Dynamic Landing Response Analysis of a Flexible Tailless Delta Wing Aircraft

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Abstract

Modern tailless delta wing aircraft is built for high performance with light weight leading to structural flexibility. During landing, high vertical sink rate of aircraft causes peak transient loads in and around the landing gear attachment locations. These reactions forms the load cases for local sizing of airframe and its responses determine the overall integrity. This paper describes the co-simulation approach to carry out the dynamic landing analysis on a flexible tailless delta wing aircraft and examines the responses at certain critical locations such as the tip of wings, fin and nose for nominal landing conditions. The reactions are obtained from the Landing gear supplier through MSC Adams multi-body dynamic simulation of full aircraft with non-linear stiffness and damping models of Nose and Main landing gear systems. The landing response analysis is carried out on a flexible aircraft using industry standard MSC Nastran as transient dynamic problem with base enforced motion. It is observed that the regions that are farther located such as wing, fin and nose tips are susceptible to get excited at their inherent modes thereby picking up intense responses. This co-simulation approach of solving the transient dynamic analysis from the force response of multi-body simulation provides the specifications very early in the design process and aids in structural dynamic checks before getting validated from the full fledged flight test.

NOMENCLATURE

θ	*pitch angle (deg)*
θ_{maxa}	*maximum pitch angle (deg)*
$[\Phi]^T$	*modal matrix*
δ_y	*lateral displacement (mm)*
δ_z	*vertical displacement (mm)*
$\delta_{\lvert ymax \rvert}$	*maximum absolute lateral displacement along y-axis (mm)*
$\delta_{\lvert zmax \rvert}$	*maximum absolute vertical displacement along z-axis (mm)*
$\{F_a\}$	*shock absorber forces (N)*
$\{F_{A/L}\}$	*forces reacted on the aircraft by the landing gear (N)*
$[F_C]$	*non-linear forces due to damping (N)*
$\{F_{L/A}\}$	*forces applied by the L/G on the aircraft (N)*
$\{F_0\}$	*external forces (N)*
$\{F_r\}$	*tyre forces (N)*
g	*acceleration due to gravity (mm/sec^2)*
$[k]_g$	*matrix of generalized aircraft stiffness (N/mm)*
$[m]_g$	*matrix of generalized aircraft mass (kg)*
$[m]_{lg}$	*matrix of generalized masses of landing gear (kg)*
N_y	*lateral acceleration along y-axis (g)*

N_z	*vertical acceleration along z-axis (g)*
$\lvert N_{ymax}\rvert$	*maximum absolute lateral acceleration along y-axis (g)*
$\lvert N_{zmax}\rvert$	*maximum absolute vertical acceleration along z-axis (g)*
$\{q\}$	*geometric co-ordinates*
t	*time (sec)*
$[V_a]$	*shock absorber forces geometric transformation matrix (N)*
$[V_r]$	*tyre forces geometric transformation matrix (N)*
V_s	*sink rate (m/s)*
V_{smax}	*maximum sink rate (m/s)*
$\{x\}$	*modal coordinate*
x, y, z	*global rectangular Cartesian coordinates (mm) (longitudinal , lateral, vertical axis)*

1. INTRODUCTION

During landing, the airplane vertical velocity is quickly reduced to zero when the wheel strikes the ground. The kinetic energy due to the sink rate is transferred as internal energy for the shock absorber system that efficiently absorbs due to nonlinear stiffness and damping characteristics. The rapid change in velocity causes large landing impact forces at the attachment locations of Landing Gear (L/G) to the airframe. This dynamic phenomenon as transient loads will primarily be the dictating load case for local sizing of airframe at attachment locations. Qualification of structures from strength perspective at these locations is essential; nevertheless the overall structural integrity of the aircraft in terms of local responses at locations farther away from aircraft Centre of Gravity (CG) is equally vital and safety critical.

It is reported that more than 50% of accidents happen when the aircraft is on the ground (including take-off and landing) [1]. The requirement for higher performance with light weight had driven the airframe design to be more flexible that were the precursor for these dynamic responses to peak up. There is a specific need to understand these ground loads related problem through reliable simulation at the early stage of development process or else it would jeopardize the program time schedule leading to disproportionate cost and leaving little space for design improvements.

First attempt to handle the dynamic landing response problem is from the assumption that "the time history of landing impact force is independent of elastic properties of the structure" [2-3]. The 'uncoupled assumption' allows the problem treatment as two separate systems namely the L/G and aircraft. The L/G is a complex and highly non-linear system that includes the landing gear kinematics, components such as axles, wheels, tyres, leg oleo struts / shock absorbers, drag struts and jacks etc. The aircraft is considered rigid when handling the problem as uncoupled. The landing gear numerical model used by the Landing gear supplier is validated with the drop test result and this model is used to obtain the transient loads at the attachment locations as force response output. Then, these loads time-histories are applied to a flexible finite element model of the aircraft validated for modal frequencies through Ground Vibration Test (GVT) to obtain the responses of full aircraft.

