International Forum on Aeroelasticity and Structural Dynamics
IFASD 2017
25-28 June 2017, Como - Italy

AN INVESTIGATION IN HI-FI FINITE ELEMENT MODELLING AIMED TO IMPROVE LCO PREDICTION

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Keywords: LCO, pylon, aircraft, FEM

Abstract: This paper is aimed at the investigation on the building of accurate numerical structural model aimed to investigate in the Limit Cycle Oscillation (LCO) phenomenon which is an actual issue on several aircraft configurations and which is generally encountered in external store configurations that are theoretically predicted to be flutter sensitive. Primary tools used in the industry are based on linearized and reduced order models. These models exhibit great difficulties in the prediction and reproduction of LCO most likely due to non-linear effects. Therefore, in the present paper, a numerical non-linear Finite Element Model (FEM) has been built in order to reproduce the mechanical behaviour of a representative structure of an aircraft pylon. Particular attention has been paid to highlight the sources of non-linearity: the friction between the spring and the payload has been identified as the main cause of the non-linear behaviour.

1 INTRODUCTION

The primary tools used in the industry to predict the aeroelastic characteristics of aircrafts are based on linearized and reduced order models including both structural and aerodynamic models. The validity and affordability of these models have also been demonstrated for combat aircrafts carrying underwing stores. These models are therefore a relatively quick and simple computational tool to predict the aeroelastic behaviour with adequate fidelity in most parts of the flight envelope. However, there are parts of the flight envelope where structural and aerodynamic non linearities can significantly influence the aeroelastic response, resulting in the need to support simple models by more complex ones, which have to be able to treat the physics at a higher level of fidelity. Limit cycle oscillation (LCO) is an actual issue on several current fighter aircraft configurations. It has been a persistent problem on the fighter aircrafts, F-16 and F/A 18 [1, 2], and it is generally encountered on external store configurations that are theoretically predicted to be flutter sensitive. The typical LCO is characterized by the gradual onset of sustained limited amplitude wing oscillations, where the oscillation amplitude progressively increases with an increase of the Mach number and the dynamic pressure. Limit Cycle Oscillation (LCO) of external stores often imposes a practical limit to the flight envelope, or to the load capability of fighter aircrafts, as well as the increase in the structural weight, and can be found sometimes only by means of flight testing. Predictive methods generally fail to predict the onset velocity or severity of the LCO, which are aspects of primary importance in the certification of external store configurations on fighter aircrafts. When a linear system becomes unstable, the amplitude of the response increases exponentially, whereas a nonlinear system has bounded motion such as LCO, or chaotic motion, which occurs above or below the linear flutter speed [3]. Since the aircraft structure usually exhibits some structural nonlinearities, such as friction, free-play, large deformation, etc... [4], the moderate growth of amplitudes corresponding to the low negative aerodynamic damping may be suppressed. The result is then a steady state oscillation. This is sometimes referred to as the nonlinear structural damping (NSD) model of the aeroelastic LCO [5].

Therefore, the prediction of LCO is very complex and requires the development of non-linear approaches in the simulation technique. Project ISSA (Integrated Simulation of Non Linear Aero-Structural Phenomena Arising On Combat Aircraft In Transonic Flight) was defined to improve the knowledge of the LCO phenomena and to investigate possible predictive methods. Several activities were carried out within this project, including an investigation on the capability of an FE approach to simulate in an efficient and reliable way the structural non-linearity involved in the pylon-store system.

2 ACTIVITIES

The present work is aimed at describing the development of a Hi-Fi non-linear Finite Element Model (FEM), able to reproduce the mechanical response of a representative non-linear structure. Formerly, non linearities have been investigated in terms of free-play, gaps [4, 3] and geometrical non-linearity [6]. However, very recently, an investigation on the effect of airframe non-linear structures including store mounts has been carried out [7]. Therefore, it has been decided to focus on the behaviour of pylon / sway braces / store system under different external loads. The complete pylon system, shown in Figure 1 and Figure 2, has been designed to mimic the non-linear phenomena taking place due to the pylon – store interaction. According with the experience of the ISSA team, the attachment of the payload to the pylon is considered critical and worth investigating. More specifically, the hook restrain force and the contact between the payload and the pad of the sway-braces may determine a non-linear behaviour of the store with respect of the pylon when subjected to aerodynamic loads. This could be a source of energy dissipation that may be involved in LCO phenomena.

