MAJOR IMPROVEMENTS IN STORES SEPARATION ANALYSIS USING FLEXIBLE AIRCRAFT

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Abstract

By tradition, missile separation analyses have been considered as rigid body simulations. However the flexible "down the rail" behavior used to be taken care of by the structural dynamics department in order to calculate hook loads and separation simulation start values. The launch simulation then started after missile tip off. This method is very time consuming and also not exact with respect to the limitation of the structural dynamic method's possibility to simulate a correct aircraft motion at the separation case.

Modern missiles launch envelopes tend to be more expanded and the aircraft motion during the launch is then very complex. Firing a wing tip missile at high load factors in combination with a rolling maneuver demands a new thinking of how to solve the launch problem. Therefore a method where the structural dynamic characteristics of the flexible aircraft with flexible launcher combined with the advanced aerodynamic and flight mechanics model is needed.

1 Introduction

The Stores Separation methods and tools used at Saab for clearance of released stores relative a flying aircraft are described in reference [1]. Traditionally the aircraft has been modeled as a rigid body. In simulation of rail launched missiles, some simple spring elasticity has been used to model the flexibility in the launcher and in the missile hooks.

Since the Saab 39 Gripen aircraft is a small, relatively flexible aircraft, carrying and separating heavy external stores it is essential to model the flexible behavior during stores separation analysis. The need for a better modeling of the structural dynamic behavior became obvious in the integration of a new missile in the wing tip pylon. The missile would be launched in a wide aircraft launch envelope.
The aircraft, pylon, launcher and missile hooks elasticity properties should not only be described by the flexibility properties but also by the structural dynamic behavior. This also includes mass and damping properties of the structure. Hence it is advisable to use a modal model.

This paper shortly describes the modal analysis method, the Modal Rail concept and the implementation in the simulation program that realize the concept.

The Modal Rail has been used in Stores Separation simulations with different missiles launched from three aircraft pylon stations. Comparisons between flight tests and simulations prove much better agreement with the Modal Rail model than with the simpler rail model. This model progress has achieved major improvements to the simulation results.

2 Stores Separation Analysis

The main purposes of stores separation analysis are to guarantee the flight safety at store release, check disturbances on the store in order to ensure autopilot and homing functions as well as analyze the risk of aircraft engine disturbances due to missile plume ingestion.

These analyses are obviously improved by taking the structural dynamic behavior of the fuselage, wings, pylons, launcher and missile hooks into account. Especially in simulations where the missile is launched from wing tip stations at high aircraft load factors.

When the missile moves down the rail at high aerodynamic and mass loads it will affect the aircraft structure and hence the position and motion of the rail. The rail response will in turn affect the missile rates at tip off. The missile roll rate at tip off is a sensitive parameter when looking at seeker performance and it is therefore of great importance to simulate the tip off rates as accurately as possible.

The store separation model is a 6 degree of freedom model of both aircraft and missile respectively. The model is generated from traditional flight mechanics and aerodynamics [2]. By including a modal description of the structural dynamics in the standard flight mechanics simulation model, a fast and robust method is still obtained.

3 Modal Analysis

Modal analysis is a common method in structural dynamic simulations [3]. The new thing is to use modal analysis in flight mechanics and aerodynamic simulations.

3.1 General

The great advantage of using modal analysis instead of other methods is the possibility to use a reduced amount of degrees of freedom. Only the most important normal modes have to be taken into account to get an accurate structural response calculation. This makes it possible to implement the structural flexibility in the simulation model that still mainly shall manage flight mechanics and aerodynamic relations.

Representing the structural dynamics by a set of normal vibration modes, the equations of motion become coupled only through the forcing terms. Each generalized degree of freedom can be solved separately and independent of the others. The connection between physical degrees of freedom and generalized degrees of freedom are performed through the modal matrix. The modal matrix is composed from the structural normal modes which can be extracted from structural dynamic tests or finite element calculations.

Figure 1 and 2 illustrate two typical aircraft normal modes.

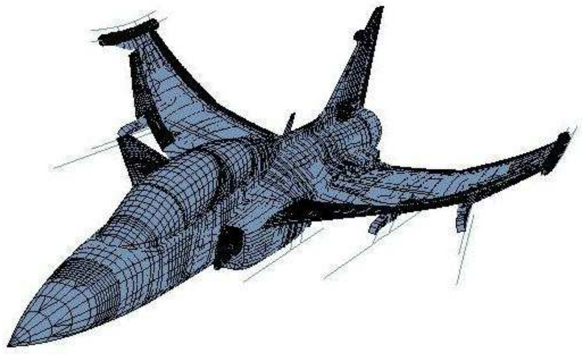

Fig. 1. Aircraft normal mode. Wing bending.