The requirement for landing impact load cases for military aircrafts of US origin is covered in section 4.1.2.2 of MIL-8863 specification [4]. As stated, "Ground loads flexible airframe analyses program shall be established to determine the static and dynamic loads and responses that result from the conditions of the ground loads design criteria". The requirement considers the aircraft weight is balanced by lift at the time of touch down. Inline to this, the Design and Airworthiness requirements for service aircrafts [5] (DEF STAN 00-970 Volume 1; Chapter 304) standard of British origin covers the requirement for ground loads on L/G for military airplanes. Accordingly, the overriding limitation of structure and L/G may be checked and satisfied by carrying out a dynamic analysis of the aircraft. The civil aircraft requirement is regulated by Federal Aviation Regulations [6] (FAA-25) of US origin and British Civil Airworthiness Requirement [6] (BCAR) of British origin are much similar to the military requirements except the descent velocities are lower.

The problem of determining the loads on the elastic aircraft structure due to landing impacts was treated by Williams [7] with the assumption that the landing gear loads to be known functions of time. The loads in the structure are considered to be the sum of the loads which would be experienced by a rigid structure and the loads due to the response motion of the elastic Wing. This method of approximately calculating wing loads in elastic structures is called the “mode acceleration method”. A publication by Biot and Bisplinghoff [2] introduces the concept of “normal modes” as a very first attempt in the field of Aeronautical Sciences. In this work, the loads acting in the wing are calculated by means of a summation of basic load distributions, which in turn are the distributions of inertia loads produced by vibration in one of the normal modes. The total response follows from a summation of normal modes, each multiplied with different participation factors, in the so called generalized coordinates. The total load follows from a summation of these basic load distributions, each multiplied with the momentary values of the respective generalized coordinates. This method for calculating loads is known as the “mode summation method”.

Another method for the calculation of dynamic loads in elastic structures is presented by Shou-Ngo-Tu [8]. Assuming known velocity time histories of the landing gear connection points to the wing, it is shown that for a simple beam the response can be described by a superposition of rigid modes and normal modes of the elastic structure with nodal points at the landing gear attachments. As a consequence the landing gear connection point time history cannot contain components due to structural elasticity. This is due to the velocity time history, which is assumed to be known, has been determined assuming the wing structure to be rigid. The interaction between landing gear load and wing elasticity is the subject of an experimental as well as a theoretical investigation by Mc-Pherson, Evans and Levy [9]. It is found that landing gear loads are reduced by approximately 10% taking into account wing elasticity.

A comparison of the accuracy of the different methods for the calculation of landing loads, viz., the mode acceleration method of Williams [7], the mode summation method of Biot and Bisplinghoff [2] , and the method of Levy [9], is performed by Ramberg [10]. This is done by comparison of calculations with results of model drop tests. It was found that the mode acceleration method and the method of Levy [9] are superior to the mode summation method. With all these methods of calculating landing loads it is always assumed that the landing gear load time histories are unaffected by Wing elasticity.

Therefore the calculation can be split into two phases. Firstly, the calculation of the time histories of the landing gear loads assuming the structure to be rigid, and secondly the response calculation of the elastic structure to the known external loads. Until now, this two step uncoupled simulation approach is being followed for majority of the aircrafts that has horizontal stabilizer, either forward as Canard configuration or in the aft as conventional tail plane configuration [11-12]. The main interest of this paper consists of performing a dynamic response analysis and estimation of the elastic behavior for flexible tailless delta wing aircraft which does not have a horizontal stabilizer for pitch control. The location of these movable control surfaces are farther away from the centre of gravity than it is for conventional airframe which are susceptible to pick up intense acceleration.

2. ANALYSIS PROCEDURE

2.1. Configuration of the Aircraft

Figure 1. shows a typical tailless delta wing aircraft which consist of four ELEVONS (ELEVator + ailerON) at trailing edge (symmetrically placed at inboard and outboard), as the primary control surface for lateral (Roll) and longitudinal (Pitch) control, with a Rudder hinged to single vertical tail for directional (Yaw) control. The aircraft considered is longitudinally unstable, controlled by digital fly-by-wire system to meet the twin objectives of low structural weight and high maneuverability. The non-existence of separate horizontal stabilizer has enabled to utilize ELEVONS for pitch and roll control. This tailless wing configuration of aircraft makes the problem interesting to understand the responses obtained at locations that are farther away. The aircraft has a tricycle landing gear arrangement with steerable nose wheel on front and main wheels located just aft of aircraft CG on either side. The main wheels are fuselage mounted with oleo pneumatic shock absorber and drag strut to limit lateral deflection during landing. The nose wheel is a two stage oleo pneumatic shock absorber. Both nose and main wheels has telescopic landing gear layout [13].

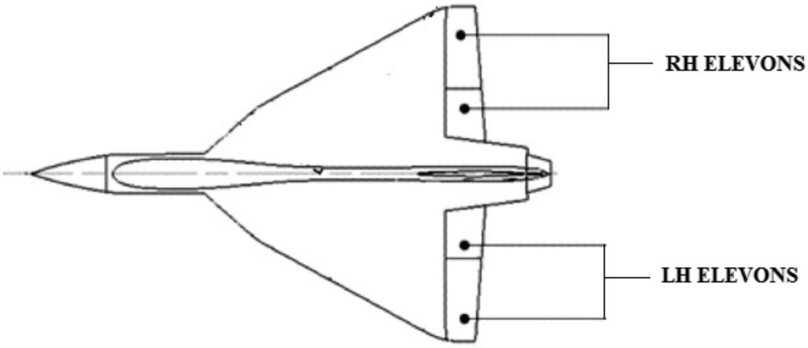

Figure 1. Typical Tailless Delta Wing Aircraft with ELEVONS

2.2. Problem Statement

The aircraft structure is considered a linear system, its characteristics and deformation are governed by a set of equations formulated in modal coordinates. The landing gear equations of motion involve the kinematic non-linearities and the elastic non-linearities of tyres and shock absorbers, considering all the structural components that constitute the landing gear as rigid. These two systems coupling leads to a system of landing gear equations of motion that takes into account its non-linear behavior and its interaction with a flexible structure [14]. The aircraft equations of motion in modal coordinates are:

$$[m]_g\{\ddot{x}\} + [c]_g\{\dot{x}\} + [k]_g\{x\} = [\varphi]^T\{F_0\} + [\varphi]^T\{F_{L/A}\} \tag{1}$$

