NONLINEAR AEROSERVOELASTIC ANALYSIS FOR A THREE-DIMENSIONAL HORIZONTAL STABILIZER WITH AN ACTUATOR COMPOSED OF ELASTIC LINKS

Yoo Jin Kang,[1] Chan Hoon Chung,[2] Jae Hyeok Jeon,[3] Sang Joon Shin,[4] and Young Ho Na[5]

[1] Seoul National University, Korea
yj000000@snu.ac.kr

[2] Seoul National University, Korea
chan3241@snu.ac.kr

[3] Seoul National University, Korea
jhyeok31@snu.ac.kr

[4] Seoul National University, Korea
ssjoon@snu.ac.kr

[5] Defense Agency of Technology and Quality, Korea
christ00@dtaq.re.kr

Keywords: Horizontal Stabilizer, Link, Flutter, Aeroservoelasticity, Dynamic Stiffness

Abstract: A horizontal stabilizer connected with a link, which has 5 elastic beam-like components, is manipulated by an actuator and its attitudes are prescribed in that way. This stabilizer is equipped in a high-speed vehicle flying at a supersonic speed. This paper is mainly about the dynamic torsional stiffness between the horizontal stabilizer and the link, and how the change of such stiffness has an influence on the structural and aeroelastic responses of the horizontal stabilizer. By comparing with an experiment, the structural analysis using MSC.NASTRAN was verified. The flutter analyses under two boundary conditions were performed, one with dynamic torsional stiffness and the other with the root of the horizontal stabilizer fully cantilevered. From these results, the effects of the dynamic stiffness due to the flexible link are observed in flutter analysis. For further aeroservoelastic analysis of the complete horizontal stabilizer control system, the dynamic response analysis of the movable link is performed.

1 INTRODUCTION

Human have had a desire to fly to the sky and eventually Wright brothers flied in the air with the flight distance of 36 meters for 12 seconds on December 17th in 1903. The flight vehicle at that time, was named Flyer and it contained elevators, a vertical tail fin and a rudder. So it was the first time to control the flight attitude by machines, without human’s power. By taking the event as a stepping stone to develop the aircrafts, diverse configurations have appeared by the purpose of flight and the mission requirements. It leads to the large range of the flight speed from subsonic to even hypersonic region. At the same time, there has been the advance in materials and engines of the aircraft for the weight reduction and faster flight respectively. In the effort to improve the lift to drag ratio and the flight performance, aircrafts have the limitation in the weight, and it accompanies the decrease in structural stiffness [1]. Thus, aircrafts structure will become flexible, and also exhibit the structural nonlinearity.

The flexibility of the structures affects the airflow around the structures because of their elastic deformation. The airflow simultaneously gives an effect on the structures by applying the aerodynamic forces. This interaction between the inertial and elastic forces of the structures, and the aerodynamic forces of the airstream is studied in the field of aeroelasticity [2]. Owing to the interaction, aircrafts face the aeroelastic problems. In this area, there exist two representative phenomena. One is divergence and the other is flutter, which are the static and dynamic aeroelastic instability, respectively. This instability brings the fatal damage to aircrafts during flight and even enforces the aircrafts become destructed. With regard to the undesired matter, there have been many types of flutter not only on a main wing of an aircraft but also on missile fins, tail fins, stabilizers and even elevons. Flutter of these submachines may cause aircrafts to be unstable. Limit cycle oscillation (LCO), one of the nonlinear flutter, on a control surface may have bad effect that aircrafts may experience difficulty to control the flight attitude. There are some examples about this phenomenon. IDF fighter in Taiwan dropped and crashed because of the flutter on the horizontal tail fin. F-22 fighter also crashed for the same reason in 1992. In 1997 F-117, which is a stealth attack aircraft in the Air Force of the United States, also failed in flight due to the flutter induced by the beginning of the oscillations in the loose elevons [1].

In a case of a control surface with an actuator, the actuator may apply additional control forces besides inertial, elastic and aerodynamic forces [3]. Therefore when the flutter analysis of a structure such as a control surface and a missile fin with an actuator is performed, the control system is added to the aeroelastic problem. In that, the control forces were also considered in the interaction between the inertial, elastic and aerodynamic forces. Advanced studies on aeroservoelasticity are mainly about analysis and control of aeroelastic responses. Recent aircrafts have various control surfaces for pilot or trimming, and so the aeroservoelastic analysis is required in the design of aircrafts to keep them from aeroelastic phenomena such as flutter and divergence.

In this paper, examination about a three-dimensional horizontal stabilizer is performed, which is equipped on a high-speed vehicle as a control surface to control the vehicle attitude. The horizontal stabilizer is manipulated by a control system. The control system is made up of the mechanical link composed of five beam-like components. First, structural analysis on the horizontal stabilizer is performed. For this analysis, MSC.NASTRAN is used. Then the flutter boundary is obtained for the analysis of dynamic aeroelastic stability using ZAERO. Independently, by using RecurDyn a research about structural dynamics of the control system containing link system is conducted. And then the transfer function of the control system is applied to the horizontal stabilizer. The aeroservoelastic analysis is presented by combining the horizontal stabilizer and the control system containing the mechanical link in this paper.

