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BRAZILIAN F-5 EXTERNAL STORES AEROELASTIC INTEGRATION

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Abstract

The present work summarizes the development of a project for flutter clearance of external stores installed in the Brazilian Air Force (FAB) Northrop F-5E aircraft. The work is described in the same sequence of the project development. Initially, ground tests have been performed to determine the dynamic characteristics of the airframe. Then, a finite-element model has been constructed and updated to reproduce the tests results. After this phase, aeroelastic models have been developed, by introducing appropriate aerodynamic theories, depending on the flight regime to be analyzed. The final step in the project is the in-flight flutter clearance, where the aeroelastic models shall be validated based on measurements of the airframe total damping. The paper describes the theoretical and experimental methodologies involved in this integration and provides details of the difficulties and solutions found during the work.

Introduction

The integration of new external stores to any type of military aircraft requires some preliminary studies in order to predict its airframe behavior after change. Some major aspects to be considered in this analysis are the aerodynamic and inertial modifications, the jettison dynamics and aerodynamics, the structural aspects associated to the dynamic and static loads, and, finally, the aeroelastic stability. With regards to aeroelasticity, the main parts of the work are the structural dynamic identification, the aeroelastic modeling, and the flight test to be conducted for final validations.

Among several aeroelasticity related studies within the Brazilian Institute of Aeronautics and Space(1), an official project(2) has been created with the following goals: to prepare personnel specialized in structural dynamics and aeroelasticity; to specify, to acquire, and to use dedicated equipment to support the testing phases on the ground, the aeroelastic analyses, and the flight tests; and, finally, to evaluate the flutter clearance of the FAB F-5E aircraft carrying specific external stores. The final objective of the project is the definition of the aircraft flight envelope with each new system.

This paper provides a progress report on some of the tasks involved in this project, elaborates on some preliminary results obtained, and presents guidelines for the on-going project tasks.

The project has started in 1995, and is presently entering in its third phase. In the first phase, efforts have been dedicated to gain knowledge on the aircraft and on the external stores structural and dynamic properties. In the second phase, simulation models have been developed on computer for the determination of the theoretical aircraft flutter boundaries. Finally, in the third phase, flight tests are being conducted to validate the theoretical conclusions and to define the allowable operational conditions. During these phases, group leaders, researchers, pilots, and technicians have been trained in the required techniques and equipment, in order to provide the answers necessary to the project advancement.

The ground vibration tests (GVTs) have been divided in three groups. First, the external stores have been tested as if they were independent systems. Next, the actual aircraft has been tested in its clean configuration. Finally, loaded configurations have been tested in order to evaluate the overall dynamic effect of external stores. The results obtained during the GVTs are, from the structural point of view, the most important natural frequencies, damping coefficients, and normal modes. A lot of knowledge and experience in acquiring, installing, and operating sensors, shakers, and data acquisition systems has been gained by the personnel involved in these tasks.

In the second phase of the project, a dynamic model of the complete system has been established on computer to fit the experimental data gathered. Then, suitable aerodynamic formulations have been added to the updated dynamic model in order to complete the theoretical aeroelastic analysis. The aeroelastic models used in this work are capable of treating the subsonic, transonic, and supersonic flight regimes. With these theoretical developments and the associated planning, the project has been cleared for the flight phase.

For the flight tests, an aircraft has been taken out from the FAB flying squadrons and is being currently prepared with sensors, cabling, video, and data recording systems. The excitations of the structure shall be provided by pilot induced vibrations, atmospheric turbulence, or by pyrotechnic bonkers installed in several locations of the airframe. Flights shall be conducted to examine the aircraft behavior at the critical points of the envelope, which have been determined by theory.

This is the first time that a project of this type and scope is being conducted by a Brazilian organization. The results of this effort are the capacitation of the involved personnel and the development of complete procedures for aeroelastic integration of new external systems.

In the sequence, we provide details on ground vibration tests, theoretical model construction, and flight trials preparation required by this project.

Ground Vibration Tests

As pointed out in the introduction, GVTs have been required to gain knowledge on the systems involved and have been divided into three major groups: external stores alone, clean aircraft, and aircraft loaded with the stores. In this section we discuss the conduction of these tests and present some of the results obtained.

External Stores

The external store to be taken as example in this discussion is an air-to-air missile, the MAA-1, shown in Figure 1 installed at the wing tip of a FAB F-5E aircraft. This missile has been developed in the Aerospace Technical Center (CTA), a research and development organization of the Brazilian Air Ministry.

