Aeroservoelastic Analysis of RLV-TD HEX01 Mission

Mahind Jayan, P. Ashok Gandhi, Sajan Daniel, and R. Neetha

Abstract Study of Aeroservoelastic (ASE) interactions is of prime importance in modern aircrafts employing autonomous flight control systems. The complex nature of unsteady aerodynamic forces can induce adverse ASE coupling effects leading to mission failure. This study discusses the ASE analysis of Reusable Launch Vehicle Technology Demonstrator Hypersonic Experiment (RLV-TD HEX01) of the Indian Space Research Organisation (ISRO). Pertinent modeling philosophy adopted for various subsystems, analysis methodology, validations, and simulations carried out to establish closed loop stability of RLV-TD system is discussed in detail. The results of the study clearly indicate the absence of adverse modal coupling in the presence of unsteady aerodynamic and control forces. The existence of adequate closed loop damping for critical structural modes is established through simulations to ensure adverse interaction free environment in the experimental flight.

1 Introduction

RLV-TD HEX01 of ISRO employs autonomous navigation, guidance, and control systems in the descent phase of flight. These systems have to perform with a high degree of reliability under demanding re-entry environment. The flight control system uses motion sensors (accelerometers, pitch, roll, and yaw rate gyros) to measure aircraft rigid body responses which are then processed by the control law embedded in the digital flight control computer to provide appropriate feedback signals to the primary control surface actuators to stabilize and control the aircraft. As the total vehicle response is the sum of a rigid body and elastic body responses, the motion sensors also pick-up the airframe dynamic responses due to elastic vibration modes of the structure at the sensor locations. These signals when processed by the digital flight control computer and fed back to the actuators may generate an undesirable

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effect on the aircraft responses if adequate attention is not paid on the closed loop stability of the system.

The adverse effects include degradation in the handling qualities, adverse modal coupling, and increased elastic vibrations or, in extreme cases, dynamic instability of the aircraft [1]. RLV-TD descent phase configuration is a system with strong aerodynamic and structural coupling. These characteristics were established and validated from the series of wind tunnel and ground vibration tests conducted. The unsteady aerodynamic effects present in the descent phase can induce modal coupling which can prove detrimental to the mission [2]. Aeroservoelasticity represents this mutual interaction between the flight control system and the airframe dynamic response due to inertial and unsteady aerodynamic forces.

2 Mathematical Models

The primary prerequisite for a linear ASE stability analysis is the availability of a mathematical model representing the rigid body and elastic structural vibration modes of the vehicle. The unsteady aerodynamic loads produced by airframe oscillations and dynamic characteristics of the closed loop control subsystem including control actuator dynamics are to be incorporated for generating an integrated ASE computational model.

MSC.NASTRAN™ 2014, has been used as the analysis environment due to the proven capability of the software in capturing the integrated effects of structural dynamics system, unsteady aerodynamic system, and servo dynamic system [3]. Figure 1 illustrates the different component models that are assembled together to create the integrated aeroservoelastic model.

2.1 Integrated Finite Element Model

A detailed Integrated Finite Element Model (IFEM) was created to capture the rigid body and flexible body dynamics of RLV-TD descent phase configuration. Eigenvalue analysis was performed on the model, and the relevant elastic mode shapes and corresponding frequencies were established. The results of the Eigenvalue analysis were validated against those obtained from Ground Resonance Tests (GRT). Modal parameters of critical structural modes were matching closely with the experimentally estimated values. Figure 2 illustrates the IFEM highlighting major structural components. Rudder and elevon are the control surfaces employed during the descent phase of flight.