2 METHODOLOGY

2.1 Structural Modeling

A three-dimensional horizontal stabilizer is attached to a high-speed vehicle flying at a supersonic flight speed in nominal flight. This horizontal stabilizer is made of an isotropic material. With a few number of holes, there are skins on the holes of the solid horizontal stabilizer. A link between the horizontal stabilizer and an actuator is composed of five elastic beam-like components. Among the five components, one beam-like component has only one degree-of-freedom in the axial direction, as depicted in Figure 1. Joints connecting the five components of the link may have free-play, but in this paper they are not considered yet. By generating torque, the actuator controls the pitch angle of the horizontal stabilizer through the mechanical link, which is between them.

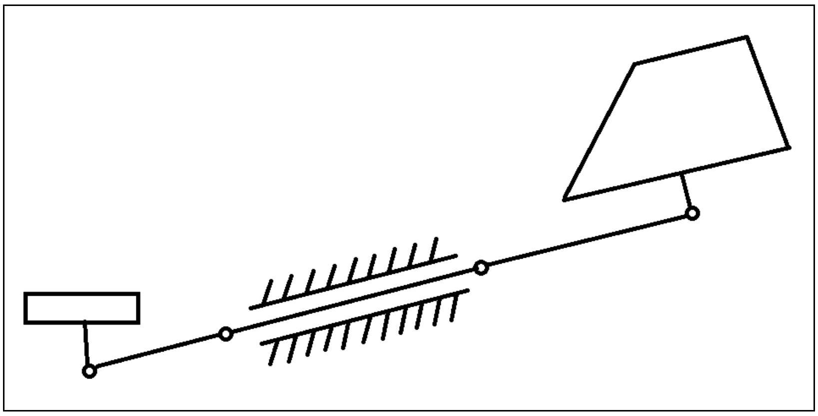


Figure 1: Sketch of the horizontal stabilizer and the mechanical link

2.2 Structural Analysis of the Horizontal Stabilizer

First, structural analysis is performed by the finite element method using three-dimensional solid elements. In this section, the structural analysis of the only horizontal stabilizer is performed. Considering its skins and holes, the horizontal stabilizer is analyzed by modal analysis. In order for more accurate structural analysis, an experiment is fulfilled with some part of root of the horizontal stabilizer being fixed but having a little free-play. Through 15 accelerometers attached on the horizontal stabilizer, the natural frequencies and mode shapes of from the first to the fourth natural modes are obtained. And by using the MSC.NASTRAN, modal analysis of the horizontal stabilizer is performed. The horizontal stabilizer modeled in PATRAN has twenty thousands of tetrahedral grids. The boundary condition is that the all grids on the root of the horizontal stabilizer has only one torsional degree-of-freedom in pitch rotation. It is because the horizontal stabilizer is not fixed to the vehicle but connected with a movable link through a pin, which allows a pitch motion. Considered the results from the experiments as references, the prediction results of modal analysis from the MSC.NASTRAN are verified.

2.3 Trim Analysis for Verification

For the verification on ZAERO aerodynamic loads prediction, trim analysis considering only the horizontal stabilizer is performed. ZAERO provides aerodynamic results under a few assumptions, for example, inviscid flow, compressible flow, when by using the doublet lattice method (DLM). Trim analysis for the horizontal stabilizer uses the following boundary condition that the horizontal stabilizer is completely cantilevered. The aerodynamic coefficient results obtained by the present trim analysis are compared with those by ANSYS Fluent. ANSYS is a commercial program and conducts computational fluid dynamics interacting with structures based on the finite element analysis (FEA).

2.4 Flutter Analysis of the Horizontal Stabilizer

After the structural analysis of the horizontal stabilizer is completed, aeroelastic stability analysis is conducted for the verification on the safety of the horizontal stabilizer. The present flutter analysis is conducted by using ZAERO, which is a program established by the ZONA Technology. This program is capable of analyzing the unsteady aerodynamic characteristics using doublet lattice method (DLM) for a given flight condition assuming compressible, inviscid flow. For flutter analysis of the horizontal stabilizer, ZAERO flutter module is used. The flutter module contains two flutter solution techiques. One is the k-method first proposed by Theodorsen, adding the artificial complex structural damping ig_s as in Equation (1). And the other is the g-method including the first order modal structural damping matrix $\mathbf{Z}$ according to Equation (2), rigorously derived from the Laplace-domain aerodynamics. The g-method can also provide the unlimited roots of the flutter equation in contrast with the k- and p-k methods. This method was developed by the ZONA Technologies, USA [4,5]. By applying this procedure, for a given flight condition of Mach number and flight altitude, the flutter analysis is performed. By drawing V-g and V-f plots, the flutter speed of the horizontal stabilizer will be finally predicted.