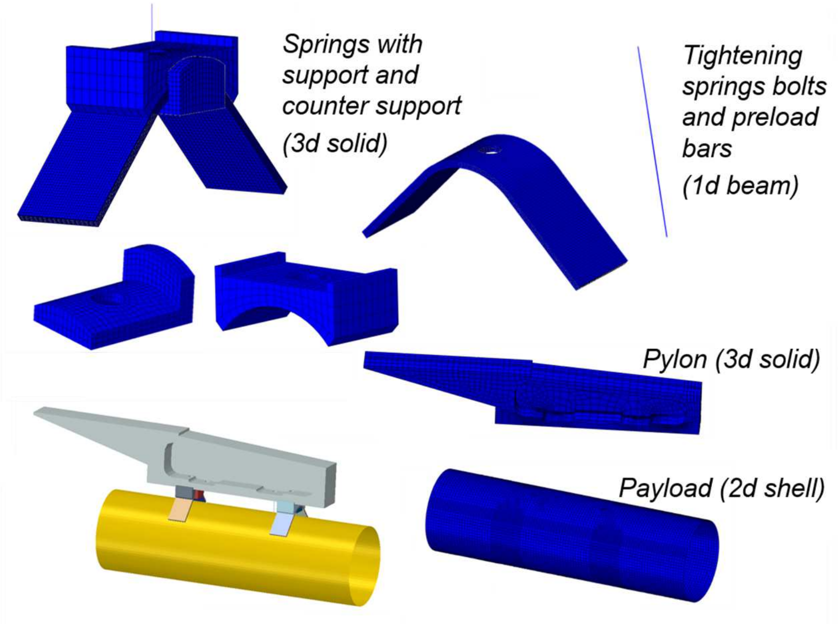


Figure 1: The model of the system including subparts

In order to investigate these phenomena and to limit further complications, a direct investigation of an actual pylon (whose restrain system is very complex) has been avoided and instead a phenomenological numerical model has been designed. The model of the pylon system has been defined in order to be used also as a benchmark for an experimental demonstrator which in turn can be used to validate the results of the model. The FE model of the whole system has been built using the commercial software ABAQUS 6.12, adopting the standard solver. The geometrical model of the pylon / sway braces / store system is reported in Figure 1 both as an assembly and as subparts (already meshed). It is composed of a payload (a cylinder) and a pylon. The two items are joined by a complex system where preload bars (constrained to the pylon) tighten the payload against leaf springs (also constrained to the pylon) that simulate sway-braces. The description of the complete model as well as the results of the model when subjected to external forces are herein presented and discussed in the light to exploit these findings for predictive analyses aimed to investigate LCO phenomena.

3 THE STRUCTURAL NON-LINEAR FEM

The structural model is aimed to show the sources of non-linearities inside the pylon by evaluating its response in terms of stiffness. The non-linearities taken into account in the model are: geometry, contact and friction. As it is clearly shown in Figure 1, the model is composed of several parts and different element types have been adopted for each one including beam, shell and solid. More specifically, 3D solid has been used for the support, counter support, pylon and spring. Beam elements have been used for bolts and preloads and finally shell elements for the payload. In particular, the cylinder representing the payload has been described as a rigid body because the interest is not focused on the stress state but rather on its trajectory. Except for the spring layers, which are made of steel, all the other components are made of aluminium. The adopted properties are listed in Table 1.