Where $\{x\}$ is the modal coordinate, $[m]_g$ is the matrix of generalized mass, $[k]_g$ is the matrix of generalized stiffness, $[\Phi]^T$ is the modal matrix, $\{F_0\}$ are the external forces and $\{F_{L/A}\}$are the forces applied by the L/G on the aircraft. The term $\{F_0\}$ is to include the terms such as gravity, aerodynamic forces, engine thrust, braking forces etc.,.

The landing gear is considered as a kinematic mechanism consisting of elements such as tyres, shock absorbers and supports the rest of the aircraft structural weight. The L/G elements mass characteristics are represented by lumped masses with their corresponding inertial moments. The equations of motion are derived from the Lagrange equations, obtaining the following system in matrix form:

$$[m]_{lg}\{\ddot{q}\} = [V_r]\{F_r\} + [V_a]\{F_a\} + \{F_{A/L}\} + \{F_C\} \tag{2}$$

where $\{q\}$ represent the landing gear geometric co-ordinates, $[m]_{lg}$ is the matrix of generalized masses, $[V_r]$ is the tyre forces geometric transformation matrix, $\{F_r\}$ are the tyre forces, $[V_a]$ is the shock absorber forces geometric transformation matrix, $\{F_a\}$ are the shock absorber forces, $[F_c]$ are non-linear terms in {q} and $\{F_{A/L}\}$ are the interaction forces of aircraft-landing gear. The system matrices (2) have a non-linear dependence on the degrees of freedom that define the L/G position $\{q\}$.

The force produced by all the L/G elements depends on its deformation in the non-linear form, and its deformation speed in the shock absorber case. The motive will be to transfer the force $\{F_{A/L}\}$ extracted from a multi-body simulation and transfer it as $\{F_{L/A}\}$ on to the whole aircraft model at attachment locations.

2.3. Multi-Body Simulation model

In the world of Computer Aided Engineering (CAE), Multi-Body Simulation (MBS) is the most preferred tool for analysis of the dynamics of ground-based vehicles. In research programme and industrial applications, MBS has proven to be an efficient tool for analysis and evaluation of the ground dynamics of large and flexible aircraft structures. In most cases, it is in-house software of aircraft manufacturers or Landing gear suppliers. Some of these applications are in modular form prepared as custom-made codes such as GRAP [15] and SD-Approach (BAe Systems, Stirling Dynamics Ltd.)[16]. Commercial engineering software tools offers improved handling qualities, more detailed documentation and a high degree of expandability. In general, they represent the latest state-of-the-art techniques in their specific discipline. These tools, e.g. MATLAB Simulink [17], MATRIXx [18], System build [19], offer easy-to-use possibilities for conventional (linear) system analysis.

The most common tool in this respect is MBS software, e.g. SIMPACK [20], DADS [21] or MSC Adams [22] which can be used for very detailed, nonlinear simulation of complex scenarios. With increasing importance of an aircraft's dynamic behaviour on the ground and growing complexity and interdisciplinary nature of the problems to be solved, the use of specialized commercial simulation tools is clearly favoured in industry and research. Today, almost all major aircraft and landing gear manufacturers use one of the major MBS software packages for their ground dynamic analyses.

The full aircraft assembly consists of the rigid airframe with main and nose landing gear systems modeled using MSC Adams as shown in Figure 2. The landing is considered to be 3-point landing with both the main landing gear (Starboard & Port) and nose landing gear touching down. The main landing gear represents the actual geometric kinematics and components such as oleo-pneumatic shock strut assembly with appropriate non-linear damping and stiffness, actuation jack, drag brace strut, wheel and axle assembly with non-linear tyre model. The nose landing gear represents the actual geometric kinematics and components such as two stage oleo-pneumatic shock absorber with hydraulic actuation jack. The aerodynamics lift and the engine thrust are also modeled. Tyre deflection characteristics with horizontal and lateral frictional forces are modeled appropriately. At the time of touch down the lift balanced by weight of the aircraft is considered [2]. Aircraft landing is a critical event which has certain form of uncertainties attributed to data and model. Data uncertainties such as statistical nature of atmosphere, trim and handling parameters, unsteady air load distribution due to turbulence, the mass and CG variation due to fuel consumption can partially be attempted by robust interface codes. Model uncertainties such as landing gear damping characteristics on a hot and cold day, flexibility of structures at attachment locations, accurate contact forces due to friction can be catered by high fidelity 'verified mathematical' models. The reaction loads derived from the co-simulation approach is on the conservative side covering up for the uncertainties.

