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# MODELING THE SUBSONIC AERODYNAMICS OF AIRCRAFT WITH EXTERNAL STORES FOR FLUTTER ANALYSIS

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***Abstract.*** *This work reports some experience acquired in modeling the subsonic unsteady aerodynamics of external stores of a fighter aircraft for flutter analysis. Theoretical results, obtained for an F-5E configuration using MSC/NASTRAN and ZAERO software systems are presented. These theoretical results are compared with experimental results obtained in subsonic wind tunnel tests by the manufacturer of the airplane. With basis in this comparison the relative advantages and disadvantages of some different ways of modeling the bodies (airplane fuselage and the external stores, with or without its shape details and/or the external store fins) are discussed. For the specific configuration analyzed it was observed that the slender bodies theory used in MSC/NASTRAN can lead to a significative overestimation of the flutter speed.*

***Keywords****. external stores, flutter, singularity methods, aeroelasticity.*

## 1. Introduction

Flutter is a dynamical aeroelastic instability in which the airflow around a structure transfers mechanical energy to it in a manner that increases the amplitude of initially small vibrations of that structure. This phenomenon is generally catastrophic and can occur in civil structures, such as bridges and smokestacks, as well as in airplanes. The flutter of civil structures (that seldom have a streamlined shape) is generally associated with complex non-linear and viscous phenomena, such as von Kármán vortices shedding. For this reason, its prediction and prevention studies have been mostly based on wind tunnel test results. The special shape of aircraft is more amenable to theoretical aerodynamic analysis, and the risks and costs involved in the aeronautical industry have justified the development of sophisticated methods for theoretical aircraft flutter prediction.

The CFD techniques for solving the complete Reynolds averaged Navier-Stokes and non-linear Euler equations have greatly evolved in the recent years, and the computational resources needed to effectively use them are becoming widely available. Even so, the aerodynamic theories most used in flutter analysis of aircraft, especially when it can carry many different external stores, are based on the potential flow and small perturbations hypothesis.

These theories lead, with the help of singularity methods like the vortex-lattice, the doublet-lattice or more conventional panel methods, to a linear relation between aerodynamic loads and the deformations of the aircraft structure. Such a linear relation allows a relatively fast flutter analysis (that consists basically in the examination of the eigenvalues of a system of equations that describes the aeroelastic behavior of the airplane in the frequency domain).

The present paper discusses the aerodynamic representation of external stores attached to an airplane in the context of singularity methods for unsteady flow. The discussion is guided by results obtained, for low subsonic flow, with the MSC/NASTRAN™ aeroelastic module, the ZAERO™ software and in wind tunnel tests.

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Some previous works have dealt with the effects of external store aerodynamics in aircraft flutter. Sotomayer et al. (1981) presented results obtained in wind tunnel and theoretically, using panel methods and also the doublet-lattice method, for an F-5 wing with an AIM-9J missile (with corresponding launcher) at the wing tip or mounted on a pylon under the wing. Pollock et al. (1982) reports the continuation of the work of Sotomayer et al. These two papers do not discuss specifically the differences between the results obtained with different modeling techniques for the stores. They observed, however, that the aerodynamics of the tip launcher and, more importantly, of the missile at the wing tip, are detrimental for the flutter of the configurations studied. The underwing-mounted pylon is beneficial according to their observations, since it decreased the aerodynamic loading at the outer portion of the wing. The work of Turner (1981) is directed to the identification of aircraft configurations in which the aerodynamics of external stores has a significative effect in the flutter velocity. Turner based his work in the analysis of a data basis that was composed of theoretical and experimental results. The theoretical results in that data basis were obtained with MSC/NASTRAN using the slender bodies theory that will be succinctly described in the next section and further discussed in the present work. Turner concluded that no general guidelines could be applied to all aircraft for identifying configurations to which the aerodynamic modeling of external stores is critical, although some specific guidelines for particular aircraft were developed in his work.

The results reported in the present work, for an F-5E with underwing stores, do not reveal any special importance of the aerodynamic modeling of these stores to the flutter speed prediction for the configuration analyzed. But an important (and unconservative) overprediction of the (beneficial) effect of the underwing store aerodynamics, by the MSC/NASTRAN using its slender body theory, emerged as the most interesting aspect of these results.

## 2. Theories for subsonic aerodynamic modeling of aircraft with external stores

The doublet-lattice method used in MSC/NASTRAN for modeling the aerodynamics of lifting surfaces is different from the panel method used in ZAERO in the singularities (acceleration potential doublets) distribution admitted, in the location of the control points where the normalwash is evaluated and in the integration of the kernel function. But for a sufficiently refined grid, both methods give equivalent results for lifting surfaces.

When these software deal with the bodies of the fuselage and external stores, a different situation arrives. The techniques utilized are so different in this case that even in the limit of infinitely refined grids the results would be different.