$$[-\omega^2\mathbf{M} + (1+ig_s)\mathbf{K} - q_\infty\mathbf{Q}(ik)]\mathbf{q} = 0 \tag{1}$$

$$[g^2\mathbf{A} + g\mathbf{B} + \mathbf{C}]\{\mathbf{q}\} = 0 \tag{2}$$

where

$$\mathbf{A} = \left(\frac{V}{L}\right)^2 \mathbf{M}$$

$$\mathbf{B} = 2ik\left(\frac{V}{L}\right)^2 \mathbf{M} - \frac{1}{2}\rho V^2 \mathbf{Q}'(ik) + \left(\frac{V}{L}\right)\mathbf{Z}$$

$$\mathbf{C} = -k^2\left(\frac{V}{L}\right)^2 \mathbf{M} + \mathbf{K} - \frac{1}{2}\rho V^2 \mathbf{Q}'(ik) + ik\left(\frac{V}{L}\right)\mathbf{Z}$$

2.5 Dynamic Properties of the Link

When the actuator manipulates the horizontal stabilizer, the link between those may have a considerable effect on the dynamic response of the horizontal stabilizer. As depicted in Figure 1, one link in the five components has only one degree of freedom in its axial direction. In the relevant structural dynamic analysis, only four components are considered except for one, which is directly connected with the actuator. Among the four beam-like components, the one that is linked next to the horizontal stabilizer is considered as a rigid body. The remaining three components are considered as elastic beams. The effects of the free-play in the joints between each beam-like component are not considered yet in this paper. Prior to the structural dynamics of the link, the natural mode analysis is performed using RecurDyn, which is a commercial multi-body dynamics analysis program. To find out how the link influences on the horizontal stabilizer, transfer function of the link is obtained. Before obtaining the transfer function, structural dynamic responses of the link are required in time domain. The responses in time domain are also transferred to the frequency domain by fast Fourier transform (FFT). Then, Bode plot and the transfer function of the mechanical link will be obtained. The boundary condition for the present structural dynamic analysis is as follows. Of the four components considered in this analysis, one end of a beam-like component which is adjacent to the actuator is assumed to be fixed, and considered to be a revolute joint. To observe the structural dynamic response of the link, an input force or moment is needed and for that, a torque is applied to the joint between the horizontal stabilizer and the component directly connected with that. The output of interest is the pitch angle of the horizontal stabilizer. Thus the transfer function will be obtained as the pitch angle versus the torque. For these procedures, RecurDyn is used to obtain the dynamic responses of the link, and MATLAB is used to predict the transfer function of the link.

2.6 Aeroservoealstic Analysis of the Horizontal Stabilizer and the Link

When the aeroelastic system of the previous Section 2 is excited by the actuator’s pilot input command, it may generate structural vibration. For this reason, the aeroservoelastic analysis of the complete horizontal stabilizer control system will be performed. By adding the control system of the link to the horizontal stabilizer, structural, aerodynamic, and control effects will all be included. The inertial, elastic, aerodynamic, and control forces applied to the horizontal stabilizer are handled by this combination [5]. An equation of motion of the aeroelastic system is introduced in Equation (3). $[M_{hh}]$, $[C_{hh}]$, and $[K_{hh}]$ are the generalized mass, damping, and stiffness matrices. $[M_{hc}]$ is the generalized control coupling mass matrix. $\{\xi\}$, $\{\delta\}$ are the generalized coordinates and the control surface deflections, respectively. This equation allows the aeroelastic system to couple with the control system, by adding two terms about control surface deflections. Within the present ASE analysis, the flutter and the stability analyses are conducted for the integrated objects containing the horizontal stabilizer and the link. ZAERO is also used for the present ASE analysis.

$$[\mathrm{M}_{hh}]\{\ddot{\xi}\}+[C_{hh}]\{\dot{\xi}\}+[K_{hh}]\{\xi\}+[\mathrm{M}_{hc}]\{\ddot{\delta}\}=q_{\infty}[Q_{hh}(ik)]\{\xi\}+q_{\infty}[Q_{hc}(ik)]\{\delta\} \qquad (3)$$

3 RESULTS

From the structural analysis on the horizontal stabilizer to the combined analysis of the horizontal stabilizer and the link, several results of those are presented in this section. The present results are obtained from several analyses and experiments.

3.1 Structural Modal Analysis of the Horizontal Stabilizer

3.1.1 Material Properties of the Complete Horizontal Stabilizer Control System

The material properties of the horizontal stabilizer and the link are same and written as shown in Table 1.