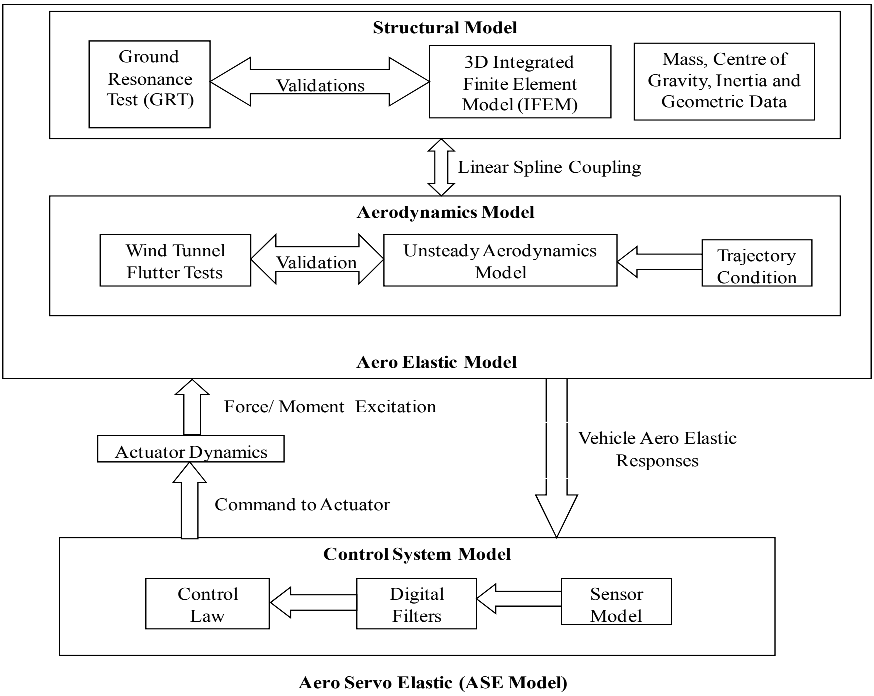
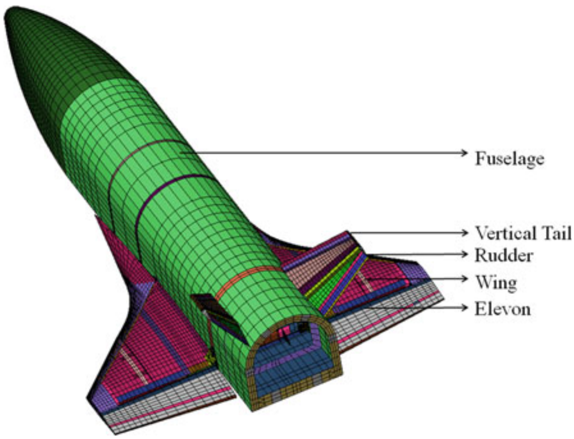


Fig. 1 ASE model synthesis

Fig. 2 RLV-TD integrated finite element model



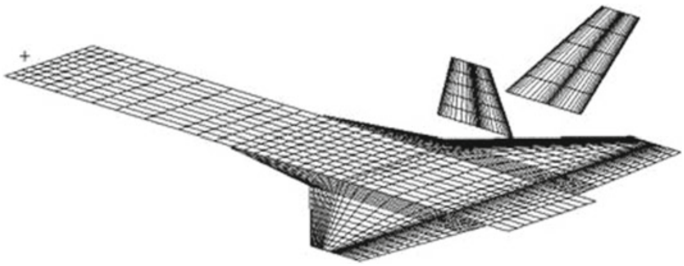


Fig. 3 RLV-TD aerodynamic mesh

2.2 Unsteady Aerodynamics Model

Unsteady aerodynamic forces are produced by flow disturbances due to elastic vibrations and due to turbulence where the flow itself is unsteady [4–6]. Unsteady aerodynamic forces have a characteristic phase lag with respect to the aerodynamic excitation which depends mainly on the flow Mach Number and reduced frequency [7]. Steady and quasi-steady aerodynamic models are not adequate to capture the effects of phase lag, and therefore, proper simulation of unsteady aerodynamic effects is a prerequisite for ASE study of winged body vehicles.

Aerelasticity module of MSC.NASTRAN™ 2014, has been used to generate the complex unsteady aerodynamic influence coefficient matrices for various regimes of flow. The unsteady aerodynamic mesh used for RLV-TD is shown in Fig. 3. Linear spline theory has been used for coupling the structural degree of freedom displacements of RLV-TD IFEM to the aerodynamic degree of freedom displacements and thereby synthesize the aeroelastic model. The present analysis has used ZONA51 method for the supersonic regime and Piston Theory for the hypersonic regime of flight, respectively, for generating aerodynamic influence coefficient matrices [8].