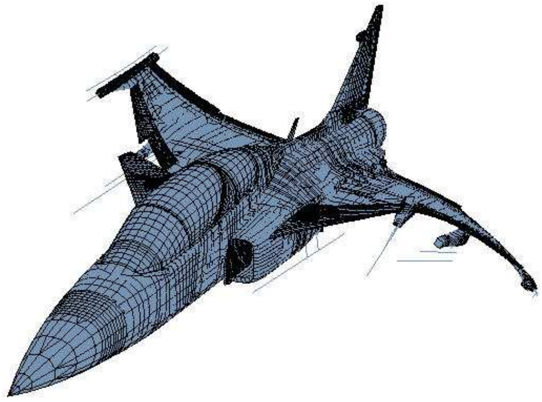

Fig. 2. Aircraft normal mode. Wing Torsion.

3.2 Equations of Motion

The uncoupled Equations of Motion in generalized coordinates have the form

$$m_j \cdot \ddot{q}_j + c_j \cdot \dot{q}_j + k_j \cdot q_j = f_j \qquad (1)$$

whereas

$\ddot{q} =$ generalized acceleration
$\dot{q} =$ generalized velocity
$q =$ generalized displacement
$m =$ generalized mass
$c =$ generalized damping
$k =$ generalized stiffness
$f =$ generalized force

and j represents normal mode number j

further on

$$\zeta = \frac{c}{c_c}$$ damping ratio; c_c critical damping

$$\frac{c}{m} = 2 \cdot \zeta \cdot \omega$$

$$\omega^2 = \frac{k}{m}$$ natural frequency

3.3 Modal matrix

Each normal mode (or eigenvector) is represented by a column in the modal matrix ($\Phi_{i,j}$). Hence the number of rows corresponds to the number of physical node points and the number of columns corresponds to the number of normal modes.

3.4 Generalized forces

The generalized forces (for each normal mode) can be calculated from the physical node forces and the modal matrix. All node forces and node moments in all directions and in all positions are taken into account.

$$f_j = \Phi_{i,j} \cdot F_i \qquad (2)$$

3.5 Generalized acceleration

Hence, the generalized acceleration can be solved from

$$\ddot{q}_j = \frac{f_j}{m_j} - (2 \cdot \zeta_j \cdot \omega_j \cdot \dot{q}_j) - (\omega_j^{\,2} \cdot q_j) \qquad (3)$$

3.6 Physical displacements and velocities

The physical displacements and velocities can be calculated from the generalized displacements and velocities, and the modal matrix.

The procedure is known as the mode summation method, where the displacement of the structure under force excitation is approximated by the sum of a limited number of normal modes of the system, multiplied by the generalized coordinates.

$$x_i = \Phi_{i,j} \cdot q_j \qquad (4a)$$

$$\dot{x}_i = \Phi_{i,j} \cdot \dot{q}_j \qquad (4b)$$

4 Modal Rail

The structural dynamic properties of aircraft fuselage and wings as well as weapon pylons and launchers have a modal representation. The normal modes can represent both global modes on fuselage/wings and local modes on pylon/launcher.

4.1 The launcher rail

The launcher rail is modelled by a limited number of nodes along the rail (about 10 for a common launcher). The normal mode displacements shall be expressed in these nodes. Normal mode displacement between rail nodes can be calculated by linear interpolation. Even forces acting between the rail nodes can be moved to the adjacent node point positions by linear interpolation.

Figure 3 and 4 illustrate examples of displacements from a typical missile launch response analysis. Figure 3 show generalized displacements from the first four natural modes. Figure 4 show the physical z displacements in launcher nose and launcher rear end respectively, based on a mode base of 50 natural modes.

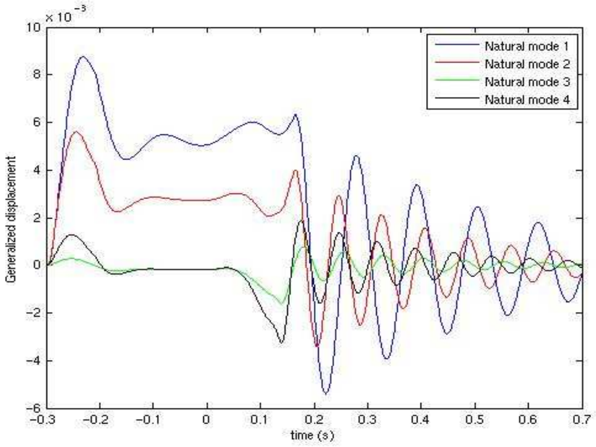

Fig. 3. Generalized displacements.