Property	Horizontal Stabilizer and Link
Young's modulus	116 GPa
Shear modulus	43.0 GPa
Poisson's ratio	0.34
Density	4500 kg/m^3

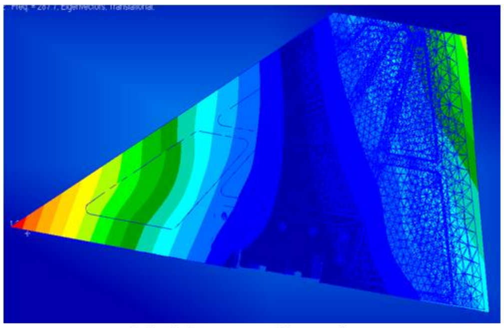
Table 1: Material properties of the horizontal stabilizer and the link

3.1.2 Verification of the Results by MSC.NASTRAN and Experiments

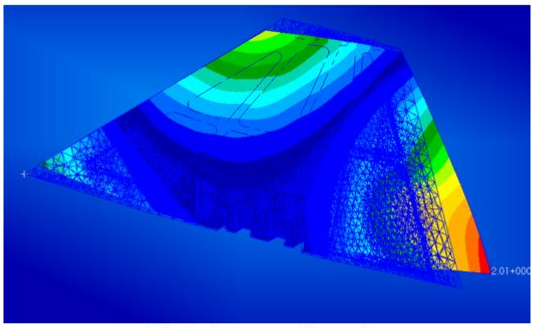
Before the results of the modal analysis of the horizontal stabilizer are obtained, an experiment is conducted to obtain the natural modes of the horizontal stabilizer except the link. By attaching 15 accelerometers to the horizontal stabilizer, the modal experiment is performed for a given boundary condition, as described in Section 2.2. The natural frequencies and mode shapes of the first to the fourth modes are compared with those predicted by MSC.NASTRAN, as shown in Table 2. According to the boundary condition, the nodes at the root of the horizontal stabilizer has only one degree of freedom, and that is the only fourth component of the global coordinate, not constrained but free. Except for the local modes in the results from MSC.NASTRAN, the natural frequencies and mode shapes for the first to fourth modes in the experiment coincide those for the second, third, eighth, and ninth mode, respectively. The differences of the first three natural frequencies between the experiment and MSC.NASTRAN prediction are below 3 percent, and it implies that the results from MSC.NASTRAN match well with those from experiment.

Mode	**Experiments, Hz**	**MSC.NASTRAN, Hz**	**Difference, %**
1^{st}	280	287.7	2.8
2^{nd}	432	424.6	-1.7
3^{rd}	702	699.14	-0.4
4^{th}	1039	853.07	-17.9

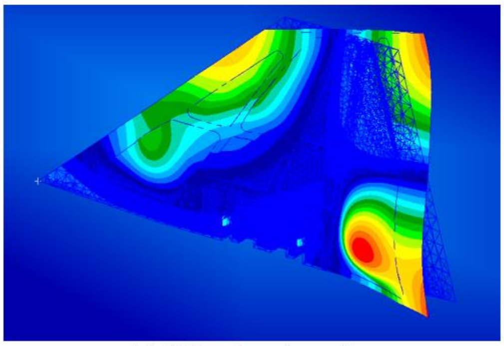
Table 2: Results of the Horizontal Stabilizer Compared with the Experimental Results



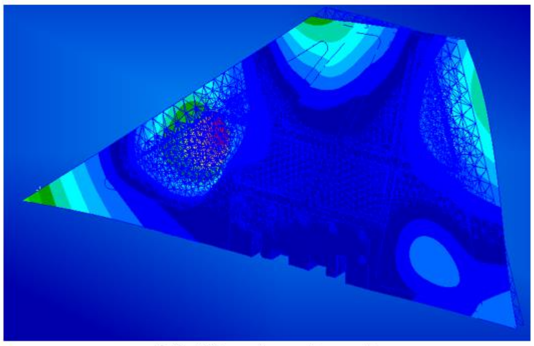
(a) 1st natural mode



(b) 2nd natural mode



(c) 3rd natural mode



(d) 4th natural mode

Figure 2: Mode shapes of the horizontal stabilizer from MSC.NASTRAN

3.2 Trim Analysis on the Horizontal Stabilizer by both ZAERO and ANSYS Fluent

For the fully cantilevered horizontal stabilizer, the trim analysis is conducted by using both ZAERO and ANSYS. In addition, three angles of attack are considered. In order to compare the results regarding the aerodynamic coefficients, the assumptions used in both analyses need to be the same. The two analyses consider compressibility effect, but neglect viscosity of the flow around the horizontal stabilizer. ANSYS Fluent computes the Euler equation as a governing equation, which is from energy equation by neglecting viscosity terms.