With the input as aircraft vertical sink rate the simulation is carried out for duration of 2.5 seconds to extract the force reactions at the attachment locations of main and nose landing gear systems represented as $\{F_{A/L}\}$ in equation (1). The simulation time captures the most worst event of impact loading realized by the Aircraft. A typical reaction force along the vertical direction (z) with the time history plot indicating the main and nose landing gear initial impact is shown in Figure 3. with the respective time stamps.

Figure 2. Typical MBS model showing Main landing gear and Nose landing gear

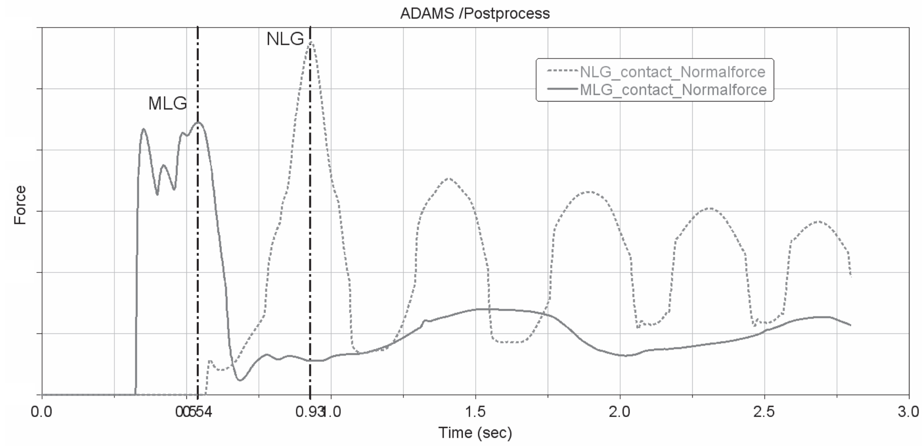

Figure 3.Landing simulation showing force response plot for Main landing gear and Nose landing gear using MSC Adams

2.4. Dynamic response model

MSC Nastran is used for carrying out this transient dynamic response problem [23]. The dynamic model consists of finite element mesh having more than one hundred thousand degrees of freedom as shown in figure 4. Masses are lumped at their respective locations using CONM2 cards. Natural frequencies and modes are extracted from the full finite element model and validated against GVT data. Modal damping is provided as frequency damping pairs obtained from GVT data. The numerical model is suitably fine tuned to represent the characteristic of aircraft that is tested.

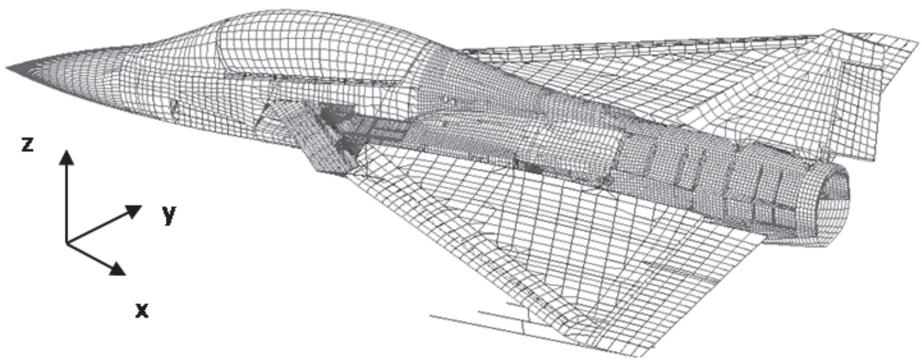

Figure 4.Finite Element Mesh model using MSC Nastran

2.5. Dynamic landing analysis

Response of the structure to the dynamic landing can be carried out using Direct transient response method or as Modal transient response method. While the former method uses numerical integration technique to solve the coupled equations of motion the later method uses the mode shapes of the structure to reduce the size, uncouple the equations. The Modal transient response method makes the numerical integration more efficient as the problem is handled in terms of behavior of modes rather than the grid points. The mode shapes are typically computed as part of the characterization of the structure, Modal transient response is a natural extension of a normal modes analysis. The number of modes computed is typically less than the number of physical variables and hence the modal transient response method can be very effective for large model and smaller integration time steps.

The spatial information of the location and direction of forces that are applied is specified using Force and Moment cards. The time dependent loads are provided using the relevant in MSC Nastran. The force inputs are converted from MSC Adams results and written in the compatible format for MSC

Nastran. Delay between the Nose and Main L/G impact can be handled in two ways. The first approach is to use Delay card in MSC Nastran such that the time difference can be specified. This approach is useful when the drop test results are available and the results have to be incorporated. The second approach is to capture the delay inherently from MSC Adams and applied directly. The modal approach with inherent time delay is followed.

The most important consideration for transient dynamic analysis is the integration time step. The time step size determines the accuracy of the solution, the smaller its value, the higher the accuracy. A time step which is too large will introduce errors that affects the response due to higher modes. A time step which is too small will exhaust the resources and increase the computation time. The optimal time step should be small enough to resolve the motion of the structure. Since the dynamic response can be thought of as a combination of modes, the time step should be able to resolve the highest mode which contributes to the response. It would be a good approximation to use twenty points per cycle of the highest frequency of interest that results in a reasonable accurate solution.

3. RESULTS AND DISCUSSION

Landing response analysis for the full aircraft model is carried out for two landing cases. The Maximum Pitch Angle (MPA) load case simulates the soft landing with low sink rate. The Maximum Sink Rate (MSR) load case simulates the high sink rate landing with less pitch angle. The axis convention followed for result interpretation is represented in Figure 4. The displacement and accelerations are considered to be positive in vertical up and lateral right directions.