MAA-1 is a missile of the AIM-9 class[3] which is currently under serial production in the Brazilian industry. Although MAA-1 is considered similar with AIM-9 missiles from the dynamical point of view, tests have been conducted to assess this similarity. The first step towards answering this question has been the vibration testing of both missiles, in order to identify the modal properties of their frames. A warhead inert MAA-1 missile and a dummy AIM-9B missile, the latter modified in order to approximate the weight of a MAA-1 model, have been chosen as the closest ones in terms of mass and moments of inertia.

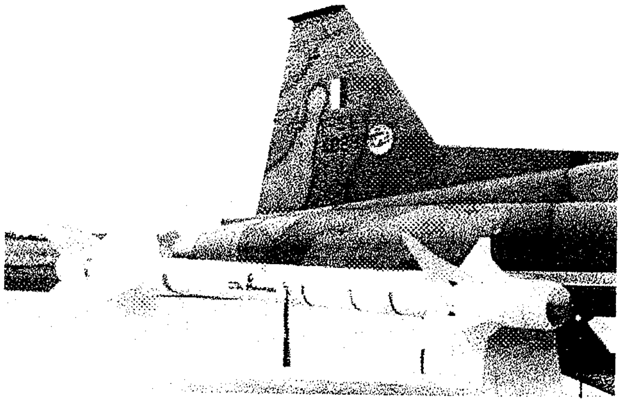

Figure 1 - MAA-1 air-to-air missile in the FAB F-5E.

The experimental setup has consisted simply in the suspension of the missile by the use of elastic sandows. This has been made in order to isolate the frame free vibration modes. It has been observed that, in order to obtain better isolation, it is interesting to adjust the natural frequency of this suspension system to a value at least one quarter of the value of the lowest natural frequency of the first elastic mode of the test bed[4].

Several accelerometers have been bonded to the missiles surfaces. With the boundary conditions described and the installed instrumentation, their structures have been excited with an impact hammer. In the head of this hammer there is a load cell whose function is to acquire the dynamic load input converted into an electric charge. This appropriately conditioned signal has been used as reference to measure the response signal from each accelerometer. The test setup has been based simply on two channels: one to pick up the accelerometer response, and the other to read the load cell reference signal.

The acquired signals have been analyzed by a commercially available modal analysis method[5], with the complex exponential technique. The resulting parameters have been the frequencies of the natural mode shapes and their related modal damping factors.

The tests results have shown that the modified AIM-9B and the MAA-1 missiles have somewhat close natural frequencies and mode shapes. A few natural frequencies identified in the modal analysis of the tests results are presented in Table 1.

Table 1 - Natural frequencies of the two tested missiles.

Missile	MAA-1 Freq. (Hz)	Mod. AIM-9B Freq. (Hz)
1st mode	**45.41**	**43.76**
2nd mode	**51.02**	**57.19**
3rd mode	**60.05**	**61.97**

The first conclusion is that the missiles are similar from the point of view of dynamics. Based on this reasoning, it is possible to state that the physical integration is also similar, because the two missiles employ the same launch rail. But the same conclusion cannot be drawn from the aeroelastic point of view. The two missiles have different aerodynamic shapes; thus, it becomes necessary to investigate the influence of these differences in geometry on aeroelastic phenomena.

The aeroelastic modeling of the missile-airframe integration requires, as part of the problem, the knowledge of the complete aircraft structural-dynamical properties. Then, a modal analysis of the complete airframe is imperative as means of obtaining these desired dynamic properties. This analysis is described with details in the sequence.

Airframe

In order to obtain some knowledge on the F-5E structural dynamic properties, a complete specimen has been designated from one of the FAB flying squadrons to be used in the laboratory tests. It is interesting to observe that this decision has provided to the project engineering team a specimen which is the best available representative of the actual system in terms of structure. The airframe used had some real operational life history to be accounted for. Different dynamic behaviors could have been obtained if a structural mock-up or a customized airframe would have been used instead of a real airplane.

Having selected the aircraft, in order to separate its rigid body modes from its elastic vibration modes, the experimental setup has consisted of a rubber suspension system(4) similar to the one used for the tests of the missiles alone. The following items have also been considered while preparing this laboratory setup: instrumentation of the aircraft, installation of the external excitation system, and performance of the data acquisition chain(6)-(9).

The first step considered in the aircraft instrumentation has been the definition of the position of accelerometers and shakers in the frame. These positions have been chosen by obeying some general rules, such as:

- installation over rigid or reinforced places, in order to avoid the pick-up of "localized" accelerations;
- preferable alignment with major directions of the reference system of coordinates;
- electrical isolation of sensors in order to avoid any undesirable interferences;
- regular distribution of accelerometers on the structure surface in order to provide wide coverage of the complete frame; and
- care with and suspension of accelerometer cabling.

In the experiment conducted with the clean wing configuration, a set of 152 piezoelectric accelerometers has been disposed on the whole airframe in order to identify all the major vibration modes. Figure 2 provides a view of this setup by focusing on the aircraft wing.