Angle of attack	Aerodynamic coefficients	ANSYS Fluent	ZAERO
0°	C_l	-2.6558×10^{-4}	0.0
	C_d	9.0158×10^{-3}	0.0
	C_m	1.0901×10^{-4}	0.0
2°	C_l	6.9314×10^{-2}	5.14×10^{-3}
	C_d	1.1540×10^{-2}	2×10^{-2}
	C_m	-3.2391×10^{-3}	-1.55×10^{-3}
4°	C_l	1.3915×10^{-1}	1.028×10^{-2}
	C_d	1.9148×10^{-2}	4×10^{-2}
	C_m	-6.6529×10^{-3}	-3.09×10^{-3}

Table 3: Aerodynamic coefficients of the horizontal stabilizer for various angles of attack

According to the results in Table 3, the aerodynamic pitching moment coefficients by both ZAERO and ANSYS are similar and comparable. The lift and drag coefficients, however, have significant discrepancies. When compared with the results from ANSYS, the lift coefficients are quite small and the drag coefficients are rather greater predicted by ZAERO.

3.3 Flutter Boundary of the Horizontal Stabilizer

In this section, the effects of the boundary condition will be investigated. The root of the horizontal stabilizer has free motion in pitch rotation with variable torsional stiffness coefficients, on the flutter boundary. In order to observe the effects, flutter analysis will be required with completely cantilevered boundary condition as a reference. The flutter analysis is performed using non-matched point flutter solution method for several reference Mach numbers. Two analyses are fulfilled about two altitudes at sea level and 5,000 meters. Figure 3 shows the flutter boundary and the flutter speed for all the reference Mach numbers. It says that the horizontal stabilizer with completely cantilevered at the vehicle will be stable below Mach number 10. For the same boundary condition of the horizontal stabilizer, the V-g plot and V-f plot are depicted in Figure 4. In the left hand side in Figure 4, the V-g plot represents that the first and fourth modes cross each other with the zero damping. This suggests the flutter occurs at certain flight speed where the V-g plot meets with zero damping. The right hand side of Figure 4, the V-f plot says that the first and second modes merge at the approximately Mach number 40, and similarly the third and fourth modes merge at approximately Mach number 47.

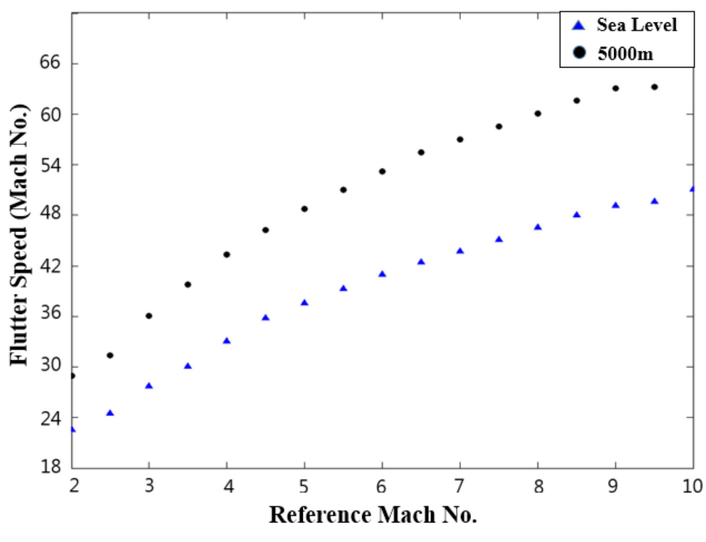


Figure 3: Flutter boundary prediction on the horizontal stabilizer with completely cantilevered root

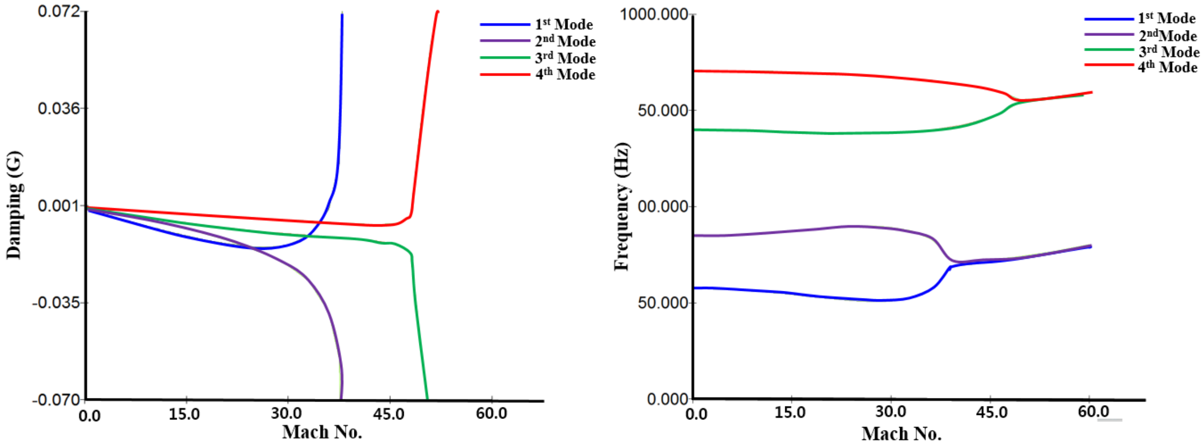


Figure 4: V-g and V-f plots of the horizontal stabilizer with completely cantilevered root