### 2.1. Slender bodies modeling in MSC/NASTRAN

Slender bodies immersed in subsonic flow, and their interference on the velocity field around lifting surfaces attached to them, can be modeled in MSC/NASTRAN using a combination of an images method, based on the Circle Theorem of Milne-Thomson (1966), with singularity distributions near the axis of the body, resembling those used for describing the flow around a fuselage alone by Schlichting and Truckenbrodt (1979, Ch. 5). In this modified slender bodies theory, developed by Giesing et al. (1971) a system of images of the singularities that represent the aircraft aerodynamic model (with the exception of the body in consideration) is generated inside an imaginary tube (called interference tube in MSC/NASTRAN) drawn around the body axis (see Fig. (1)). This system of images (generated according to an essentially two-dimensional theory) does not induce a three-dimensional flow satisfying exactly the impenetrability boundary condition at the body surface (as it does for the infinitely long fuselage studied in the early work of Lennertz (1927) apud Schlichting and Truckenbrodt (1979, Sec. 6-2-2)). To alleviate this problem a distribution of doublets or quadrilateral vortices (according to the orientation of the cross section of the body, that must be an ellipsis with axis aligned with the coordinates system) is placed near the slender body axis as sketched in the Fig. (2). The local intensities of this singularities distribution can be determined readily, given the shape of the slender body, the frequency of the oscillating flow and the free stream velocity.

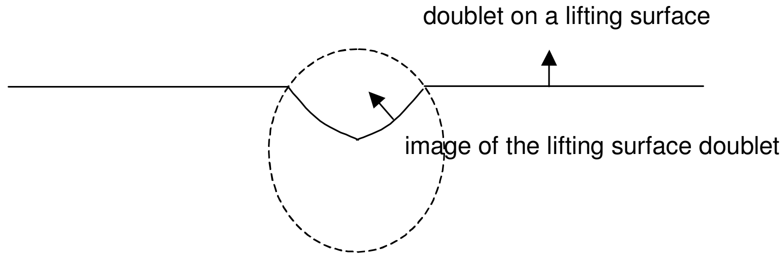


Figure 1. Image of lifting surfaces inside an interference tube (represented by the dashed line) of elliptical cross section. (adapted from Giesing at al. (1971)).

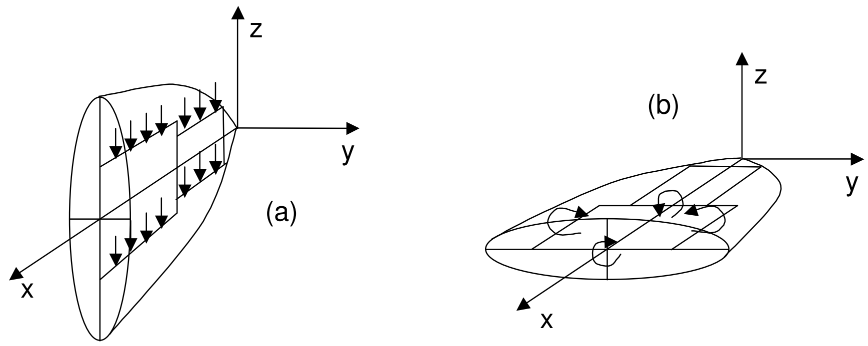


Figure 2. Doublet lines (a) and quadrilateral vortex (b) used to model slender bodies in MSC/NASTRAN (adapted from Giesing at al. (1972)).

The singularities distribution near the axis of the body can not ensure the impenetrability in a flow field disturbed by the presence of singularities apart from that body, as the images system can not cope with the three-dimensionality of the slender bodies. And even the combination of these two techniques does not preclude a residual flow violating the impenetrability condition over the slender body surface. To minimize it, additional doublet distributions are placed along the axis of the body. The intensities of these latter distributions (they are two for each MSC/NASTRAN interference element, one for the $z$ and other for the $y$-direction) are new unknowns added to the problem and an averaged (over sampling points chosen on the periphery of the interference elements) impenetrability condition leads to the corresponding new equations to be satisfied.

It is interesting to note that the doublets represented in the Fig. (2) and those mentioned in the paragraph above are all of velocity potential, in contrast with the acceleration potential (equivalent to a linearized pressure coefficient) doublets used for lifting surfaces modeling. One doublet of the latter type was depicted in the Fig. (1).

**2.2. Modeling the fuselage and external stores in ZAERO**

In ZAERO the external stores and the fuselage are modeled using unsteady source panels, that combined with the doublet panels used for lifting surfaces modeling form a rather conventional panel method in accordance with the proposal of Morino (1974). The only singularities placed inside bodies are doublet panels, joining the roots of the lifting surfaces attached to a body to the axis of that body (in order to avoid the appearance of spurious root vortices at the wing-fuselage and horizontal empennage - fuselage junctions, as well as ill-located tip vortices at lifting surface tip-body junctions). These vortex-carry-through panels are indicated in the Fig. (3).

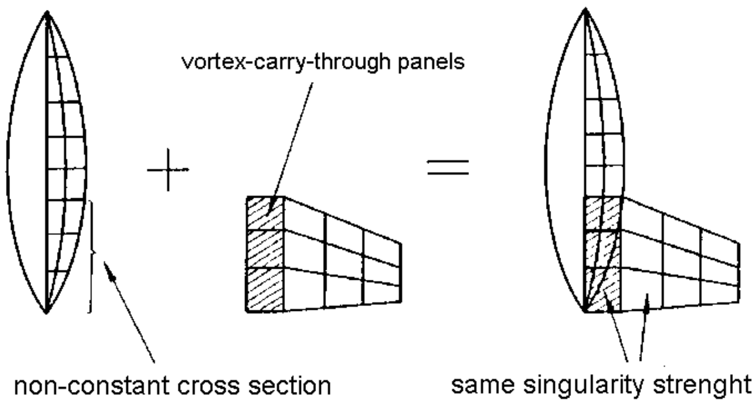


Figure 3. Doublet panels placed inside a body, to avoid a lifting surface root vortex in ZAERO (adapted from Zona Technology (2003b)).