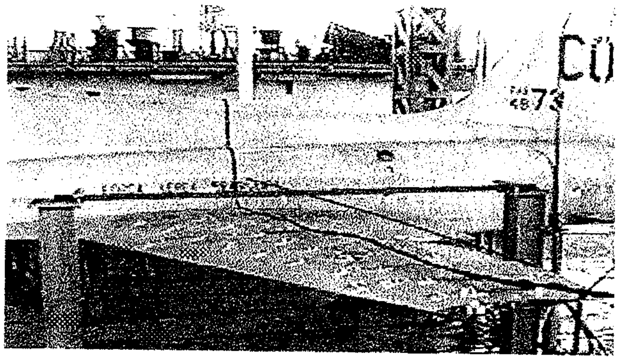

Figure 2 - Accelerometers on the F-5E wing.

The excitation system has consisted of a single electrodynamic shaker, which can be moved to predetermined points along the frame. The chosen points are positions where, by experience, the action of the shaker can excite all the major aircraft structural modes. This system has been programmed to excite the structure with "chirps" in a band from 4 to 120 Hz.

The major vibration modes have been determined between the lowest value of frequency of an elastic mode (first mode) and the frequency that turns aeroelastic phenomena irrelevant (about 60 Hz for this type of aircraft). The choice of the excitation frequency band has been related to the elimination of any leakage associated to this interested frequency range.

The data acquisition and the excitation control have been performed by a spectrum analyzer which sends the excitation signal through the shaker and acquires the accelerometers response. In the same system it has been possible to treat data via a modal analysis software which has as input the measured responses. In this case the modal analysis technique used has been the polyreference method. This method is capable of analyzing the output signal generated by three different excitation positions simultaneously. In Figure 3 a block diagram of the test setup is presented.

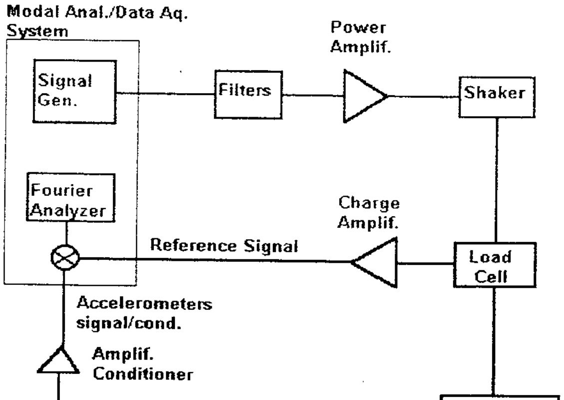

Figure 3 - Block diagram representing the experimental modal analysis setup.

The vibration results obtained(10) have verified those provided by the manufacturer(11),(12), with some small differences in the frequencies and modal damping coefficients. Reasons for these differences may be presented as result of different global measurement errors and also as result of different structural properties. In Table 2, in order to allow some numerical comparison, some frequencies and damping values obtained from the test of the clean wing configuration (without launch rail) are presented.

Table 2. Some frequencies and modal damping factors of the F-5E aircraft in the clean wing configuration.

Mode	Present Test	Manufacturer Test	Beam Model
	frequency/ damping	**frequency/ damping**	**frequency/ damping**
2nd	**12.268/ 0.04%**	**10.51/ 0.00%(12)**	**9.889/ N/A**
6th	**21.191 1.44%**	**20.79/ N/A(11)**	**20.92/ N/A**

In Figures 3 and 4 it is possible to visualize the identified mode shapes for the frequencies of Table 2. With these modes, it has been possible to obtain the associated generalized masses, stiffnesses, and damping factors. Therefore, it has been possible to complete a dynamic model identification from the modal tests.

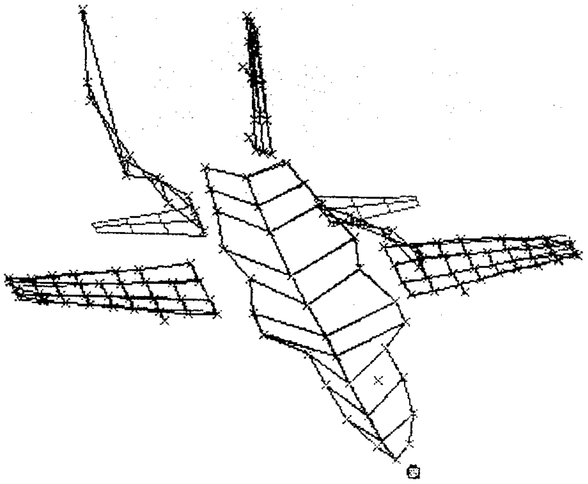

Figure 4 - Elevator bending identified in the modal tests (6th mode).