Material name	**Elastic modulus**	**Poisson's coefficient**	**Density**
	[Mpa]	[-]	[ton/mm^3]
Al6082/SS4212	69000	0.33	2.71E-9
11R51/SS2331	190000[a]	0.3	7.9E-9
Common steel	210000	0.3	7.9E-9

Table 1: mechanical properties

Except for the data obtained from a Sandvik datasheet (spring steel SS2331), the other material data are typical, and the data can be found in literature. Spring bolts (10.9) as well as the preload bars are made of steel. The behaviour of all materials is linear thus only elastic modulus and Poisson's coefficient are required for the building of the model. The performed analyses are static. This choice implies that any inertia effect has been neglected. This is reasonable because for the present research the focus is on the sources of energy dissipation and stiffness non-linearities, therefore the application load rate is considered very slow. Standard solver is very suitable to describe static problems but it potentially shows convergence problems dealing with non-linear problems. In the present case, because of the many different contact surfaces and the kind of constraints applied to the payload (its position is determined only by the two preloaded bars and the springs) the convergence is highly dependent on the contact algorithm.

A key aspect of the model regards the connection between the payload and the pylon. The connection between the support and the counter support of the leaf spring has been reproduced as constituted by bolts which can be effectively described by beams. The beams representing the bolts have been connected to the structure by rigid connections and also a preload has been applied to them, see Figure 2. More complicated is the connection between the payload and the pylon. Such a connection is not direct but the payload is connected firstly to the preload bars and then to a support. Finally, the support is connected to the pylon, see Figure 2. A pin connection has been modelled between the preload bars and the support, and an encastre between the bars and the payload. The preload bars are important because, as the name implies, a certain preload which is responsible to maintain pressure between the leaf spring and the payload is applied on them. Finally, with regards to the boundary conditions, the pylon has been grounded by means of an encastre applied in a reference point, which is linked with the pylon via a coupling interaction, see Figure 3. The described model is therefore a phenomenological model, which is thus not aimed to reproduce the mechanical details of an actual pylon-store interface but its phenomenological behaviour in terms of non-linearities mainly represented by the contacts.

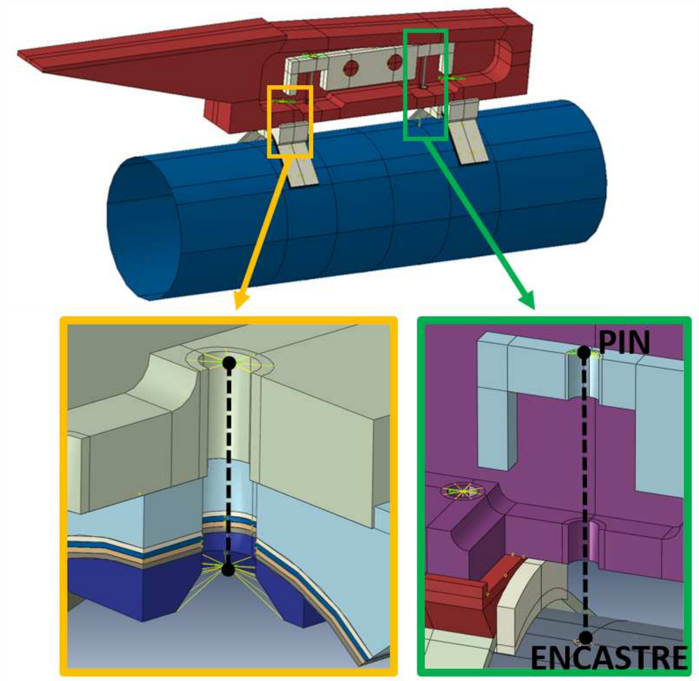


Figure 2: Connection between the spring and the support and counter support (bottom on the left), connection between the preload bars and the pylon (bottom on the right). The black dashed line is a beam representing: the bolt on the bottom left and the preload bar on the bottom right

