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AEROELASTIC ANAYLSIS OF A MISSILE CANARD WITH FREE-PLAY NON-LINEARITY

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ABSTRACT

Canards are the control surfaces which are frequently used in missiles. They are operated by a control system including actuator, driveline and electronics. Aeroeleastic behavior of canards should be known to comply with the control system. However, structural non-lineraties such as free-play affect the aeroelastic behavior. This study focuses on dynamic response of a canard system which has free-play non-linearity in its shaft-actuator connection. Fluid-structure interaction (FSI) method was used to investigate the aeroelastic behavior. Two different free-play sizes were evaluated and effect of the free-play compared with zero free-play condition. As a result of FSI analyses, amplitudes of canard and shaft vibrations increases with increasing free-play sizes. On the other hand, response frequencies decreases as the free-play increases.

INTRODUCTION

Canards which are used as control surfaces on missiles are based on airplanes. The first glider of Wright brothers had canards for its rolling motion control [Lawrence et al, 2003]. In late 1970s, canards were adapted to missiles [Blair Jr A. B., 1981; Gur I. et al, 1963]. Since guidance systems located at the front of missile bodies, canards have advantages in packaging. Therefore, they are often preferred as control surfaces for missiles. However, stall angles of canards are low and vortices generated by them reduce control effectiveness of other aerodynamic surfaces such as wings and tails [Fleeman E. L., 2001].

Fluid-structure interaction (FSI) is one of the solution technique to solve aeroelastic problems. Basically, during the FSI procedure, outputs of computational fluid dynamics (CFD) and computational structural mechanics (CSM) solvers are exchanged with each other as boundary or loading conditions. Since non-linear problems require time-marching solutions, FSI is preferred to determine aeroelastic behaviors of structures. Thus, effect of free-play in canards were investigated with FSI.

Limit cycle oscillation (LCO) is bounded vibration and it is seen when structure has some non-linearities. Bae et al [Bae J. et al, 2004] conducted a study which is about linear and non-linear

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aeroelastic analyses of a deployable missile wing. Time-marching and frequency domain solutions were performed to obtain aeroelastic behavior of the wing which has bilinear root spring characteristic. As a result of the study, they claimed that LCO occurs at lower velocities than flutter speeds. Besides, they suggest to use FSI for non-linear aeroelastic problems. Since FSI analysis needs properties of non-linearities, specific experiments should be carried out to determine characteristics of non-linearity. Kim et al [Kim D. K. et al, 2005], measured acceleration, force and displacement from vibration test of a deployable wing. When they presented force-state map, which is combination of acceleration, force and displacement, characteristics of non-linearity were introduced.

Another important issue about aerodynamic control systems is aeroservoelastic stability. Zhang and Zhang [Zhang and Zhang, 2009] assert that combination of first rigid body mode and first bending mode of the tail causes instability. Therefore, nodal points on the structure should be determined by aeroelastic analyses and feedback sensors should not be assembled to this points to have effective aeroservoelastic control.

Vortices generated by missile wings or canards create forces in perpendicular direction of its separation line. If frequency of the vortex shedding matches with the natural frequency of the structure, aeroelastic instability occurs [Wood and Wilcox, 2009]. Since free-play reduces natural frequencies, high angle of attacks where flow separation occurs becomes critical for aeroelastic stability.

In case of multiple non-linearities, one of the non-linearities becomes dominant while the others show less effect. For instance, according to the Peng and Hang [Peng C. ve Han J., 2011], geometrical non-linearities are dominant at low velocities, while plasticity plays an important role over stability at high speed flows. Besides, some studies show that free-plays interact with each other according to natural frequency ratios of structure in multiple free-play conditions [Seo Y. J. et al, 2011].

Non-linear aeroelastic behavior of a structure which has free-play is dependent on initial conditions. Aeroelastic response might have damped stable motion, LCO, divergent flutter or chaotic motion according to the initial state. Gap/Amplitude ratio is commonly used to define initial conditions. Lee and Kim state [Lee I. and Kim S. , 1995] that LCO occures at low gap/amplitude ratios and high gap/amplitude ratios induce chaotic motion.

In the present study, a missile canard which has free-play in it shaft-actuator connection was investigated. FSI was used as computational method. As results of FSI analyses; amplitudes, frequencies and damping characteristics of the vibrations according to free-play sizes were discussed.

METHOD

In the present study, FSI was established between STAR-CCM+ CFD and Abaqus FE solvers. Two-way, loosely coupled FSI algorithm was used during the aeroelastic analyses. Before performing FSI analyses, natural frequencies and mode shapes of the canard were calculated and CFD model was evaluated with three different grid densities to provide mesh independence. In FSI analysis, pressure and shear forces calculated in CFD were transferred to FE solver to obtain structural displacements. According to displacements caused by aerodynamic forces, CFD domain was updated by morphing technique and new flow domain was solved at next time step. Coupling of different solvers were provided until desired time criteria, that is 50 ms for this study, was satisfied. Two different free-play sizes, which are ± 0.5, ± 1.0 were investigated and compared with linear stiffness (zero free-play) condition.