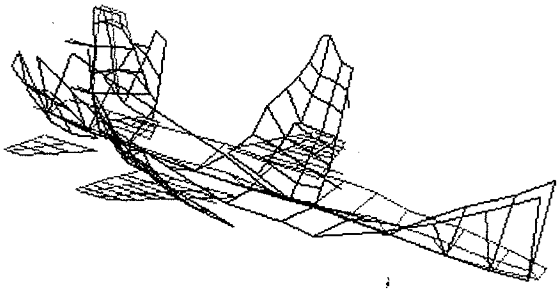

Figure 5 - Fuselage vertical bending obtained from the modal tests (2nd mode).

The loaded configurations have also been tested. Two types of missiles, the AIM-9B and the MAA-1 have been integrated to the test aircraft, and modal tests have been conducted by following exactly the same procedures applied to the clean airframe. These tests have been performed to furnish more data for subsequent aeroelastic analyses. Thus, it has been possible to evaluate the loaded configuration models based in the same methodology discussed latter in this paper.

Theoretical Analysis

In this section we describe several theoretical tasks developed after completion of the GVTs. They involve updating of the experimental dynamic models and build-up of aeroelastic models with inclusion of appropriate aerodynamic theories.

Dynamic Model Updating

The structural model has been identified with careful consideration of the experimental results. This task has been accomplished by writing a set of linear equations that relates the modal displacements to the displacements of physical points of the structure, that is, places where the accelerometers have been located. Since the mass, stiffness, and structural damping properties are well-known, the next step in the whole process has been to determine the mathematical model on computer capable of reproducing the experimental results.

The task of model updating is greatly influenced by the smoothness of the mode shapes experimentally identified. In order to circumvent eventual difficulties, the idea is to adjust a physical model, such as a beam model, by using the identified properties.

The base of the properties used in this work has been extracted from manufacturer reports(11),(13) that describe the beam dynamic model used in aeroelastic analyses. The beam model used in the present development has consisted in a finite element modeling of the aircraft structure represented by straight beams. It is an approximation of the major substructures of the airframe, like the wings, the fuselage, and the tail cone. The beams are joined together with the adequate constraints applied. The resulting structure is, therefore, an approximation of the whole airframe.

The criteria used here to match the experimental dynamic properties have been based on a manual adjustment of some parameters like the beam elements moments of area, the material elastic moduli, or the constraints, for example, the linking of the wing to the fuselage. The airframe structural mass has also been represented as lumped masses located on the resulting nodes of the beam discretization. Since the mass properties are better known than the stiffness properties(13), the use of changes in mass parameters during the adjustment process has been avoided.

As a result of this adjustment process, the updated dynamic model has become coherently scaled with the dynamic properties of the actual aircraft. As can be seen in Figures 6 and 7, the quality in terms of smoothness of the mode shapes extracted from the beam model is much better than the quality shown directly by the experimental mode shapes. The reader should contrast Figure 6 against Figure 4 and Figure 7 against Figure 5.

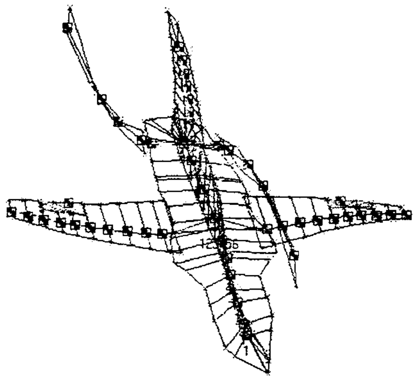

Figure 6 - The same mode shown in Figure 3, obtained in the updated model (6th mode).

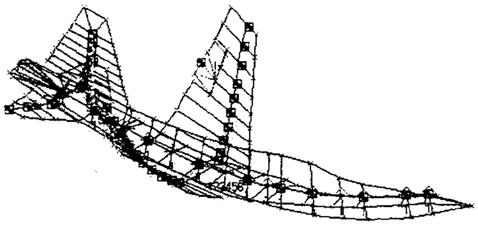

Figure 7 - The same mode depicted in Figure 4, obtained in the updated model (2nd mode).

The importance of the quality of a mode shape in terms of smoothness is associated to the fact that the aeroelastic analysis involves a spline approximation of the mode shape in order to furnish the modal displacements in the aerodynamic control points. If the mode to be approximated by the spline has some local irregularities, it is possible that the spline fitting may result in an erroneous mode shape. Quite often splining procedures are very sensitive to the capture of all the points used for the adjustment process. One way to avoid this problem is to use smoothing parameters. However, in some cases, this procedure is somewhat inefficient.

One should also observe that the updated model may be suitable for applications in dynamics, but on the other hand may be inadequate for predictions of stresses and structure dimensioning(14). Therefore, no other use of this model besides dynamics has been made during this project.