The displacement and acceleration responses at fin, nose and wing tips of the aircraft along with the time stamp are shown in Table 1. and Table 2. respectively. These responses are normalized with respect to their maximum value present in the respective column. The responses are total responses which contains three constituents namely, i) Rigid body response of the aircraft as a whole, ii) Local rigid body response of the tips with respect to geometrical distance from the C.G and angular accelerations and iii) the Flexible response at tips captured through Finite element model.

Table1. Displacement responses of Wing, Nose and fin

Load case	Sink Rate (Vs/Vs_{max})	Pitch angle (θ/θ_{max})	Location	Time stamp	Displacement (mm)	
				t (sec)	$\delta_y/\delta_{\lvert ymax \rvert}$	$\delta_z/\delta_{\lvert zmax \rvert}$
MPA (max. pitch angle)	0.27	1	Fin Tip	1.06	-0.71	-0.06
			Nose Tip	1.07	-0.38	0.08
			Wing Tip	1.77	-0.01	-0.27
MSR (max. sink rate)	1	0.85	Fin Tip	0.66	**-1.0***	-0.14
			Nose Tip	0.36	-0.18	-0.43
			Wing Tip	0.46	0.07	**-1.0**

* Unity indicates maximum value

Table2. Acceleration responses of Wing, Nose and fin

Load case	Sink Rate (Vs/Vs_{max})	Pitch angle (θ/θ_{max})	Location	Time stamp	Acceleration (g)	
				t (sec)	$N_y/N_{\|ymax\|}$	$N_z/N_{\|zmax\|}$
MPA (max. pitch angle)	0.27	1	Fin Tip	0.97	-0.68	0.06
			Nose Tip	0.87	0.05	-0.25
			Wing Tip	0.92	-0.02	-0.30
MSR (max. sink rate)	1	0.85	Fin Tip	0.40	**1.0**	-0.47
			Nose Tip	0.36	0.10	0.99
			Wing Tip	0.46	-0.05	**1.00**

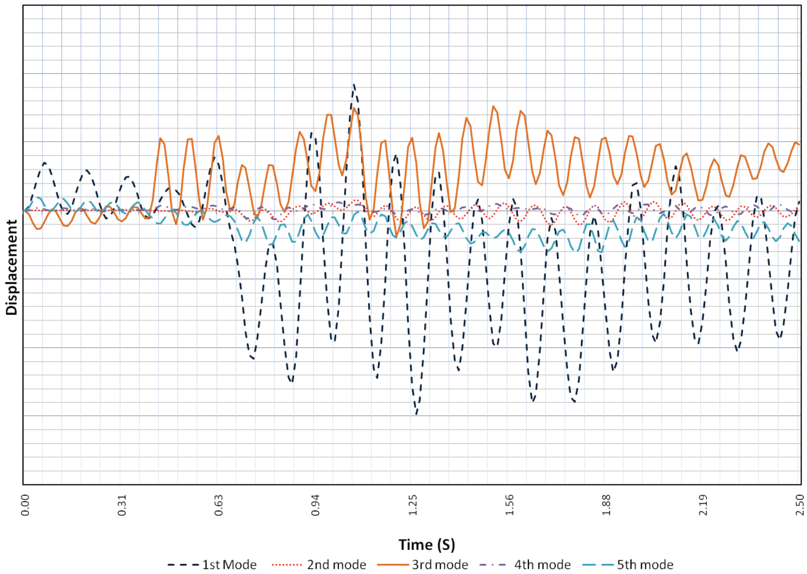

Figure 5.Modal participation displacement time history for MPA case

The modal participation displacement time histories for MPA and MSR load cases are shown in the Figures 5-6 respectively, the first five fundamental modes of the aircraft at CG are considered. It is observed that the major contribution to the maximum displacement is from the first mode of the aircraft.

All the maximum displacement and acceleration responses are observed for the maximum sink rate load case (MSR). The lateral and vertical displacement responses for the fin , nose and wing are shown in the Figures 7- 9 respectively. Maximum vertical displacement is observed at the wing tip and maximum lateral displacement is observed at the fin tip. The displacement pattern of wing tip suggests that the period is longer when compared to nose and fin tips.