In reality, the horizontal stabilizer is not completely cantilevered at the high-speed vehicle but connected at the mechanical link by a pin. This enforces the torsional stiffness between those components not to be constant. Thus it may affect the flutter boundary of the horizontal stabilizer connected with the link. As a result, as shown in Figure 5, the first natural mode, which is a single degree of freedom flutter, is significantly influenced by the torsional stiffness, and otherwise the other natural modes will be unaffected. The flutter speed in the first mode has a tendency to increase as the torsional stiffness increases.

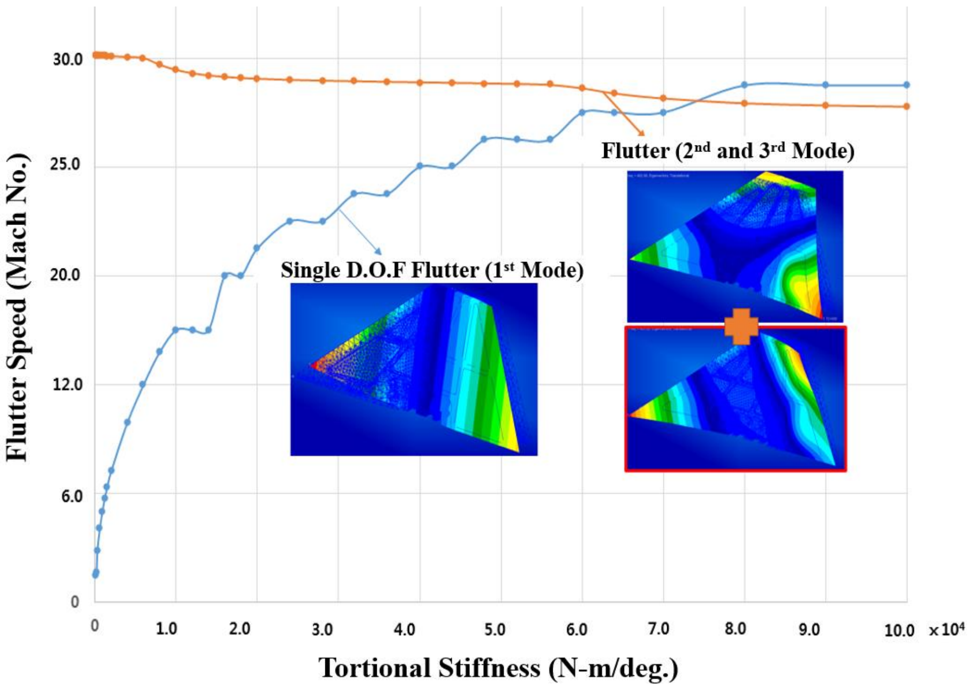


Figure 5: Flutter boundary prediction on the horizontal stabilizer as the torsional stiffness between the horizontal stabilizer and the link varies

3.4 Dynamic Responses and the Transfer Function of the Link

An actuator manipulates the attitude of the horizontal stabilizer, and there exist five beam-like components. Such five components are connected by revolute joints and those are called the mechanical link. The link may have an important role on the dynamic response of the horizontal stabilizer. For structural dynamic analysis in this section, the complete horizontal stabilizer control system is simplified by eliminating both actuator and one component of the link adjacent to the actuator. As a result, only four components of the link are considered in this analysis. There exist also some specific conditions: Link 2 is allowed only one degree of freedom in its axial direction and one component of the link, directly connected with the actuator, is considered as a rigid body. The remaining three components are, therefore, considered as elastic beams. One end of Link 1 is assumed to be fixed, and considered to be a revolute joint as described in Figure 6. The other three joints are considered as perfect revolute joints without any geometric tolerances.