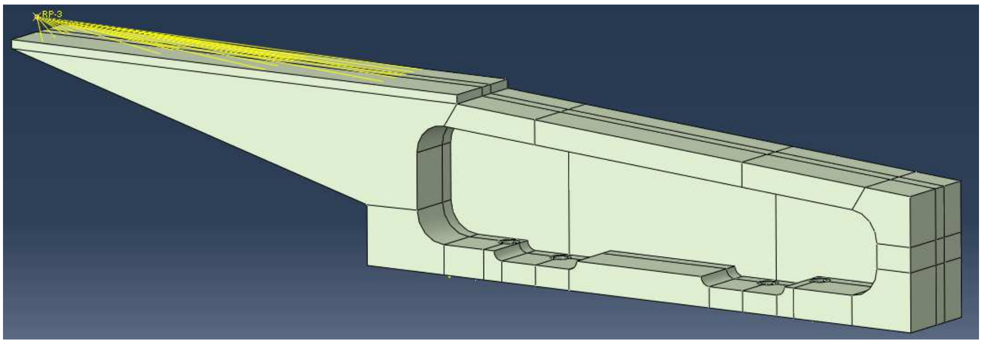


Figure 3: Constraint applied to the pylon

The preload is imposed in an initial step (step 1, Figure 4), then the length of the preload bars and of the bolts can change accordingly with the external loads and their stiffness. The external load has been applied in terms of a horizontal displacement applied in a node at one end of the store, see Figure 4. Furthermore the analysis has been divided into four different steps. In the first step, the store has its transversal displacement fixed but it is free to move vertically. The external load is not applied but only the load on the spring bolts and the preload bars is present. The proper reproduction of the mounting of the store in a way that resembles the reality is important because the tightening preload affects the contact and hence the energy dissipation. In the second step, the constraints on the store are removed and thus it is free to move, except for the presence of the contacts with the springs and the links with the preload bars. Also the external load (horizontal displacement) is applied to the cylinder. In steps three and four, the direction of the applied horizontal displacement changes in order to describe an entire load cycle. A description of what happens during the steps is depicted in Figure *4*. It is worth mentioning that it is not aim of the present paper to reproduce the actual loading condition with an aerodynamic effect but rather to investigate in the modelling technique of the possible source of non linearities that are supposed to be fundamental in the LCO phenomenon.

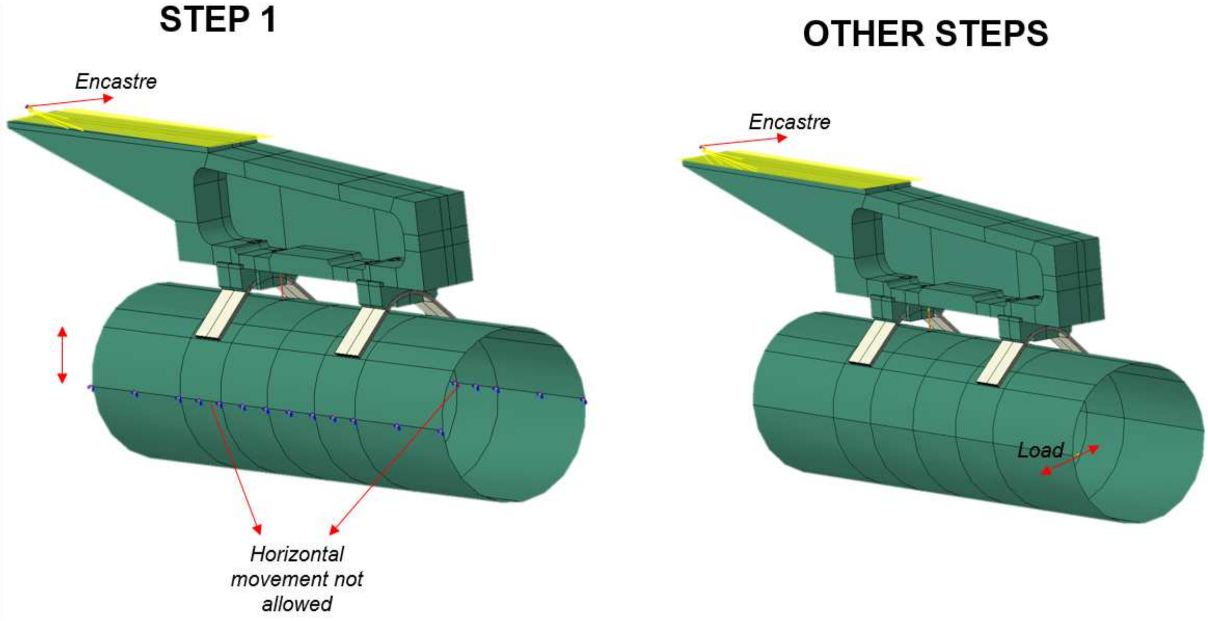


Figure 4: Boundary and loading conditions applied in the various steps

4 RESULTS

As the output of the model, the displacement of the payload measured in two relevant points placed on the frontal and rear transversal surface as depicted in Figure 5. has been considered. Thereby the trajectory followed by the payload can be evaluated.