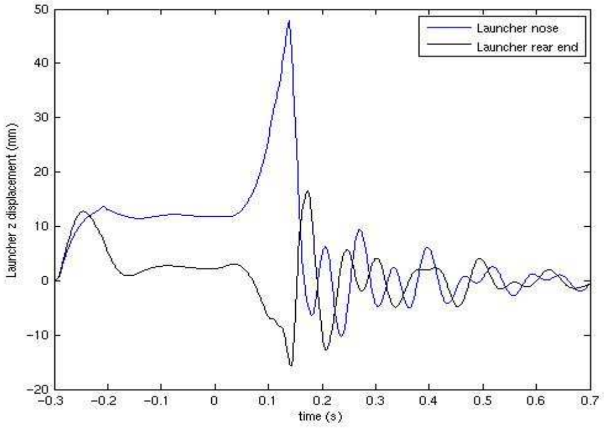

Fig. 4. Launcher z displacements.

4.2 Missile hook forces and moments

The missile hook forces and moments acting on the Modal Rail and the missile respectively are calculated from the small differences in hook positions and velocities. Displacement forces are calculated from position differences and the hook stiffness. Damping forces are calculated from velocity differences and hook damping factors.

The hook forces and moments act as physical forces in the calculations of generalized forces in Eq. (2) and as restoring forces and moments on the missile in the store equilibrium of forces calculations.

4.3 Static equilibrium

The aerodynamic- and mass loads on the missile during the captive flight just before the missile firing has to act on the launcher and aircraft wing in order to deform the structure into a preloaded condition. Hence, before the missile motor starts and the missile begin to travel down the flexible rail the static equilibrium position has to be found.

First all external loads (e.g. missile air loads and aircraft load factor) are applied in a careful way (e.g. by a cosine function). After the loading is finished there has to be a damping time period to let the system find the equilibrium position.

Initially both the modal damping and missile hook damping are scaled to high damping values. The damping then decreases to nominal values when equilibrium has been reached. Now the missile can be fired and the main Stores Separation Analysis will start.

The length of the loading and transient damping period depends on the properties of the structural dynamic system. With a proper damping model the time should be about 3 times the frequency of the lowest natural mode. In the example in Figure 3 and 4 a loading time of 0.3 s is used.

5 Simulations

The way of combining classical modal analysis with the advanced model for aerodynamic and flight mechanics analysis has been successful. The method is robust and the simulations are still very fast.

5.1 States and derivatives in model

Besides the usual states (integrators) used in a common Stores Separation Analysis the generalized displacements are chosen as states. The generalized velocities are chosen as the corresponding derivatives. It is obvious that the number of states will be the same as the number of natural modes.

5.2 Tip of effects

At the firing the tensioned situation changes during the missile rail travel depending on all external loads, hook forces, aircraft motion etc. At tip off, the missile motion is affected by the lash of the launcher.

5.3 Simulation experiences

The Modal Rail has been used in Stores Separation simulations with different missiles launched from three aircraft pylon stations.

Results from simulation of launching of wing tip missile are illustrated by some pictures in Figure 5 and 6. The corresponding Euler angles are illustrated by graphs in Figure 7, 8 and 9. The Euler angles are also compared with a simulation with a rigid aircraft. The missile is fired at time = 0 s.

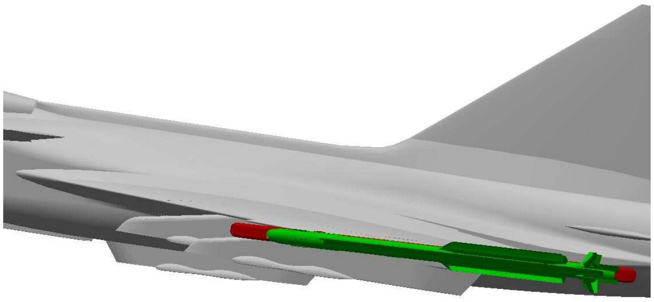

Fig. 5. Wing tip missile in captive carriage position.

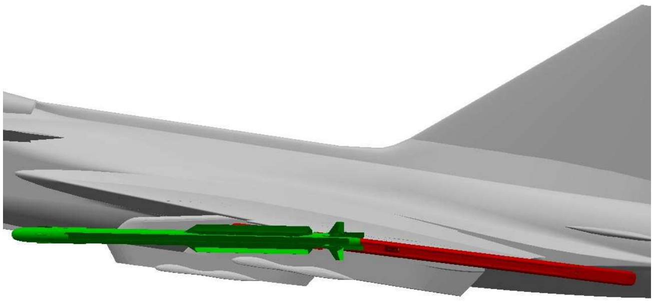

Fig. 6. Wing tip missile in tip off position.