Another feature of the ZAERO modeling of bodies is the use of singularities (a source for steady and a doublet for unsteady flow) behind the body to represent its wake. The flow induced by these singularities inside the separated wake region has no physical significance, but the stagnation point after the separated region and the low pressure region at the rear of the body can be well represented by this way in many cases. The positions of the wake and the singularities behind a simplified body are sketched in the Fig. (4).

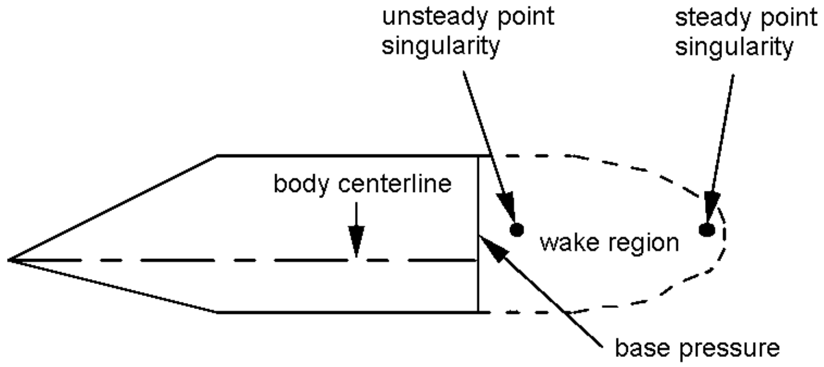


Figure 4. Singularities placed behind a body to represent its wake in ZAERO (adapted from Zona Technology (2003b)).

### 3. The test case

The configuration used for comparing different models is the F-5E with wing tip launcher rails (but without the missiles), a pair of BLU-27/B(F) bombs at the inboard station and a MK-84 bomb at the centerline pylon. The finite element structural model used for obtaining all the results shown in the present paper is the same and represents the aircraft structure by simple beams (just one for the wings, one for the fuselage and one for each stabilizer), concentrated weights, rigid bars and torsional springs adjusted to match the scaled properties of the wind tunnel test model described by Kolar and Lile (1971). This model is represented in the Fig. (5) and its details are given in Silva (1997). Some rigid bars (added to the structural model solely to support surface splines that transfer loads from the aerodynamic model to the structural and conversely) were omitted in the Fig. (5) to make the simplicity of the structural model more evident.

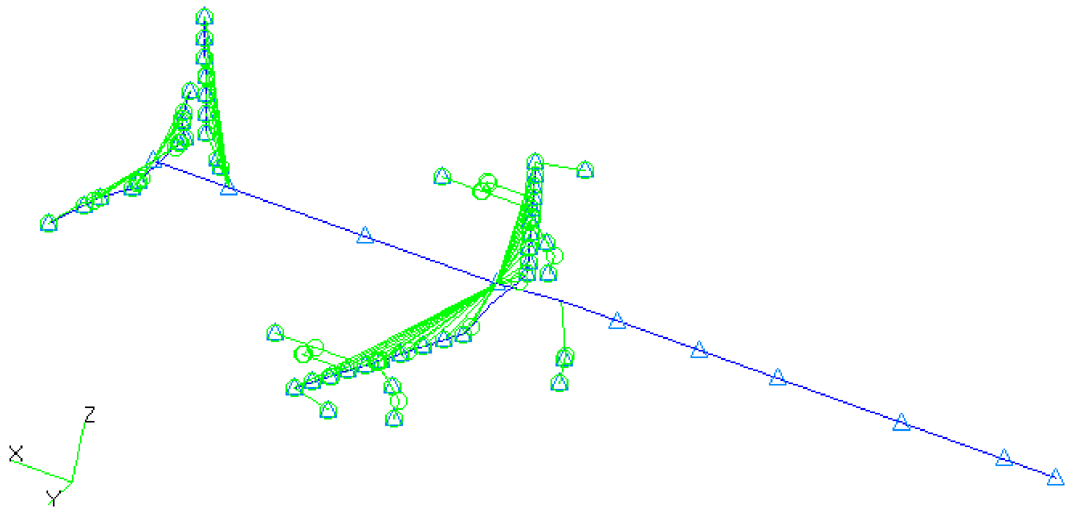


Figure 5. Simplified dynamic-structural model of the aircraft with external stores used for flutter analysis.

The wind tunnel flutter tests results that will be compared with the flutter velocities calculated in the present work were obtained in a subsonic wind tunnel. So the calculations were performed using Mach number 0.2. A set of 13 values of reduced frequency ranging from 0 to 1.0 was used in ZAERO (much larger values of reduced frequency demands some refinement of the surface discretization in ZAERO to avoid a singular aerodynamic matrix) and other set, of 22 values from 0.04 to 20, was used in MSC/NASTRAN. When the 13 reduced frequencies set used with ZAERO was also tested in MSC/NASTRAN the flutter speed calculated by the latter changed by less than 0.001%. The first 22 natural vibration modes of the structure were used for the flutter analysis in both.