Structural Modeling

A FE model was created by 21183 elements including solid and beam elements. The general view of FE model is displayed in Figure 1. The canard was supported by a bearing which is 10 mm below the flange and end of the shaft was fixed.

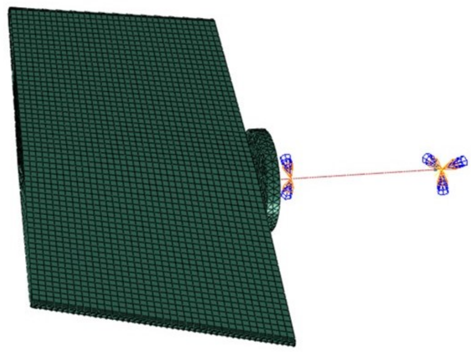

Figure 1: Canard FE model

Free-play was introduced by special connector elements which provides relative motion between nodes. Since stiffness is zero between free-play region ($\pm\delta$), the restoring force is also zero. Therefore, motion of the shaft affects the stiffness while stiffness changes the motions, thus introducing non-linearity to the system. Figure 2 explains linear and non-linear (free-play) stiffness representations of connector element. For non-linear condition, there is no restoring force between free-play boundaries. However; stiffness, which is slope of the $M - \theta$ curve, is same out of the free-play boundaries.

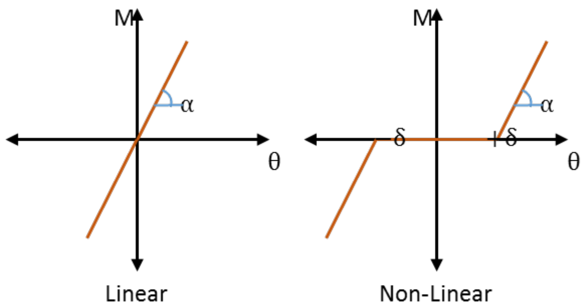

Figure 2: Linear and non-linear stiffness representation

Before FSI analyses, natural frequencies and mode shapes of the canard system were examined. Calculated mode shapes and frequencies were used to understand the effect of aerodynamic forces and free-play on aeroelastic response. The first four modes of the canard is given in Figure 3. The first torsional mode of the canard is 325.62 Hz and first bending mode is 573.56 Hz.

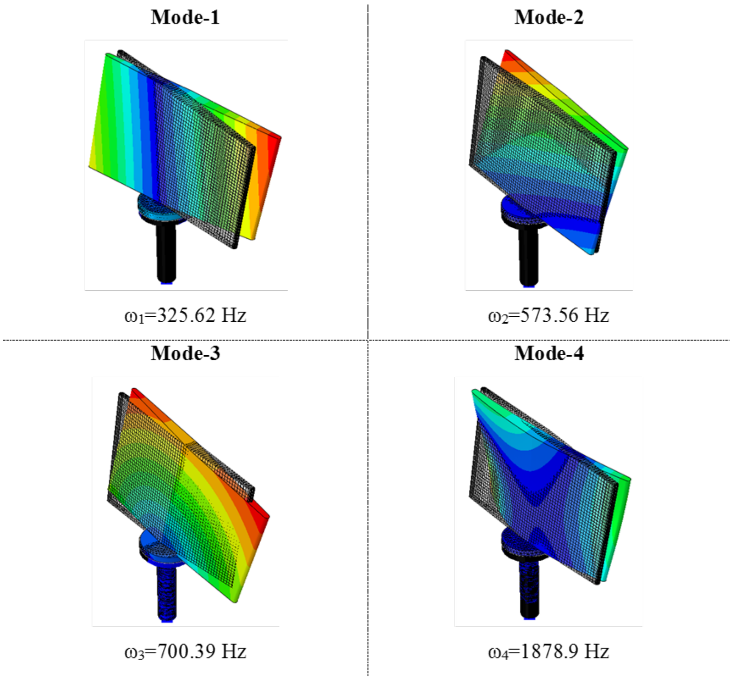

Figure 3: Canard natural frequencies and mode shapes

Computational Fluid Dynamics Modelling

Steady-stated CFD analyses were performed with three different grid densities to provide mesh independence. Also, results of steady-state solutions were used as initial condition for FSI analyses. Overset mesh method was used during the CFD calculations because of its advantages on mesh deformation. In overset mesh technique, there are two different mesh regions interacting with each others so that small gap, that is $0.8\ mm$, between canard and missile body was able to be meshed with high quality cells. Besides, prism layer elements were used to resolve the boundary layer accurately. In Figure 4, CFD domain with overset mesh is illustrated.