The dynamic analysis has been performed via finite element method for the assembling of the mass and stiffness matrices. The eigensolution of the resulting system has generated the natural frequencies and the associated mode shapes. The structural damping has been neglected in the analytical modeling.

The missiles investigated in the ground tests have dynamic characteristics such that, when compared with those of the airframe itself, create the possibility of considering the missiles as rigid bodies(9). Their identified natural frequencies are at least in the same order of magnitude as the highest frequency of the airframe to be analyzed from the aeroelastic viewpoint. Then, the influence of elasticity of this class of external stores on the airframe can be considered to be essentially null. By this way, it becomes easier to model the missiles by just considering their rigid body influences on the aircraft, that is, by adding to the total system their masses and moments of inertia.

With the observation of dynamic decoupling between airframe and missiles, the theoretical modal analysis has been performed again, this time with the previously obtained updated airframe model. The results have agreed with the corresponding tested configurations. Some small differences in quality of the mode shapes of the loaded configurations have been detected. It has been observed that identification of the mode shapes with external stores has been more difficult to obtain than the identification of the clean configuration. However, the identified frequencies have correlated quite well with the theoretical analysis results.

With the availability of updated structural models of the airframe alone and with the missiles, we have established the configurations required for analysis. If the modal model, based in the compatibility equations that characterize the modes had been employed, it would have been much more difficult to integrate the missile to the structure. This can be explained because the elastic modes of the missiles would have to be considered and they are related to the physical points in the launch rails which are common to the airframe.

In summary, we have found that the best way to treat this testing and identification problem is the way that has been described above. Some improvements which may be added to this procedure are the automatization of the adjustment tasks and of the conditioning of the resulting mode shapes in order to minimize the associated approximation workload(15).

Aeroelastic Model

With updated dynamic models available, the task of determination of aeroelastic models has been based on the inclusion of unsteady aerodynamic forces acting on the structure. The modeling of the aerodynamic behavior has been based on semi-analytic and/or numerical methods developed to represent the aerodynamics of a given unsteady flow regime.

The F-5E aircraft is a low supersonic fighter. Thus, the operational envelope of this type of aircraft involves three flight regimes: subsonic, transonic, and supersonic. In the construction of suitable aeroelastic models, the airflow has to be considered in these three cases. In the sequence, the treatment of each case will be considered separately.

The aerodynamic model of the aircraft in the subsonic flow regime has been based on a standard version of the Doublet Lattice Method(16) (DLM). All the lifting surfaces of the aircraft have been discretized in terms of interfering panels which contain singular solutions of the unsteady acceleration potential equation in a determined value of reduced frequency. The individual solution of each panel, as well as the interference of one panel onto others, has been represented by an influence coefficient matrix. This matrix relates the lifting surface pressure caused by the surface displacement to the downwash induced on all surface panels, including the one which generates the disturbance. By integrating these self-induced and mutually induced pressures on each panel area, the panel force can be obtained. If we consider the summation of all the discrete forces on the lifting surfaces, the unsteady load as a function of the reduced frequency can be determined.

The aircraft has been modeled by sets of panels that discretizes the lifting surfaces and some parts of the aircraft fuselage, such as the union of the wings with the main body. In Figure 8 it is shown a schematic panel model of main lifting surfaces of the aircraft.

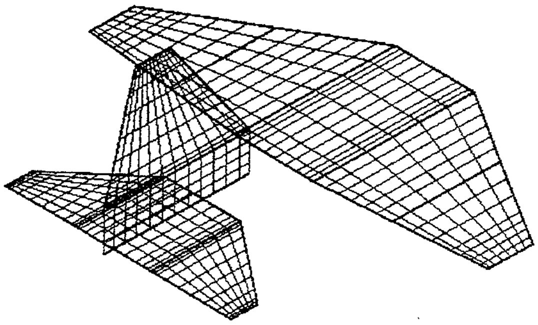

Figure 8 - DLM paneling of the F-5E lifting surfaces, and part of the fuselage.

The missile flippers and its main body have also been modeled as the projection of their spans onto the main lifting surface plane (the aircraft wing). Like the aircraft lifting surfaces, they have also been subdivided into panels. The modeling of the influence of the aerodynamic shape of the missile has been treated as a free parameter. The width of the span (projected diameter of the missile body) has been adjusted to a value of the actual projected span in order to match some aeroelastic results furnished by a report of the aircraft manufacturer(13).