### 3.1. The aircraft surface discretizations

Figures (6), (7), (8) and (9) show some of the aircraft surface discretizations used for obtaining the results reported here. The most complete of all the aerodynamic models discussed here is the panel model used in ZAERO and shown in the Fig. (6).

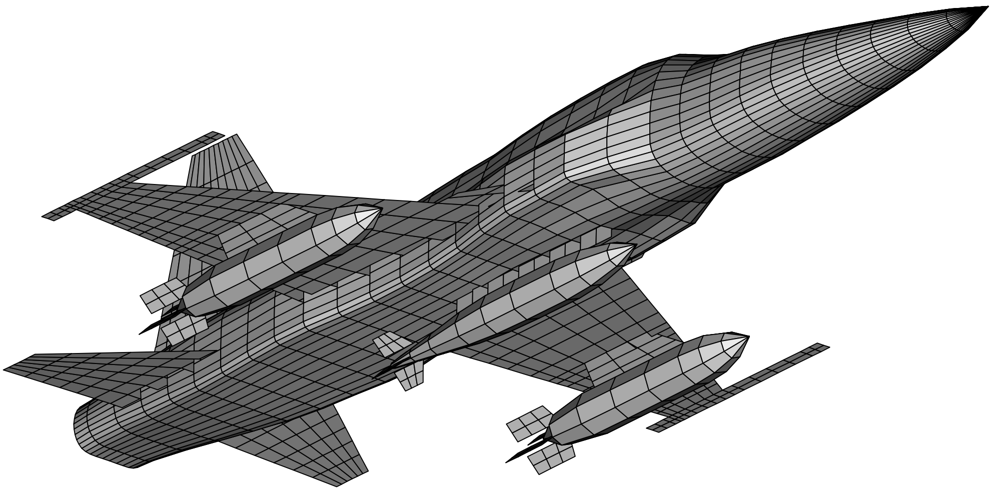

Figure 6. Aircraft surface discretizations for aerodynamic model with bodies and fins used in ZAERO.

The model without aerodynamic representation of bodies, pylons or store fins depicted in Fig. (7) was also tested in ZAERO.

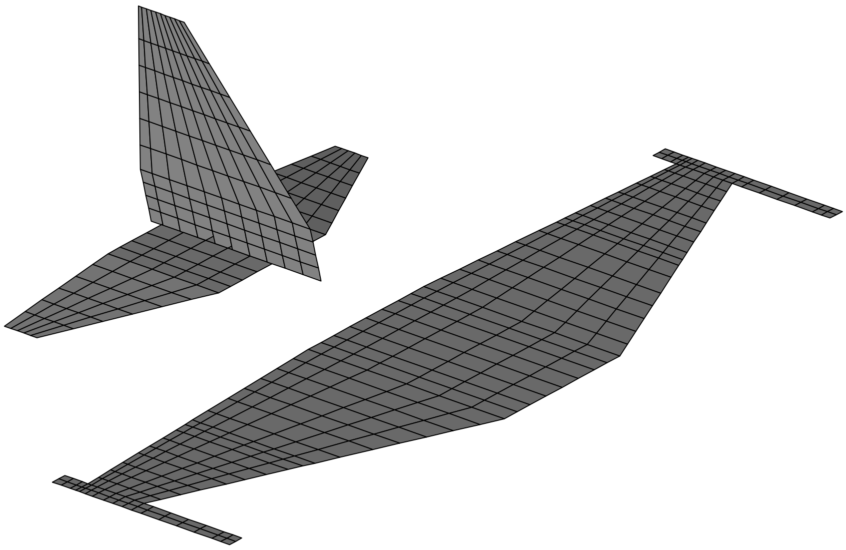

Figure 7. Lifting surfaces discretization used in MSC/NASTRAN and in ZAERO for the model without bodies or fins.

Results from three different models tested in MSC/NASTRAN are discussed in the present work. Figure (8) shows the discretization of the lifting surfaces and the slender body elements utilized in the most complete model tested in MSC/NASTRAN (with bodies, store fins and pylons aerodynamic representation). Figure (9) shows the interference elements and lifting surfaces for the same model. The simplest of the models tested in MSC/NASTRAN was similar to that shown in Fig. (7) (but in MSC/NASTRAN the doublet-lattice method substitutes the doublet panel method of ZAERO).

Some grid refinement tests based on these models were performed. In these tests, the number of panels used for modeling the fuselage and the stores in ZAERO and the number of slender and interference elements used for the same purpose in MSC/NASTRAN were doubled. The flutter speeds calculated with each o this software changed by less then 1%, with this type of grid refinement. The differences between the results of ZAERO and MSC/NASTRAN using the model shown in the Fig. (7) indicate that a refinement of the lifting surfaces discretization can change the MSC/NASTRAN results by nearly 5% (the ZAERO panel method has an order of accuracy higher than that of the MSC/NASTRAN doublet-lattice). In flutter analysis uncertainties of this magnitude are usually present and the trends to be discussed in the foregoing sections of this paper change the calculated flutter velocity by more than 5%.