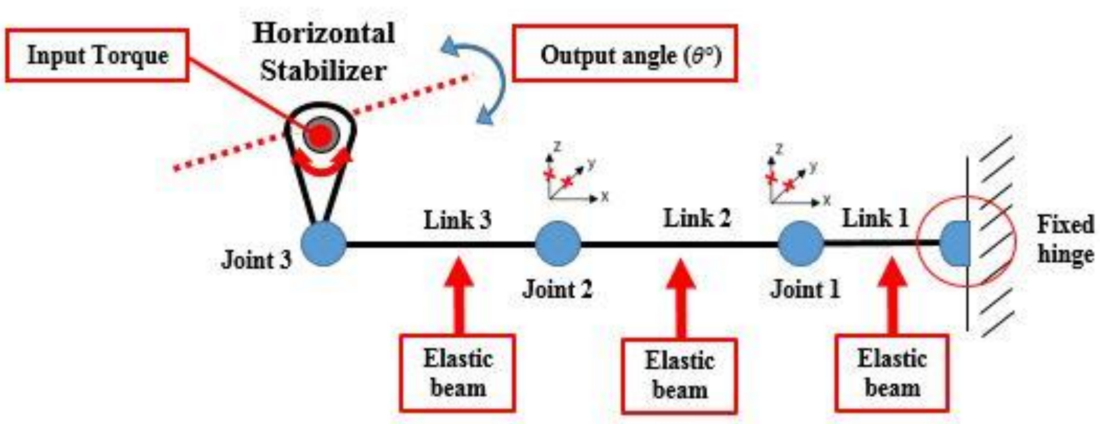


Figure 6: Diagram of simplified mechanical link in the horizontal stabilizer

Mode	Description	Frequencies, Hz
1st	Link 1 First bending	83
2nd	Link 1 First bending	305
3rd	Link 3 First bending	324
4th	Link 1 Second bending	329

Table 4: Natural frequencies of the link

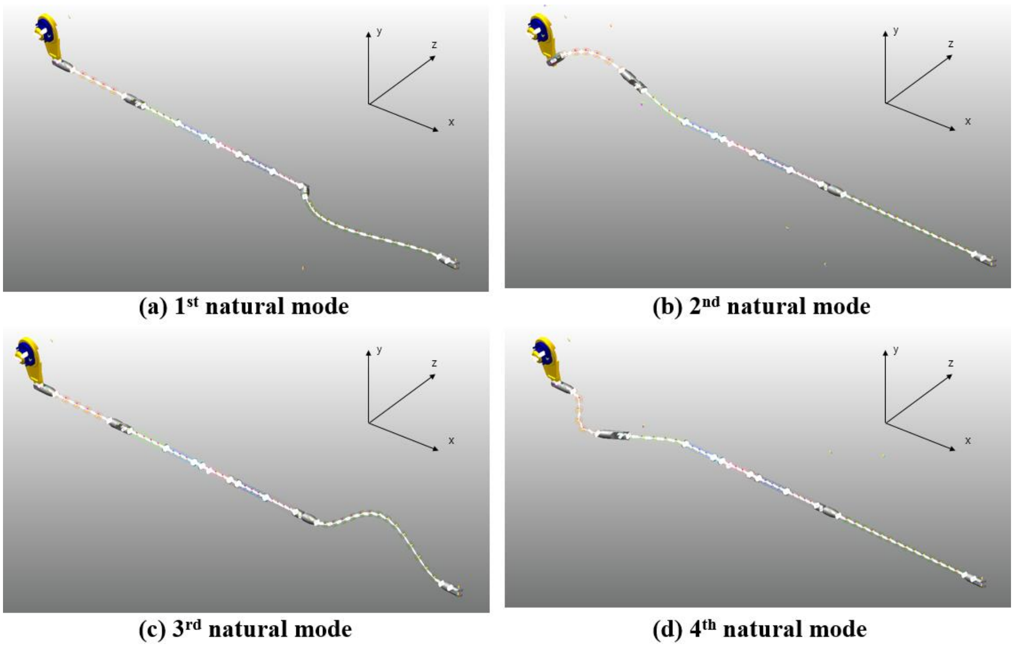


Figure 7: Natural mode shapes of the link

As shown in Table 3, before analyzing the structural dynamic responses of link, the modal analysis is performed using RecurDyn. Sine sweep torque is applied as an input to the joint between the horizontal stabilizer and the link. Its magnitude is 200 $N \cdot m$ and the frequency range is from 0 Hz to 500 Hz. This torque input is drawn in Figure 8 in time domain. The output of interest is the pitch angle of the horizontal stabilizer. In Figure 9, dynamic response of the pitch angle of the horizontal stabilizer is obtained by RecurDyn. It shows that the magnitude of the response grows in a specific time range.