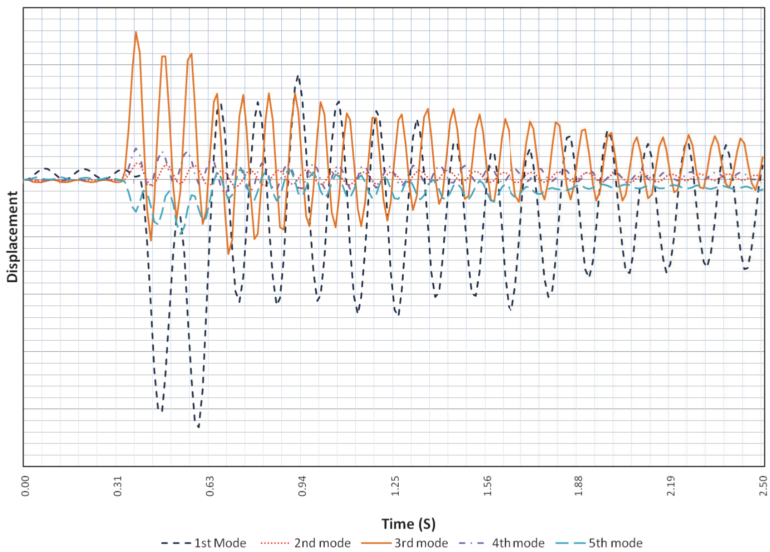

Figure 6.Modal participation displacement time history for MSR case

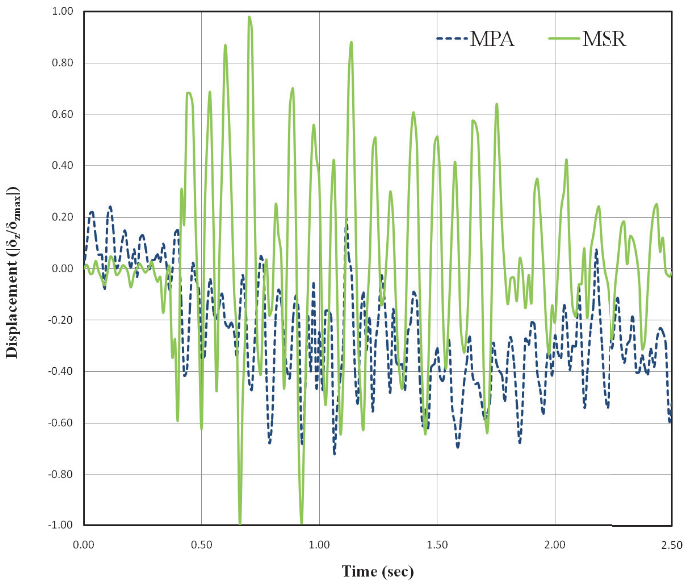

Figure 7.Lateral Displacement response at Fin tip location

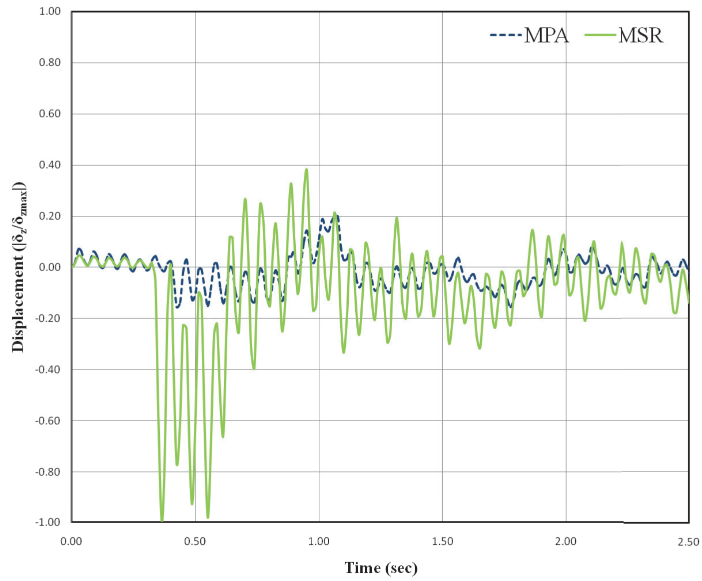

Figure 8.Vertical Displacement response at Nose tip location

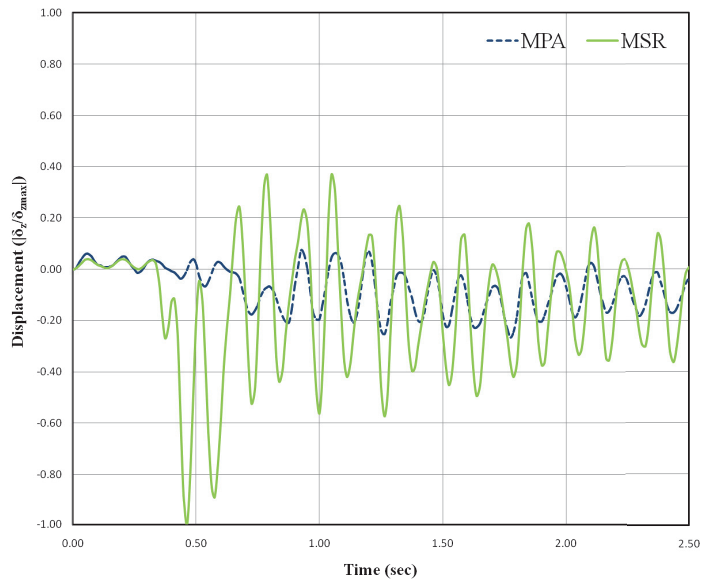

Figure 9.Vertical Displacement response at Wing tip location

Similarly, the lateral and vertical acceleration responses for the fin, nose and wing are shown in the Figures 10 -12 respectively. Maximum vertical acceleration is observed at the wing tip and maximum lateral acceleration is observed at the fin tip.