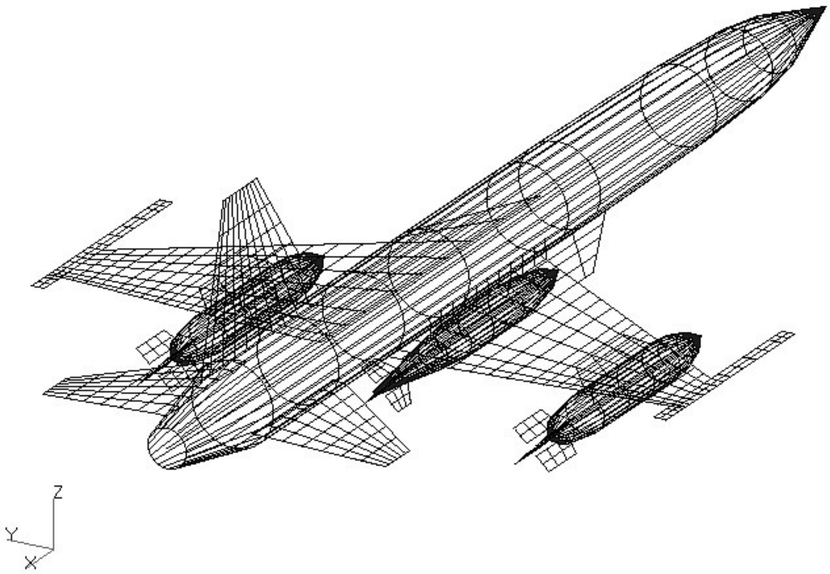


Figure 8. Lifting surface and slender body elements used in the model with bodies and fins in MSC/NASTRAN.

Notice, in Fig. (9), the diameters of the interference elements corresponding to the external stores. They were established according to the store fins root positions. This practice favors a more accurate representation of the interference of the airflow around the store body on the aerodynamic load of its fins (more accurate than the representation of the interference of that airflow on the aerodynamic load of the pylon that holds the store).

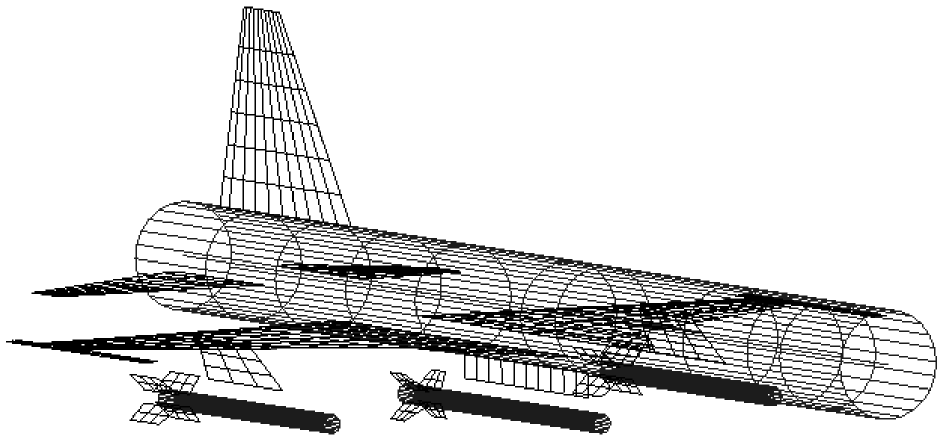

Figure 9. Lifting surface and interference elements used in the model with bodies and fins in MSC/NASTRAN.

The third model tested in MSC/NASTRAN is one in that the aerodynamic representation of the store fins was omitted (the model being otherwise almost equal to that depicted in Fig (8)). In this third model the interference tube diameter used in store representations was the maximum diameter of the store body, favoring a better description of the aerodynamic interference of the stores on the pylons where they are attached).

**4. Results**

Figure (10) shows flutter velocities obtained with the aircraft models discussed in the previous section and in wind tunnel tests. The results labeled “Kolar and Lile (1971)” were taken from the Fig. (14) of the report of Kolar and Lile (1971) and are based on wind tunnel tests (of a model of the aircraft with the external stores). The results labeled “with bodies and fins” are from the most complete models built within each software. These models were depicted in the Figs. (6), (8) and (9). Results from MSC/NASTRAN have the capital letter “N” between parenthesis at the end of its labels and those from ZAERO have the letter “Z” in its place. The results labeled “with bodies, without fins (N)” were obtained in MSC/NASTRAN with a model similar to the most complete, but without aerodynamic representation of the store fins. The results labeled "without bodies, fins or pylons" were obtained with MSC/NASTRAN and with ZAERO using just panels to represent the wings and the empennage (without any aerodynamic representation of the fuselage, external stores or pylons). This discretization is represented in the Fig. (7).

An arbitrary reference velocity was used to scale the velocity values shown in the next figures in order to protect information that is not of public domain.