2.3 Control System Model

Schematic block diagram of RLV-TD descent phase integrated digital flight control system is shown in Fig. 4. The case under study uses acceleration and rate feedback from respective sensors for generating the control surface deflection commands. Numerical models of various control loop elements viz. sensors, filters, actuators are represented in the Laplace domain as second order transfer functions. Control system elements with higher order transfer functions are cascaded and idealized as a number of second order systems. The Transfer Function (TF) option in MSC.NASTRAN™ 2014, is used to represent all the elements of the control system [9]. Control system degrees of freedom are modeled as Extra Points (EP) in the input driver deck. The output variable of a transfer function is represented in the form of linear combination of input variables as in Eq. (1).

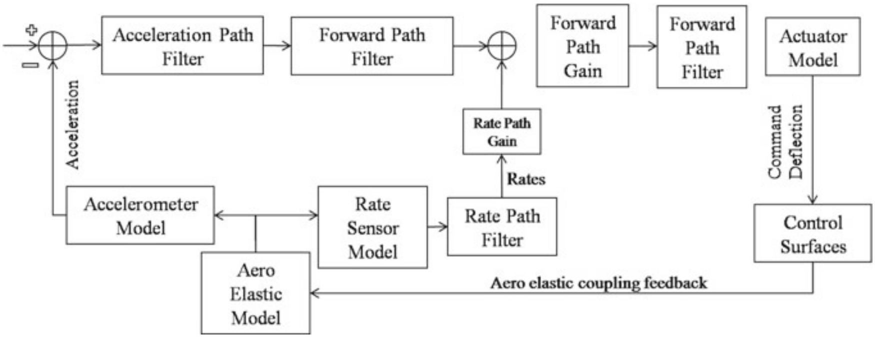


Fig. 4 Integrated ASE model

$$\{M_d s^2 + C_d s + K_d\}u_d - \sum_{k=1}^{n}\{M_k s^2 + C_k s + K_d\}u_i^k = 0 \tag{1}$$

In Eq. (1) u_d is the output/dependent variable and u_i^k is the kth input/independent variable. Terms $\{M, C, K\}$ correspond to the equivalent mass, damping, and stiffness terms, respectively, of the associated transfer function. These terms are assembled and added appropriately to the global aero elastic matrices to generate the aeroservoelastic matrices.

Actuator modeling is an important aspect of the ASE analysis [10]. In line with other control system elements, actuators have been modeled as shown in Eq. (1). Actuator transfer function is modified so that the dependent variable is a moment acting on the control surface shaft. This allows the combined dynamics of actuator, control surface, and support structure stiffness to be captured in the analysis.

3 Mathematical Formulation of ASE Problem

The synthesis of ASE problem lends itself amenable to frequency domain solution schemes. The integrated ASE matrices have the following form as in Eq. (2).

$$[M_s + \rho M_a + M_c]\ddot{q} + [C_s + \rho v C_a(\chi) - C_c]\dot{q} + \left[K_s + \rho v^2 K_a(\chi) - K_c\right]q = 0 \tag{2}$$

In Eq. (2) $\{M, C, K\}$ correspond to the equivalent mass, damping, and stiffness matrices of the structural, aerodynamic, and control subsystems with the subscript $\{s, a, \mathrm{c}\}$ representing structure, aero, and control, respectively. ρ and v represent the free stream density and flow velocity, respectively. The nondimensional parameter χ is the reduced frequency which is a measure of time taken by the flow to travel a chord length of the lifting surface to the time period of corresponding modal oscillation.

The magnitude of reduced frequency determines the level of unsteadiness in the flow. Aerodynamic matrices generated depend on χ and the free stream Mach Number (M).