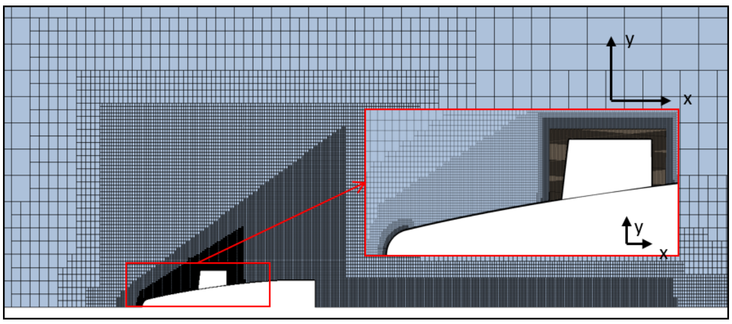

Figure 4: CFD domain with overset mesh

For the CFD analyses, quarter missile model was chosen. The free-stream velocity of the air was 2.5 Mach and the altitude is 10000 m. Besides, Coupled flow solver with second order discretization of convection and dissipation terms were used. Also, Spalart-Allmaras turbulence model which is widely used in external aerodynamics was adopted.

Coarse (5M), medium (14M) and fine (37M) grids which is seen in Figure 5 were used for mesh independence study. Results obtained with different grid densities showed that coarse grid was not enough especially to capture bowl shock seen in missile nose. On the other hand, medium and fine grids give same results so that medium grid was preferred to be used in FSI analyses. Aerodynamic forces also changes with different grids. Coarse grid predicts pressure and shear forces lower than the others. Total aerodynamic force on the canard is $75.4\ N$ and 91% of the total force is caused by pressure at initial canard position which has zero angle-of-attack.

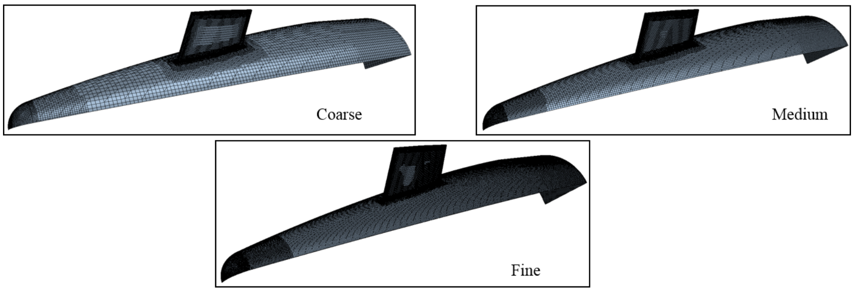

Figure 5: Grid densities used for mesh independence study

As seen in Figure 6, bowl shock occurs in front of the missile nose and free-stream pressure increases while velocity decreases behind the bowl shock. Because of the shock and curvature of the missile body, velocity profile in front the canard is not uniform in the direction of the canard span. Also, Oblique shock takes place at the canard leading edge and pressure increases again behind the oblique shock. Since the canard profile is diamond shape, flow expands at mid-chord and trailing edge.

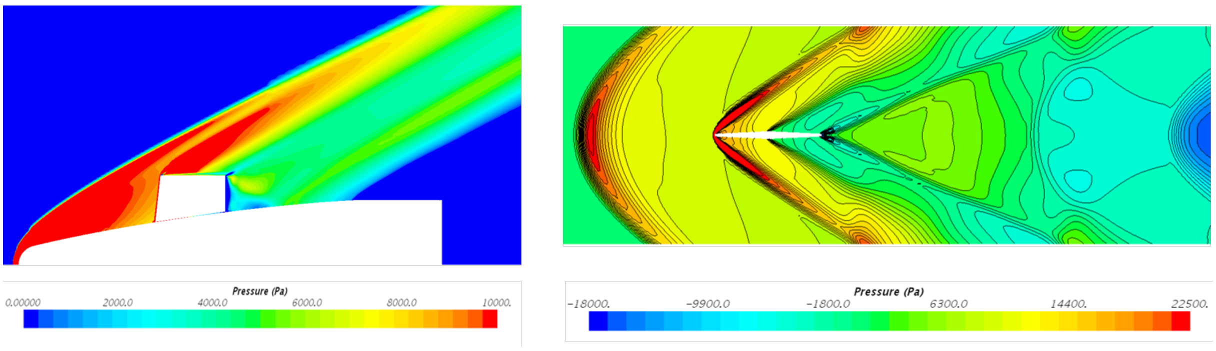

Figure 6: Pressure contours. Whole model left, canard mid-span section right

FLUID-STRUCTURE INTERACTION ANALYSES

Since loosely FSI coupling was used, data exchange between the solvers were applied only at the end of coupling time steps. Coupling time step was chosen as $2.5x10^{-5}\ ms$ which is enough to resolve the second mode of the canard at 70 time steps.