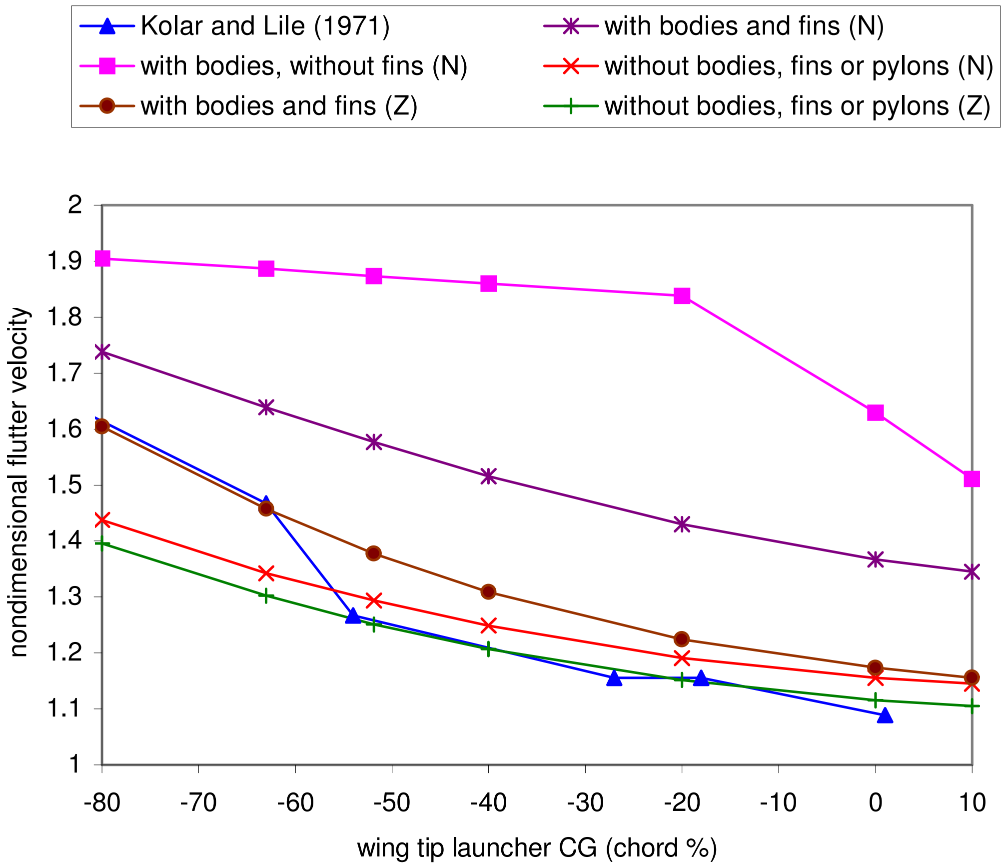


Figure 10. Flutter velocity dependence on the position of the tip launcher CG.

In the Fig. (10) it is observed an (expected) increase in the flutter speed when the center of gravity (CG) of the wing tip launcher is moved forward (to more negative *x*-positions, according to the conventional reference axis positioning where the *x*-axis points from the nose to the tail of the airplane). Additionally (and unexpectedly) it shows flutter velocities calculated by MSC/NASTRAN using the aerodynamic models with bodies representation much higher then those calculated using the models without aerodynamic representation of the bodies and than those observed in the wind tunnel tests. Notice that the results of ZAERO with bodies aerodynamic representation (using the surface source panels) agree satisfactorily with the results of the models without bodies aerodynamic representation and with the experimental results. The absence of store fins representation increases significatively the flutter speeds predicted by MSC/NASTRAN (the fins effect seems to be a counteraction of part of the store body effect).

The present authors were surprised by the overestimation of the flutter velocities that resulted from the use of the slender bodies theory to represent the external stores (and the fuselage) in MSC/NASTRAN. One possible explanation for this could be found relating these high flutter velocities to an overprediction of the underwing stores pitch damping, similar to that observed by Chen et al. (1993) in the results of a similar slender bodies theory (see the Fig. (4) in their work). The damping curves obtained in the present work using body models in MSC/NASTRAN and in ZAERO, compared in the Fig. (11), do not support completely this explanation, since for most of the vibration modes, and most of the wind velocities, the ZAERO model predicts more negative values for the damping coefficient g (and so, more aerodynamic damping) than the MSC/NASTRAN model. Of course, for the 4th mode, near the flutter velocity, the ZAERO that predicts the lower flutter speed also predicts less damping (the null value of damping indicates the flutter occurrence).