For a given operating point Eq. (2), can be reduced to Eq. (3)

$$\left[M\lambda^2 + C\lambda + K\right]\{\emptyset\} = 0 \tag{3}$$

where λ is the complex Eigenvalue of the system and is of the form given by Eq. (4).

$$\lambda = \alpha \pm i\omega \tag{4}$$

Stability of the system defined by Eq. (2), can be evaluated by estimating the complex Eigenvalue, λ of the system. The real part of,λ i.e., α of a structural mode is a measure of closed loop damping of the corresponding mode. For a closed loop ASE system to be stable, the condition for stability is given by Eq. (5).

$$\alpha \le 0 \tag{5}$$

ASE analysis aims at finding the effective closed loop damping of all critical structural modes under the influence of unsteady aerodynamics and control system feedback. The stability of the system is ensured if all structural modes have adequate positive damping ratio which is equivalent to the condition in Eq. (5) being satisfied.

4 Simulation Studies

Complex Eigenvalue Solution sequence, SOL 145 of MSC.NASTRAN™ 2014, has been used for estimating the system Eigenvalues employing the PK method as a solution scheme. Initially, complex Eigenvalue analysis was performed on the closed loop servo elastic system to estimate the changes in modal characteristics due to combined servo elastic system dynamics. It was observed that the structural mode shapes and frequencies of the servo elastic system are very close to values observed from GRT and real Eigenvalue analysis of the IFEM. Critical mode shapes are shown in Fig. 5. Analysis of the open loop structural frequencies highlights adequate spacing between the structural modes and control modes. Hence, the frequencies of close loop servo elastic system are expected to be sufficiently close to frequencies of the structural system, and this was established through Eigenvalue analysis of servo elastic system.

Figure 5 shows the existence of lifting surface modes and control surface modes with significant elastic coupling. As unsteady aerodynamic effects can induce modal coupling due to the induced phase lag comprehensive ASE analysis, simulation studies were carried out at critical time instants to ensure the absence of adverse coupling.

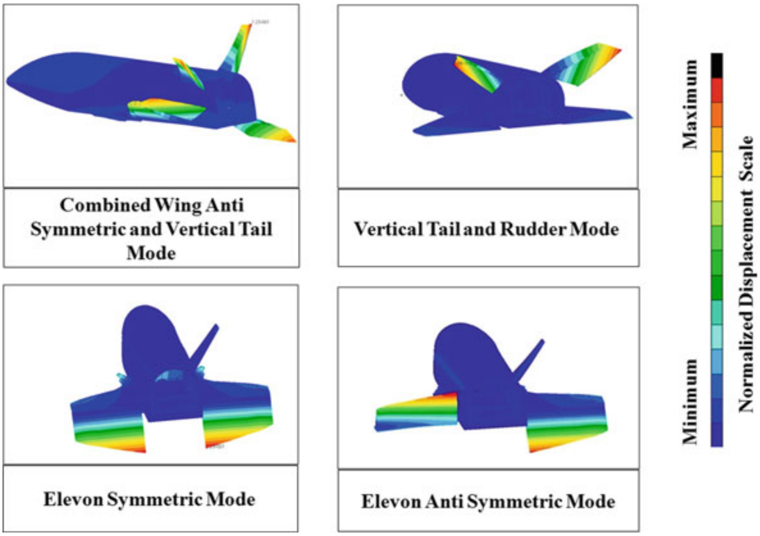


Fig. 5 Critical lifting surface mode shapes

Minimum margin cases with respect to control system stability were selected for assessing the ASE stability. These cases correspond to supersonic and hypersonic regimes of descent phase flight trajectory. ASE analysis was carried out at trajectory conditions corresponding to the minimum margin cases by using the corresponding flight dynamic pressure, Mach Number, and control system gains. Simulations were carried out with a conservative modal damping ratio of 0.5%. For the minimum margin case, all the critical structural modes have positive damping indicative of system stability.