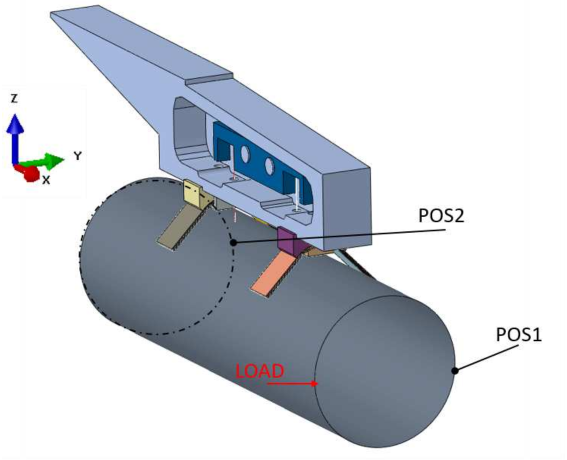


Figure 5: Assembly of the pylon model including the position of the points where the displacement is read

The deformation shape along with the Von Mises stress contours of the model when the maximum and minimum load (displacement) is applied is reported in Figure 6. As expected, the highest stresses are concentrated in the spring leaf.

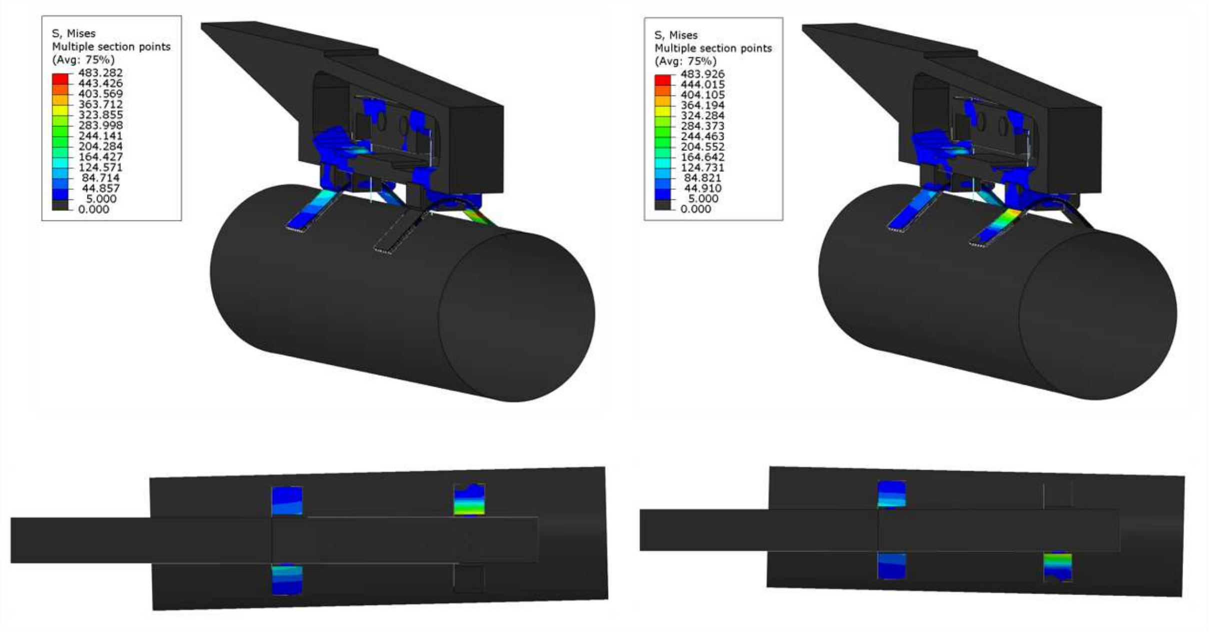
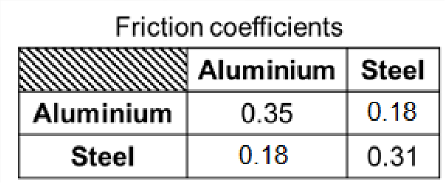