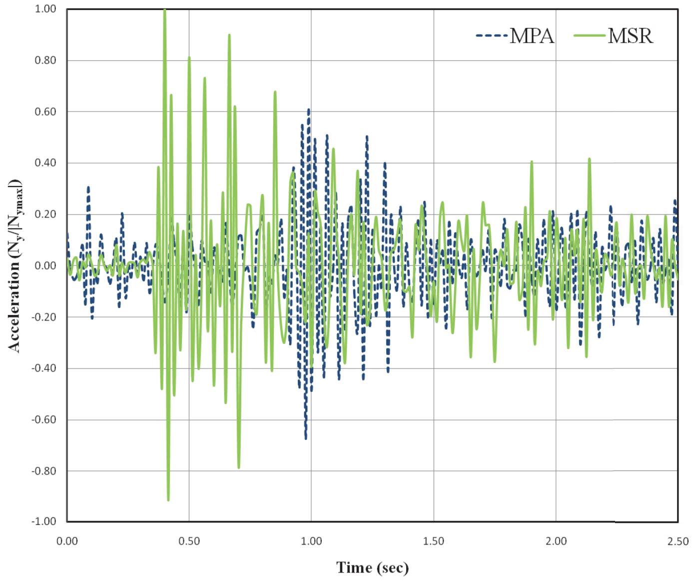

Figure 10.Lateral Acceleration response at Fin tip

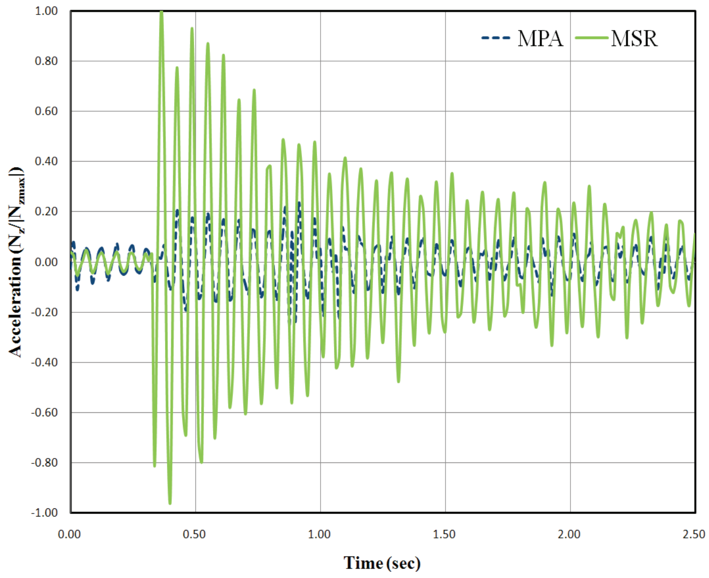

Figure 11. Vertical Acceleration response at Nose tip

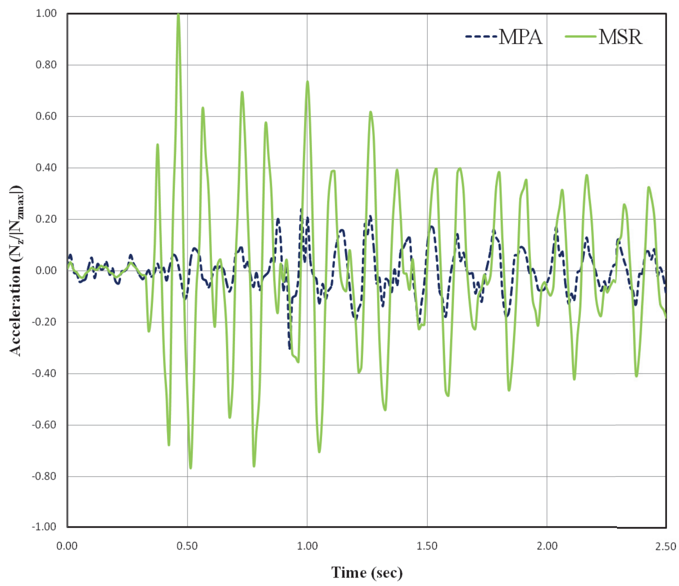

Figure 12. Vertical Acceleration response at Wing tip

The maximum lateral acceleration at fin tip for MSR case is ahead of MPA case which suggests that for the MSR case the excitation is from the landing gear impact due to higher sink rate. The MPA case assimilated as 3 - point landing case with higher pitch angle, the peak acceleration is due to Nose landing gear impact.

In order to identify the aircraft mode which excites the tips, the responses in time domain is converted to frequency domain through Fast Fourier Transformation (FFT). The lateral acceleration (N_y) response at the fin tip with respect to frequency for load case MSR is shown in Figure 13. The maximum excitation of fin occurs at higher frequency which is at the fin twisting mode.

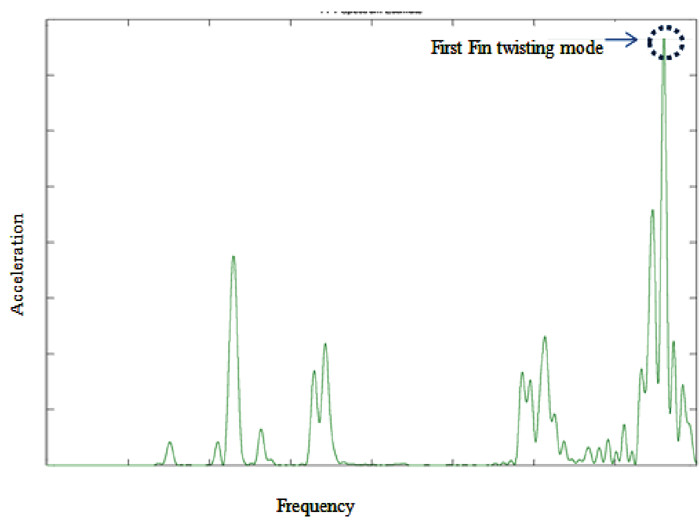

Figure 13.Lateral Acceleration with Frequency at Fin tip for MSR case

The Vertical Acceleration (N_z) response at the nose tip with respect to frequency for MSR load case is shown in Figure 14. The maximum excitation of nose occurs at the fuselage vertical bending mode.