The aeroelastic analyses in the subsonic regime have been performed up to Mach number equal to 0.9. After this value, the nonlinear behavior of the transonic flow starts to become relevant. In Figure 9, an example of the obtained aeroelastic results is shown in the form of a V-g-f plot. In this plot one can observe a set of curves indexed according to the number of the investigated vibration mode. In the upper half it is displayed the evolution of each mode frequency as function of the airplane speed. In the lower half the same happens with respect to the damping associated to each mode. The Figure displays the coalescence of the 1st and 3rd modes, with ultimate instability of the 3rd mode.

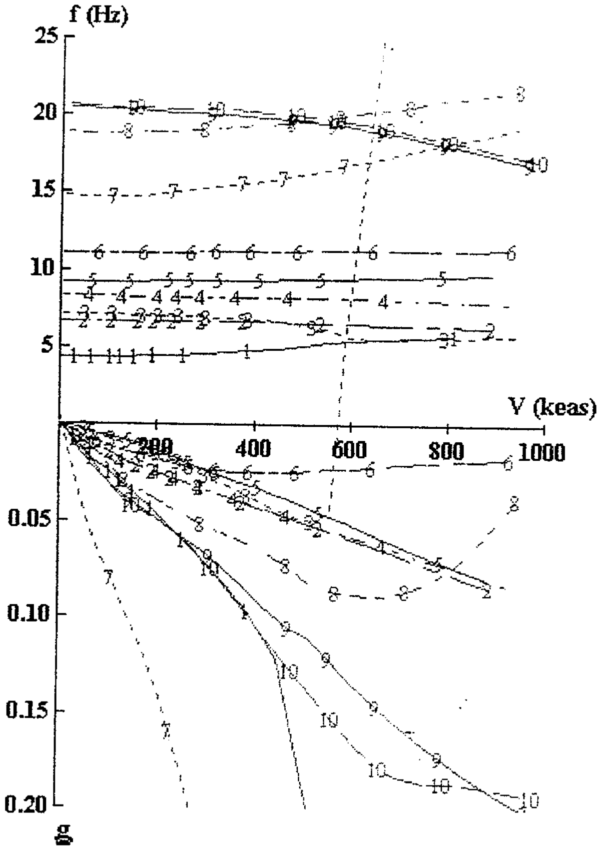

Figure 9 - Evolution of the F-5E aeroelastic modes along the velocity axis, at Mach number 0.85, carrying a modified AIM-9B to generate a subsonic flutter.

The configuration whose theoretical results are reproduced in Figure 9 is of a F-5E carrying two AIM-9J missiles at the wing tips. This case has been tested by the manufacturer in wind tunnel, with results of 552 keas and 5.87 Hz for the flutter speed and frequency, respectively. The corresponding computer results have been 571 keas for the flutter speed and 5.82 for the flutter frequency. In general, differences among analytical and experimental results in the subsonic regime for several configurations have stayed within an error margin smaller than 5%.

In Figure 10, results of another study are displayed. This time, the aeroelastic modes are concerned with the F-5E aircraft carrying two MAA-1 missiles. These frequency and damping curves are very similar to those of the case of the same airplane with AIM-9B missiles, as reported by the manufacturer. Besides this similarity, another conclusion can be drawn, as supported by these and other results: that in the subsonic regime (up to 660 keas - the validity limit for the aerodynamic model) this configuration is, at least from the theoretical point of view, free of aeroelastic instabilities.

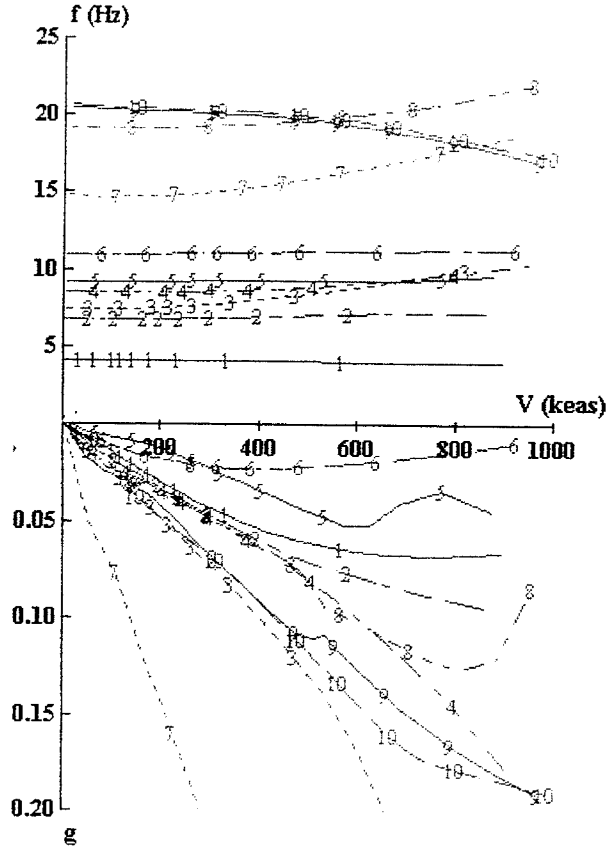

Figure 10 - Evolution of the first ten aeroelastic modes of the F-5E carrying MAA-1 missiles.