Figure 6: Deformation shape of the system on the top isometric view, on the bottom top view. The two columns refer to the maximum (on the left) and the minimum (on the right) applied load

Due to the fact that the aim of the paper is to identify possible dissipative phenomena, the effect of changing the friction coefficient is the main investigated aspect. The results are summarized in Figure 7 in terms of external load versus displacement. It is evident from the numerical results that the phenomenon is deeply non linear. In particular, during the application of the load, the system response describes a hysteresis cycle which means that there is a huge dissipation of energy due to the friction between the surfaces in contact. In the model there are several surfaces in contact and hence the dissipation energy due to the friction between them is relevant. The combinations of materials in contact are steel-steel (between each layer of the spring and between the springs and the supports) and aluminium-steel (springs vs payload and support vs payload), which is indeed contact with the highest effect. In order to improve convergence, a no-separation after contact rule has been applied to all the contact pairs apart from the contact between the payload and the springs. This means that, after a contact between surfaces has been established, it cannot be removed and the surfaces can only slide reciprocally remaining in contact. This modelling choice improves the convergence significantly. The values of the adopted friction coefficients are reported in Table 2. Tests have been performed reducing the friction coefficient of 20 and 60% in order to simulate the behaviour of an actual surface where some contaminants may be present. It is clear that friction has a high effect only between aluminium and steel (springs vs payload and support vs payload) while it has almost no effect on steel versus steel. It is worth to mention that this model allow for parametric analyses that investigate in several features, for instance the effect of the preload can be verified.