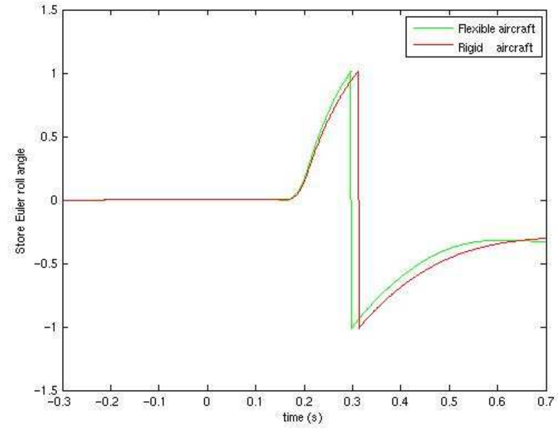

Fig. 7. Missile roll angle.

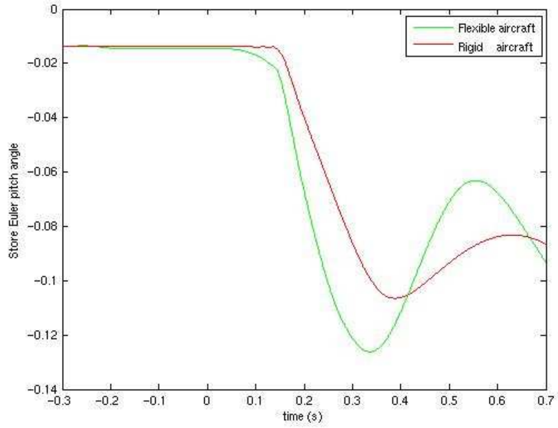

Fig. 8. Missile pitch angle.

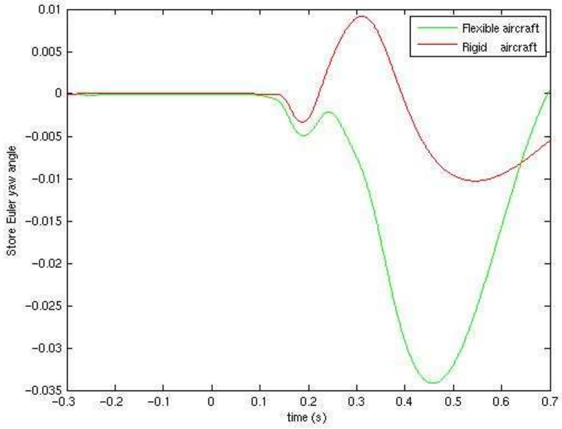

Fig. 9. Missile yaw angle.

5.4 Flight test comparisons

Comparisons between flight tests and simulations prove much better agreement with the Modal Rail model than with the simpler rail model. In Figure 10 simulations with a rigid and a flexible aircraft respectively, are compared with the corresponding flight test. The agreement between simulation and corresponding flight test is substantially improved when including the structural dynamic behavior of the aircraft.

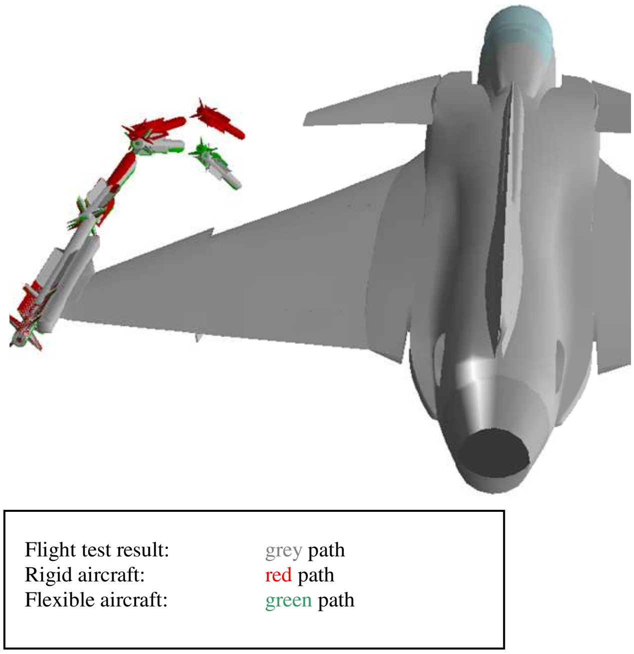

Fig. 10. Comparisons between simulation and flight test results.

6 Future

The simulation model will be enhanced to be able to also manage ejection and jettison store separation analyses with a flexible aircraft. The improvements will also include multiple store separations with short time interval between the separations.

7 Conclusions

It is essential to take the structural dynamic effects into account in missile launch analysis. But it is also very important to consider all aerodynamic and flight dynamics effects. Hence it is hard to use a common structural dynamics tool (e.g. Finite Element Method), especially in tough aircraft flight conditions. In the presented method a pleasant balance between aerodynamic, flight dynamic and structural dynamic effects has been achieved.

References

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[2] Etkin B**.** *Dynamics of Atmospheric Flight*. 1st edition, Dover, 2005.

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