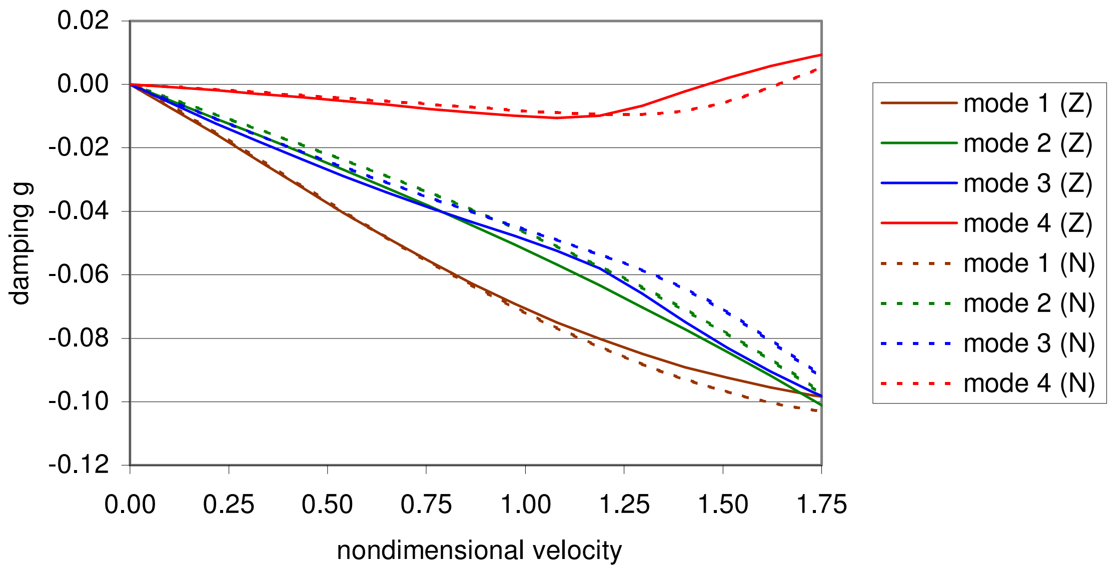


Figure 11. Damping curves obtained with the models with external stores and fins.

Figure (12) shows the evolution of the frequencies of the first four vibration modes of the aircraft model (corresponding to the damping curves shown in the Fig. (11)) with the increasing wind velocities, predicted by ZAERO and MSC/NASTRAN for the same models of the aircraft with fuselage, pylons, external store bodies and fins which generated the results shown in Fig. (11). For each velocity, the frequency and damping values were obtained using the p-k method in MSC/NASTRAN and the g method, in ZAERO.

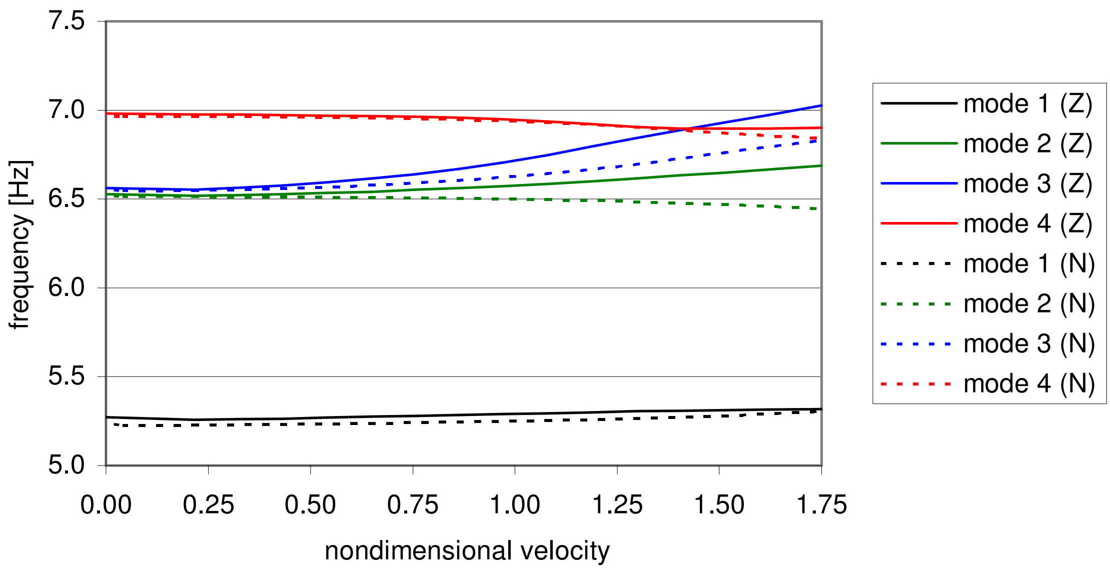


Figure 12. Frequency curves obtained with the models with external stores and fins.

To assess the extent to which the differences between the ZAERO and MSC/NASTRAN results could be due to the departure of the ZAERO g method from to the MSC/NASTRAN p-k method, damping values predicted by these two methods for the model without bodies aerodynamic representation were plotted in the Fig. (13). These results are in good agreement (and their differences are more probably caused by the differences between the panel method used in ZAERO and the doublet-lattice used in MSC/NASTRAN than by anything else). The g and the p-k methods are different ways of assembling the eigenvalues problem associated to flutter that frequently are able to make almost equally good damping predictions.