Friction coefficients

▨	**Aluminium**	**Steel**
Aluminium	0.35	0.18
Steel	0.18	0.31

Table 2: Friction coefficients

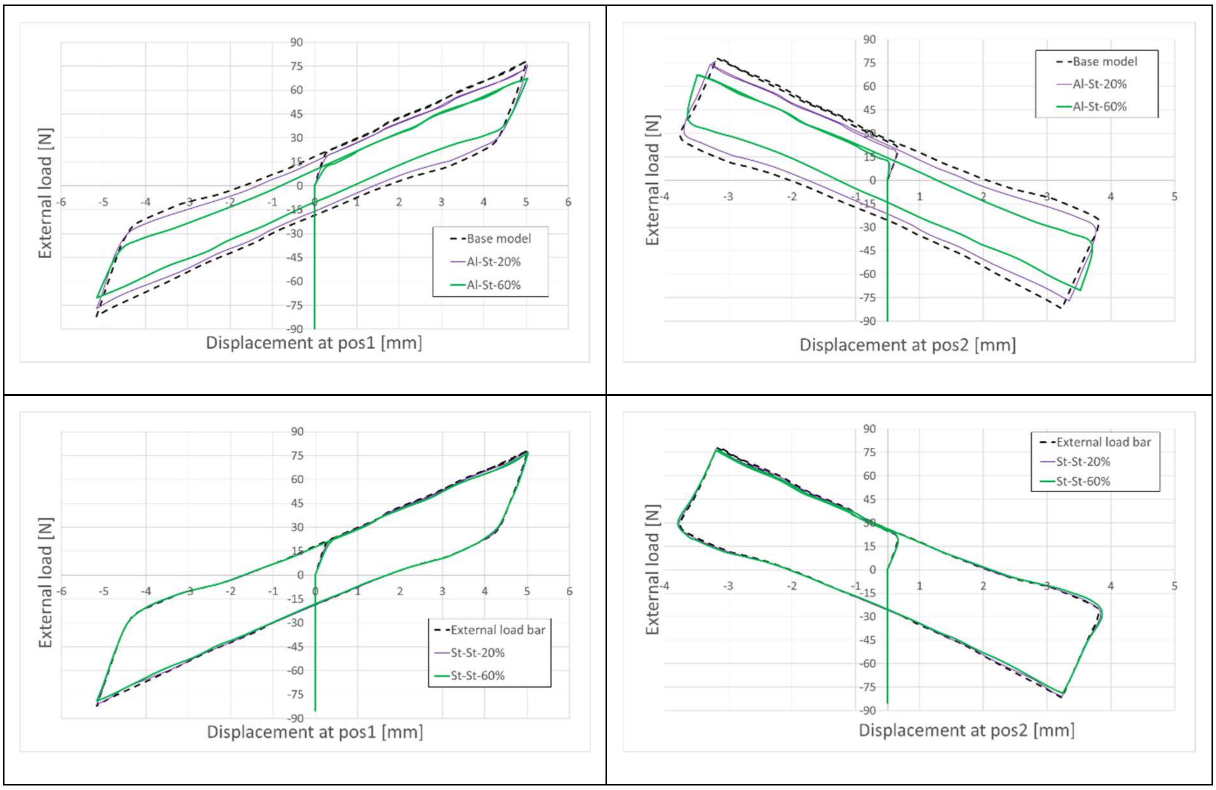


Figure 7: Numerical results considering the friction effect; base model refer to friction coefficient as reported in Table 2

5 CONCLUSIONS

A Hi-Fi non-linear Finite Element Model of a pylon-store system aimed to mimic the phenomenological behaviour of a real one has been modelled. Focus has been placed on the capability of the model to reproduce a dissipative phenomenon related to contact and friction. This phenomenon is supposed to influence the LCO and thus this model is aimed to be a first step in the creation of a nonlinear modeling environment able to reproduce the aeroelastic behaviour of a representative structure of an aircraft pylon. The idea is that non-linearities due to structure can be concentrated in the dissipative phenomenon of the friction and that the capability to correctly simulate such phenomenon is a key issue in the prediction of LCO phenomenon. Due to the many surfaces in contact, friction has been reasonably evaluated as the most important source of both energy dissipation and non-linearities. The model presented has been specifically designed to reproduce this phenomenon. In particular, the friction coefficient determines the area of a hypothetical load-displacement cycle and hence it is linked with the dissipated energy. In the present work, this cycle does not reflect an actual aerodynamic load but only a simple displacement control load in order to investigate the source of non-linearities using a simple load. Not all the surfaces involved in contact have in fact the same effect on the results. Indeed the friction between aluminum and steel (springs Vs support/counter support and payload) has the highest impact on the results. Instead, the friction coefficient between steel and steel (between spring layers) has only a very negligible effect. The conclusions drawn have been obtained only numerically and they can therefore be used as a useful guide to define a proper experimental setup.

REFERENCE

[1] C. M. Denegri Jr., Limit Cycle Oscillation Flight Test Results of a Fighter with External Stores, *Journal Of Aircraft* Vol. 37, No. 5, September–October 2000

[2] R.W. Bunton, C. M. Denegri Jr., Limit Cycle Oscillation Characteristics of Fighter Aircraft, *Journal Of Aircraft* Vol. 37, No. 5, September–October 2000

[3] J.S. Bae, D.J. Inman, I. Lee, Effects of structural nonlinearity on subsonic aeroelastic characteristics of an aircraft wing with control surface, *Journal of Fluids and Structures* 19 (2004) 747–763

[4] D. Tang and E. H. Dowell, Flutter and Limit-Cycle Oscillations for a Wing-Store Model with Freeplay, *Journal Of Aircraft* Vol. 43, No. 2, March–April 2006

[5] L. Tang, R.E. Bartels, P.C. Chen, D.D. Liu, Numerical investigation of transonic limit cycle oscillations of a two-dimensional supercritical wing, *Journal of Fluids and Structures* 17 (2003) 29–41

[6] P. J. Attar, E. H. Dowell, J .R. White, Modeling the LCO of a Delta Wing Using a High Fidelity Structural Model, 45° AIAA/ASME/ASCE/AHS/ASC Structures, *Structural Dynamics & Materials Conference* 19 - 22 April 2004, Palm Springs, California

[7] S.M. Whitican, T. J. Copeland, Structural Testbed Design and Testing with Controlled Nonlinearities, *Sound & Vibration* February 2016

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