In the transonic regime, nonlinear aerodynamic effects are known to become very important. Of particular interest in this case is the sudden reduction in aeroelastic stability shown by some systems, in a phenomenon known as "transonic dip". Then, it is necessary to consider these nonlinearities with care by the use of an appropriate formulation.

The transonic aeroelastic loads in the project have been computed by using a mixed formulation based in the determination of the steady transonic pressure coefficient from a Navier-Stokes code(17) in order to correct the nominal steady pressure coefficient distribution of the DLM(18). The Navier-Stokes solution has been based on a finite difference formulation which uses a diagonal form of an alternating direction implicit (ADI) approximate factorization procedure(17),(19).

The correction has been introduced in the DLM code as a weighting factor that multiplies the generalized aerodynamic forces vector, and then the analysis has been made in the same manner as in the subsonic case. The Mach number considered in the DLM analysis has been kept equal to 0.9. This way, it has been possible to approximately predict the unsteady transonic nonlinear loads.

Figure 11 depicts an example of the domain discretization used in the Navier-Stokes computations for the steady-state transonic case.

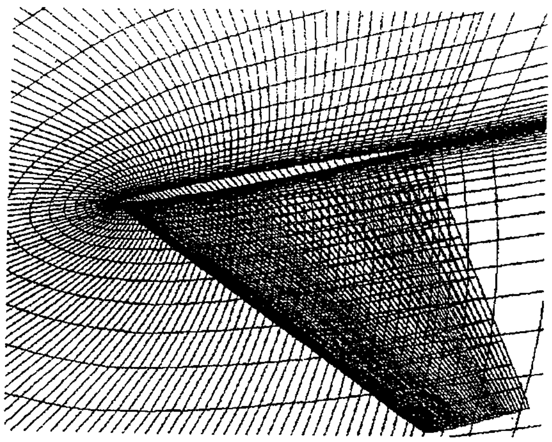

Figure 11 - Finite difference mesh that discretizes the 3-D domain surrounding the isolated F-5E wing.

In the calculations for the supersonic case, the technique employed has been the Mach Box Method (MBM)(16). The basic case studied has been the isolated wing oscillating in the modal frequencies of interest. It is important to highlight that these modes have been the same modes of the entire aircraft, but that only the parcel of the wing has entered in the formulation.

This method has been based on the solution of the potential flow equation for the unsteady flow regime, and has computed the influence coefficients of one box into the others, and into itself. This influence has been considered by respecting the natural supersonic flow characteristics, that is, the influence on a given box is due only from boxes that are inside the upstream Mach cone of that box. The number of boxes has been calculated depending on the Mach number. This computation has been made automatically by the code. The computed unsteady loads have been transformed into generalized loads in order to associate them to the generalized coordinates that represent the airframe vibration modes.

In both the transonic and supersonic cases, the aerodynamic modeling of the missiles has not been introduced in the whole model directly, but just in terms of their dynamic influence. The aerodynamic effect of the missiles has been implicitly considered in the solution of the steady Navier-Stokes solution. Then, the correction made in the transonic case by the weighting factors has accounted for the aerodynamic interference due to the missiles. In the supersonic case, the influence of the missiles has also been computed by modification of the nominal pressures determined by the MBM. The way of introducing this modification has been analogous to the procedure used in the transonic case, that is, by scaling the nominal pressures via weighting factors.

Flight Tests

The Institute of Aeronautics and Space (IAE) has, since the seventies, developed a considerable capability in conducting flight tests. Today, IAE has a Division totally devoted to this endeavor, which gives an official course dedicated to the preparation of pilots, engineers, and technicians specialized in flight evaluations of aerospace components, subsystems and complete systems. Together with worldwidely recognized efforts on quality standards and certification developed by the Institute of Industrial Fostering and Coordination (IFI), CTA has demonstrated the possession of a quite comprehensive capability in the research, development, and approval of aerospace products.

However, most of IAE's expertise regarding flight tests has been focused on the performance and handling qualities of complete systems, as well as on assessment of subsystems integration to fixed and rotating-wing aircraft. Prior to this project, little experience had been accumulated regarding the execution of hazardous flight tests. Therefore, considerable emphasis has been placed on the preparation of personnel with specific knowledge on the planning, proposal, preparation, execution, and evaluation of in-flight flutter tests(20). Considerable help in this preparation has come from experts from the Technological Institute of Aeronautics (ITA), CTA's higher education organization.