Further, perturbation studies were carried out by variation of flight velocity around the neighborhood of the minimum margin point. Modal frequency versus Flight velocity (v–f) and Modal Damping versus Flight velocity (v–g) curves was extracted to understand the associated variation in closed loop frequency and damping with variation in flight velocity. Figure 6 depicts v–f and v–g curve for a minimum margin case. A closer study of the damping curves in Fig. 6, reveals that effective close loop damping of the ASE system is more than the assumed modal damping ratio. Hence, it can be inferred that for the ASE system under study aerodynamic damping from unsteady aerodynamics and control system damping are augmenting the structural damping. All the critical structural modes studied showed damping to increase with flight velocity which implies higher aerodynamic damping due to an increase in dynamic pressure. Most of the critical modes exhibit a linear increase in damping with flight velocity as expected for a case with minimal aeroelastic coupling. However, the elevon symmetric mode shown by magenta dash dot lines and elevon asymmetric mode shown by blue dash lines displays a nonlinear variation in damping against flight velocity.

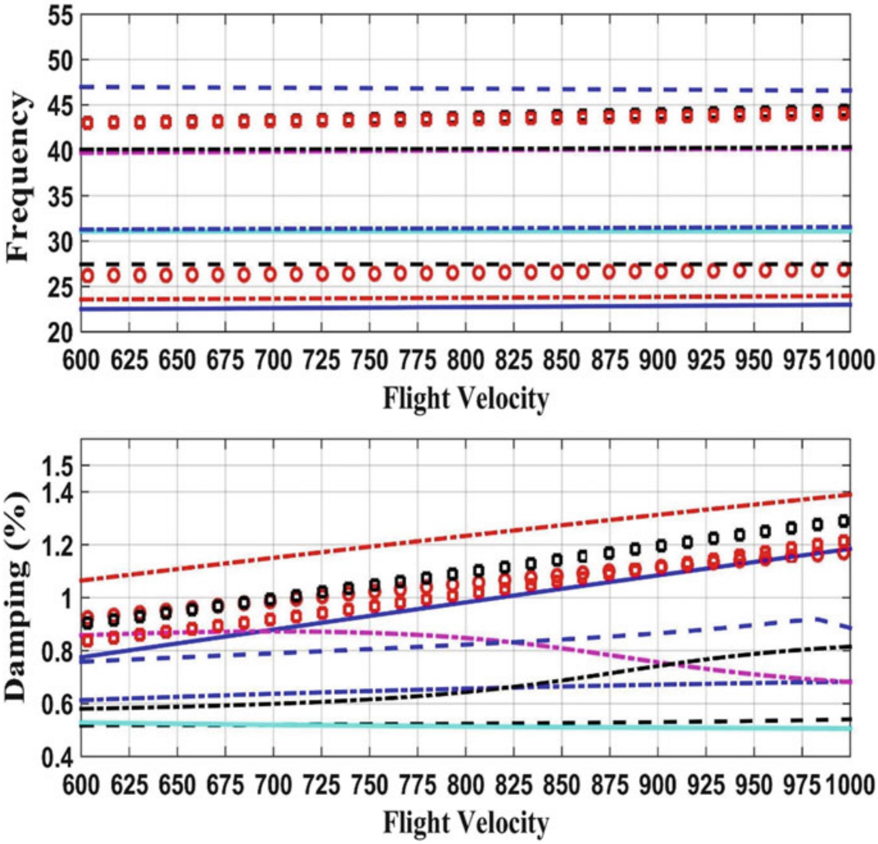


Fig. 6 Minimum margin case v–f and v–g curves of critical modes

Coupled dynamics of the actuator, control surface, and support structure stiffness combined with flow unsteadiness will have a pronounced effect on the control surface modes leading to the nonlinear variation seen. Nevertheless, the values of closed loop damping observed are within acceptable limits. High frequency modes of vertical tail and rudder show a tendency of modal frequency coalescence at higher flight velocities, however, higher positive damping for these modes with increasing damping trend assures modal stability.

5 Conclusions

This paper presents an approach to evaluate closed loop stability of an aeroservoelastic system. The problem formulation, ASE model synthesis and implementation, simulation studies, and discussion on results have been presented comprehensively.

Closed loop stability of critical structural modes of RLV-TD HEX01 mission for descent phase has been estimated and found to be within acceptable limits. The robustness of servo elastic design by allowing for significant bandwidth between control modes and structural modes has helped in achieving adequate margins from the vehicle stability point of view. Signatures of aeroservoelastic interactions clearly seen for control surface dominated modes are explained, and stability has been ascertained for various perturbations.

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