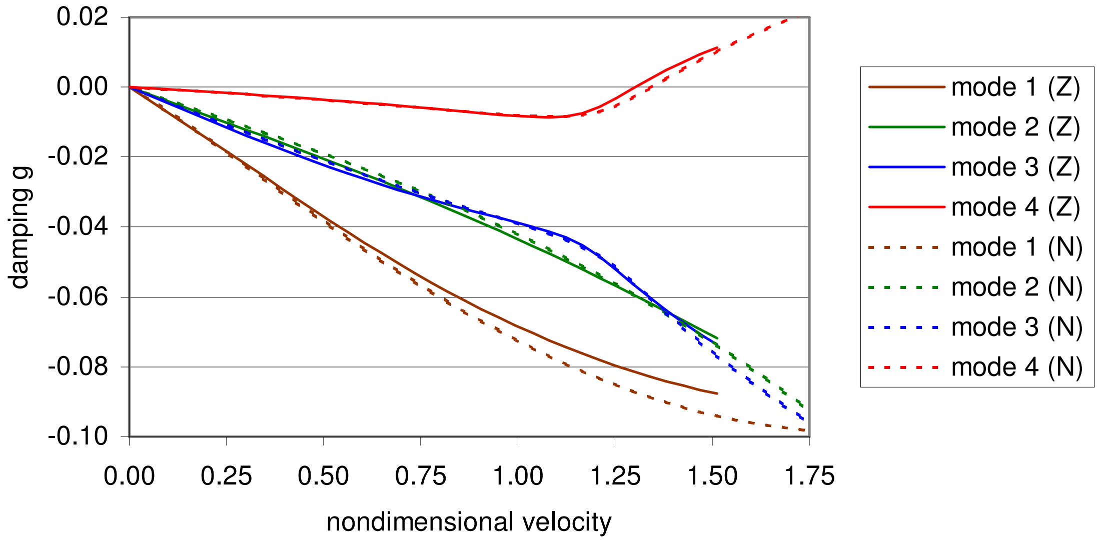


Figure 13. Damping curves obtained for the models without external stores or fins.

Figure (14) depicts the flutter mode of the aircraft, that is composed basically of the first anti-symmetrical wing torsion mode (accompanied of some underwing stores pitch) coupled with the first anti-symmetrical wing bending mode (accompanied of some rolling of the centerline store).

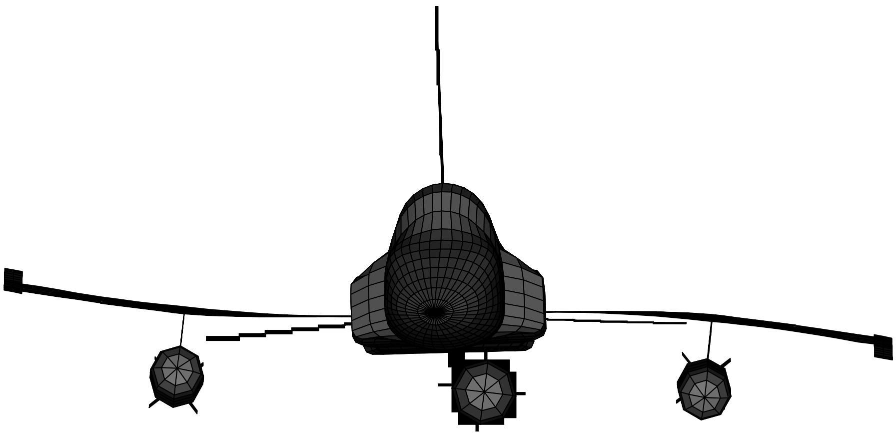

Figure 14. Representation of the flutter mode.

**5. Conclusions**

The fact that, for this configuration, the aerodynamic modeling of the stores did not play a major role in the velocity flutter determination is not unexpected. As mentioned by Turner (1981), in many flutter studies for the clearance of external stores, the aerodynamics of the store is neglected, exactly because it has commonly a minor importance (and because its consideration would increase significantly the computational and engineering efforts needed for the flutter analysis).

The interesting conclusion so found is that it is more safe (although more computationally demanding) to model the aerodynamics of the external stores using panel methods (like that used in ZAERO) than using the MSC/NASTRAN slender bodies theory.

The panel methods allow also a very detailed modeling of the geometry of the fuselage (that the slender bodies theory of MSC/NASTRAN does not). But it is not likely to the fuselage aerodynamics to have a significant role in flutter, since for most of the elastic modes of an aircraft the fuselage centerline is a nodal line. By the same rationale it is expected that as more outboard located is the store attached to a wing, as greater will be the role of its aerodynamics in the flutter, since the amplitude of the wing displacements at these locations should be larger than near the fuselage.

### 5.1. Final remarks

Besides the care with the external store modeling, special attention must be paid to the attachment of the aerodynamic surface panels or singularities that represent the pylons to the corresponding parts of the structural model. The structural model of pylons is frequently very simplified, and it may be tempting to attach the pylon aerodynamic model to the movement of the external store that is connected to that pylon. This is very dangerous, in that it can unduly transfer to that external store a strong aerodynamic load.

More recommendations are made by the flutter analysis software developers, which must be cautiously followed (e.g. those for avoiding that the line vortices shed behind the side of lifting surface panels induce infinite velocities at control points of other lifting panels or body surfaces). But the engineer who uses such software cannot forget the limitations of the theoretical predictions that it can make, those due to assumptions made in the development of the software and those due to the simplifications that he makes when he assembles his computational model. Because of these limitations, it is risky to begin a flight test campaign without confirming theoretical results with extensive (and expensive) wind tunnel tests. For already developed aircraft, the manufacturer technical reports and orders are valuable guides, but analogies and extrapolations based on these documents must be made with extreme care.

## 6. Acknowledgement

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