The final phase of this project is the verification in flight of the missile-airframe integration safety from the aeroelastic viewpoint. Thus, a plan for a series of flights has to be devised in order to safely cover the subsonic, transonic, and supersonic flight regimes and in order to investigate critical stability margins determined by theory. This section of the paper describes the efforts already developed along these directions, as well as the plans for completion of this investigation.

In the subsonic case, theory, experiment, and the available literature have determined that the aeroelastic behavior of the aircraft with integrated MAA-1 missiles is very similar to the corresponding behavior of the F-5E carrying AIM-9 class missiles. Although our investigations have confirmed this fact, it is dangerous to predict aeroelastic phenomena similarity by using dynamic characteristics exclusively. Upon completion of our theoretical simulations, a certain level of confidence has been gained in order to permit the beginning of the flight test program.

Since the aeroelastic behavior of the integrated configuration has a good stability margin, preliminary aeroelastic flight tests for the subsonic case have been performed. The tests have initially involved only the evaluation of performance and handling qualities of the aircraft carrying MAA-1 missiles, as shown in Figure 12. However, by having pilot commands and atmospheric turbulence as sources of excitation, the aeroelastic stability of the assembly has also been assessed. The tests have also verified the asymmetric configuration, with only one missile at the wing tip.

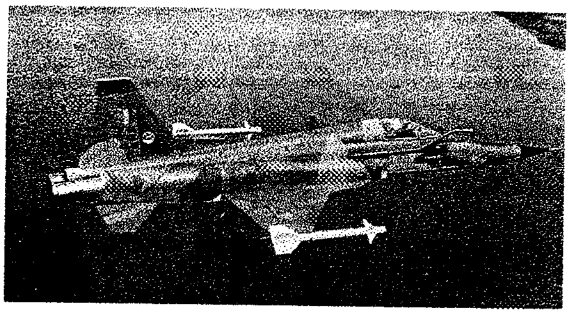

Figure 12 - The flight of the MAA-1 in the FAB F-5E.

The operational test envelope in these flights has been restricted to the subsonic regime. The full envelope expansion, that is, up to the supersonic maximum Mach number, depends on more complete analysis of all the flow regimes and configurations.

For the in-depth flutter clearance of this system, an aircraft has been taken out from the flying squadrons and is being prepared to receive the instrumentation necessary for the in-flight excitation of the structure, the measurement of the excitation response, and the data collection for later reduction and analysis.

The excitation of the structure shall be done in most cases by the use of pyrotechnic bonkers to be installed on the aircraft maximum modal displacement positions of a determined aeroelastic mode to be verified. The frame excitation can also be obtained by pilot's induced vibrations or by atmospheric turbulence. The disadvantages of these two latter methods are the low frequency capability of the pilot's actions, and the random aspect of the turbulence that can result in a difficult reduction of the measured data. The bonkers shall be activated by the pilot when the aircraft matches the velocity and altitude condition to be investigated. During the flight test a set of conditions for a determined flutter mode shall be measured. Finally, the total damping reduced from a given set of velocities related to a determined flutter mode shall possibly be compared with the analysis total damping, thus giving rise to validation of the complete procedure.

The tests shall be conducted by considering the aeroelastic analysis results for all the three flow regimes. The objective of these flight tests is to verify the adequacy of the theoretical analysis results, specially in the transonic case. Eventually, adjustments in the formulation in order to match the flight test results shall be required and shall be done accordingly.

The flight test planning considers first flights of the aircraft in the clean wing configuration. In this condition, the complete measurement chain and the associated pyrotechnic system performance shall be evaluated. Then, fully integrated configurations shall be tested in order to complete the aeroelastic analysis by investigating the flutter critical conditions theoretically determined.

The conduction of these flight tests will not only extend the current capabilities of the Center, but will also establish a necessary culture for a more precise definition of Brazilian military certification standards regarding aeroelastic stability(21)-(23).

Concluding Remarks

This progress report has described indigenous efforts developed in Brazil regarding the qualification of new external stores integration to the FAB F-5E. As example of external store, the paper has considered the MAA-1 missile.

The paper has gone through describing phases of a project specially geared towards preparation of personnel, development of analysis techniques, and conduction of flight tests for flutter clearance. This description has included ground vibration tests, updating of experimental models, development of theoretical analyses for trisonic aeroelastic stability, and flight test evaluation. Eventual difficulties found during the development of this work have been solved either by using readily available solutions or by exercising some creativity in terms of engineering.

As result of this project, CTA has now an independent capability of certifying the operational clearance for aeroelastic stability of complete systems carrying variable external stores. This capability concerns specialized personnel, theoretical methods, equipment, techniques, and procedures.

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The development of a project of this scope and time frame has necessarily involved a lot of people. The authors would like to express their recognition for the collaboration of these here unnamed colleagues.

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