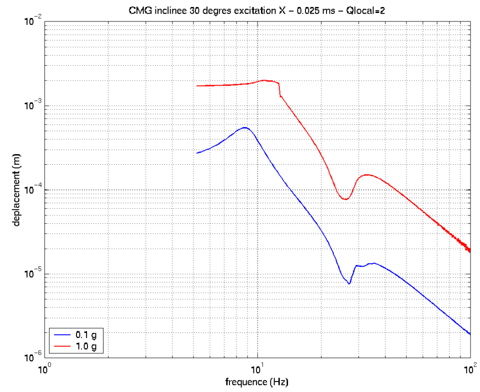

FIG 9. Analyses results with real model – disp.

Comparison between FIG 8 and FIG 9 shows that the displacement limit at 1.7 mm is not reached with the input level of 0.1 g, which explains why the system behaviour is strictly linear. On the contrary, the limit is reached for an input level of 1.0 g, with leads to the increase of the sub-system COG acceleration. Once the displacement returns under the limit value, the behaviour of the system becomes linear and is then very similar to the low level case.

The same kind of phenomena happens when the physical subsystem is placed in the physical spacecraft plat-form. Obviously, the use of physical subsystem or plat-form had needed the superelement condensation method but the results remain valuable when comparing with the mere subsystem dummy on rigid interface.

3.5. Data Processing Resources

Even if those results are promising and that many applications may be imagined, it has not to be forgotten that performing a non-linear transient analysis remains much heavier than a classical linear modal analysis. Indeed, specific non-linear algorithms need large available storage space and important calculation CPU time (depending on the machine used). The following table gives some typical values of time and space for previously described calculations.

Run	version	Time steps	Real time	CPU time	Scratch	SCR300
Dummy	NX 1.0	2600000	3h33	13'	1.2 Go	1.8 Go
Dummy	MD 2006	2600000	1h04	12'	1.1 Go	1.8 Go
Subsystem	NX 1.0	2600000	33h49	3h17	3.2 Go	4.3 Go
Subsystem	MD 2006	2600000	28h57	1h34	3.2 Go	4.5 Go
Spacecraft	MD 2006	2600000	>42h	>4h	>45 Go	>3.2 Go
Spacecraft	MD 2006	1300000	>16h47	>1h50	>21 Go	>27 Go
Spacecraft	MD 2006	491600	7h50	47’	9 Go	12.8 Go

TAB 1. Calculation time and storage space

In this specific case, it has not be possible to run a full spacecraft analysis with a model condensed up to 700 Hz because of storage space limitation (40 Go for temporary files!). The calculation has all the same been performed with a lower frequency condensation limit.

Globally, it is to be noticed that the storage space used for the calculation seems to be directly linked to the FEM size (namely number of SPOINT). On the contrary, the calculation time seems to be driven by a more complex law which leads for instance to an increase of the calculation time of only 10% when the system size growths by a factor 10 (subsystem to spacecraft level).

Anyway, such a complex calculation with full-size FEMs may be completed within 48h, which remains acceptable for specific studies. Moreover, data processing software and hardware continuous improvement may quickly decrease these current limitations.

4. SYNTHESIS AND CONCLUSION

Finally, it appears that the global treatment of non-linearities at spacecraft level is possible. After the selection of the most promising method and tools, a progressive parameters tuning thanks to simulations with increasing complexity FEM has lead to an interesting process. This final process has been successfully evaluated on a first full-size test case.

Before thinking of a global industrialisation of this process, it still has to be tested on 1 or 2 representative full-size cases in order to definitely test its industrial potential. This final step is foreseen in the next few months.