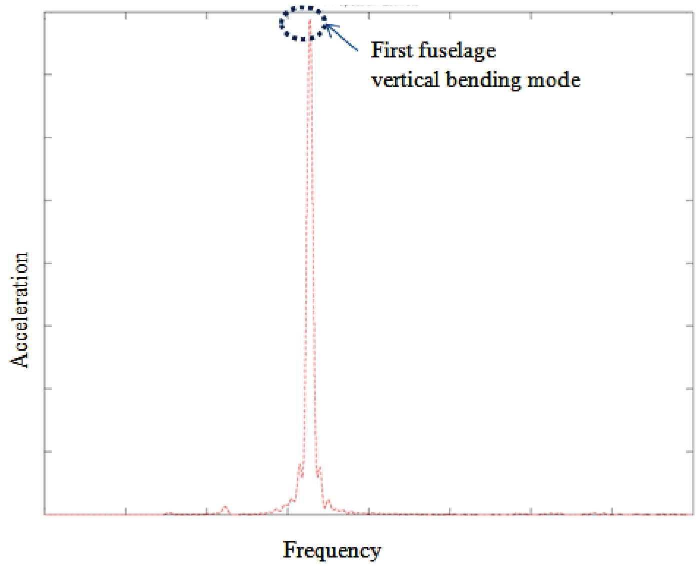

Figure 14. Vertical Acceleration with Frequency at Nose tip for MSR case

The vertical acceleration (N_z) response at the wing tip with respect to frequency for load case MSR is shown in Figure 15. The maximum excitation for the wing occurs at wing symmetric bending mode at a lower frequency and then at wing anti-symmetric bending mode.

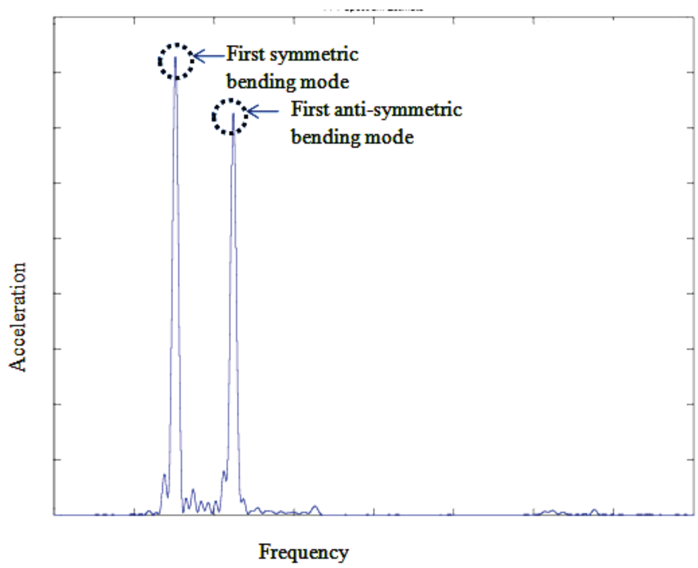

Figure 15. Vertical Acceleration with Frequency at Wing tip for MSR case

The acceleration and displacement responses extracted at various locations of the aircraft provide the information with regard to the overall assessment on structural integrity of the aircraft. The responses from the analysis gives a useful input to the Fatigue and Dynamics groups for carrying out data analysis in estimation of fatigue life, strength and stiffness requirements. The joint interface loads generated due to the concentrated masses such as engine, external stores wing, fin root fittings needs to be assessed against the cleared flight loads envelopes. This activity would trigger actions such as restriction in performance envelope or strength and stiffness enhancements at these critical locations.

Early measures can be taken if the aircraft drop test and flight validated mathematical model of L/G were used such that, the risk of introducing a major design change is minimized and the program schedule is not jeopardized. Optimization of local components near attachment location and for the undercarriage can be envisaged by introducing the flexibility of the airframe or at least the models near the attachment locations by using MSC Adams/Flex body module.

4. CONCLUSION

The co-simulation approach of performing a dynamic landing response analysis is followed wherein, tailless delta wing aircraft with main and nose landing gears as sub-systems is simulated using MSC Adams and the results at the attachment locations is captured and supplied to the full aircraft flexible finite element model for carrying out a transient dynamic analysis using MSC Nastran. The acceleration and displacement responses peaks up for the maximum sink rate case purely due to landing gear impact. The wing and nose tips peak acceleration is observed to be in vertical direction and for the fin tip in lateral direction. It has been brought out that several parameters act on the frequency of elastic modes and therefore influence the dynamic response behaviour of the aircraft. The local accelerations and displacement response manifested due to the geometric locations of masses and the effect due to structural flexibility are captured appropriately. This exercise will aid the structural design process by providing the acceleration response data for dynamic clearances and further processed interns of fatigue life reductions. The interface loads at the critical attachment locations such as fuselage to wing, fuselage to fin, engine mounts and at stores interface will be an useful data for comparing values against the cleared static envelope.

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