FSI analyses were initiated by a disturbance. This disturbance was a half sinus wave whose period is $2.86\ ms$ and it was applied to the shaft as torque. After $1.43\ ms$ disturbance totally disappeared and then only aerodynamic forces became effective on the canard.

Figure 7 shows the root-leading edge displacement according to the free-play sizes (δ). As seen in Figure 7, amplitudes of the vibrations increase with increasing free-play (δ) sizes. Besides, frequency varies in time since stiffness depends on amplitudes. However, frequency of the vibration is near to first mode of the canard for linear stiffness condition ($\delta = \pm 0^o$).

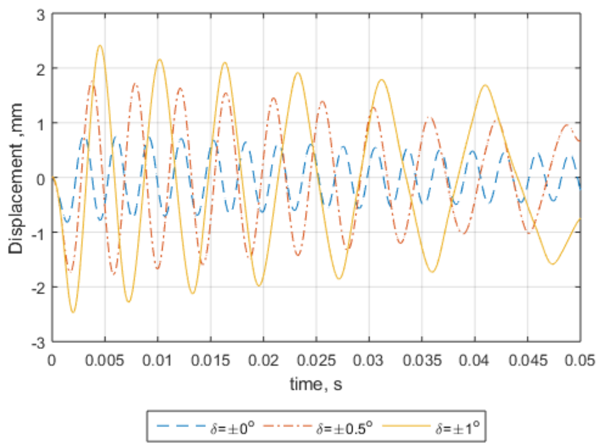

Figure 7: Root, leading edge displacement

Figure 8 shows the frequency dependence on amplitude. As it is seen from the plot, frequency doesn't change with increasing amplitude for zero free-play condition and the corresponded frequency is equal to fist mode of the canard. This situation clearly points out linear stiffness behavior. However, when free-play exists response frequencies decrease with decreasing amplitude. Besides, free-play size (δ) has reducing effect on frequency while amplitude increases.

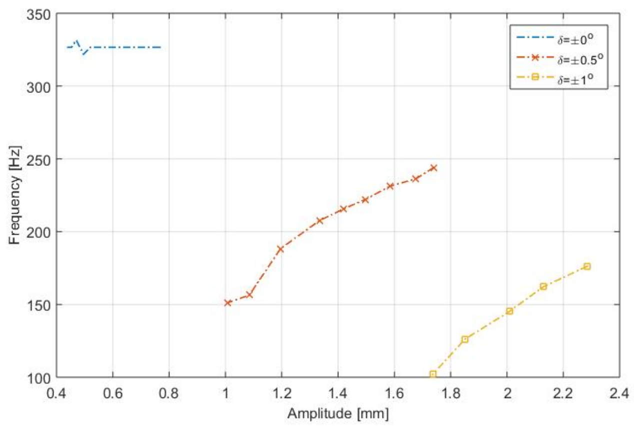

Figure 8: Amplitude-frequency plot

Also, shaft rotation amplitudes increase with increasing free-play size (δ) and the frequencies change in time since stiffness is related to amplitude. In case of free-play condition, shaft rotation peaks exceed free-play boundaries where stiffness changes from zero to a finite value. This behavior causes plateau type regions during the time history of shaft rotation.

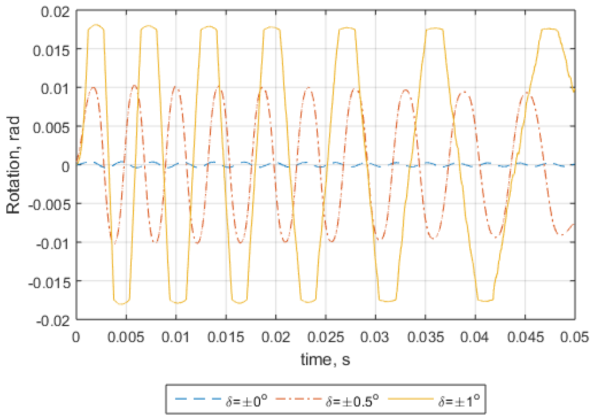

Figure 9: Shaft rotation

CONCLUSIONS

This study investigated the aeroelastic behavior of a missile canard which has free-play in it shaft-actuator connection. FSI was used as computational method to determine non-linear dynamic response of the canard structure. These analyses proved that free-play changes the aeroelastic behavior of canards. The amplitudes increases with increasing free-play sizes and frequencies decreases in time in case of free-play condition. As the amplitude decreases, equivalent stiffness reduces and response frequency decreases either. This situation states non-linear behavior of a aeroelastic system. Therefore, effect of free-play should be considered to determine aeroelastic behavior accurately in aeroelastic analyses.

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