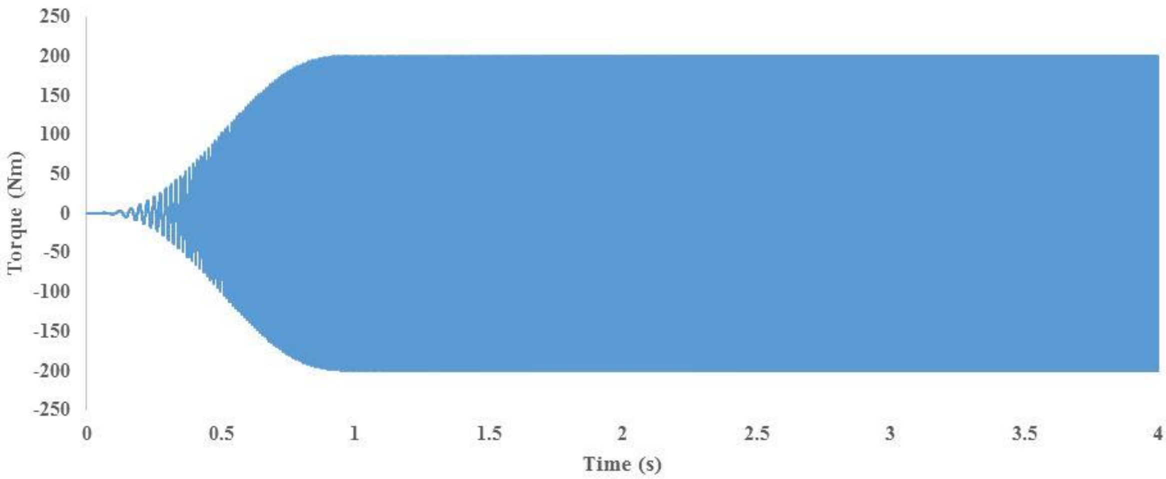


Figure 8: Time history of the torque (0 - 500 Hz sine sweep) applied at the joint between the horizontal stabilizer and the link

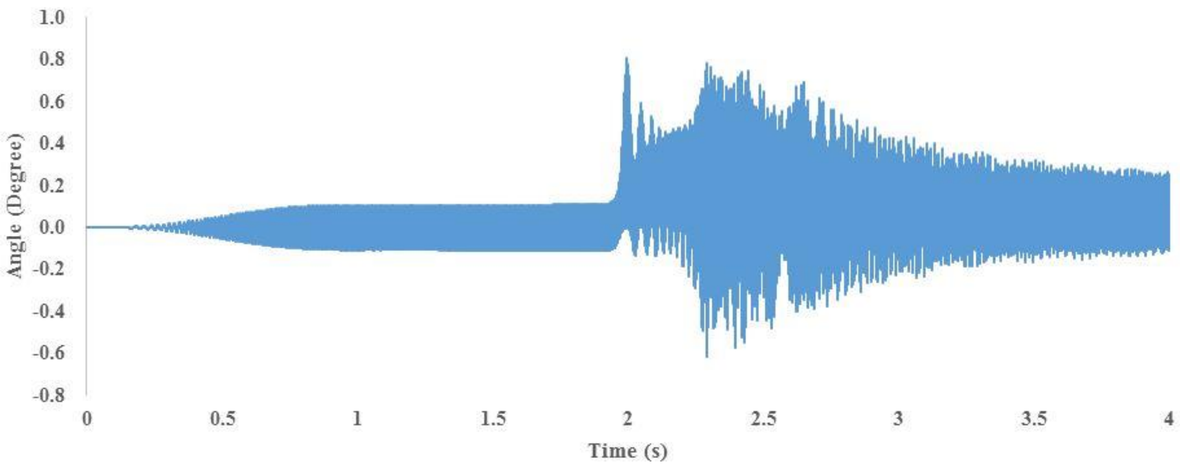


Figure 9: Pitch angle response obtained at the joint between the horizontal stabilizer and the link

The responses in time domain are transferred to the frequency domain by fast Fourier transform (FFT) by using a function included in MATLAB in order to obtain the transfer function of the link. Figures 10 and 11 represent the FFT results of the input and output. According to Figure 11, at approximately 322 Hz, there is shown a peak of the magnitude of the pitch angle of the horizontal stabilizer. From this result, the sine sweep input affects especially on the third natural mode of the link among all the modes.

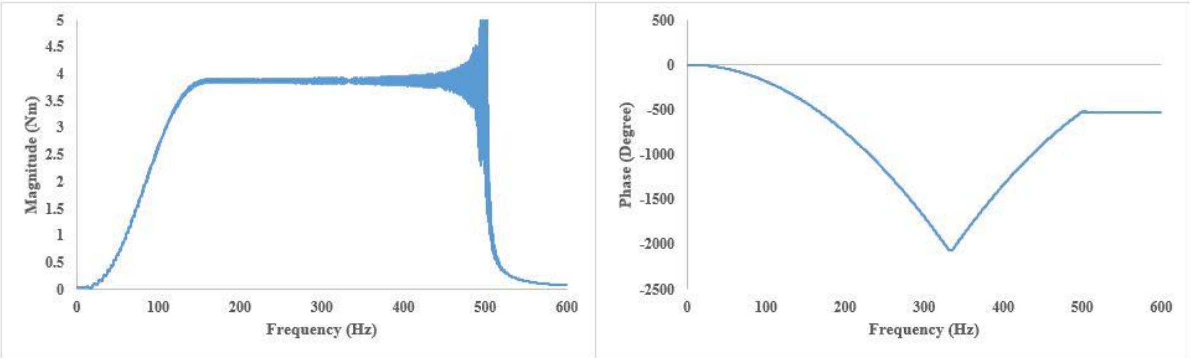


Figure 10: FFT of the torque input shown in Figure 8

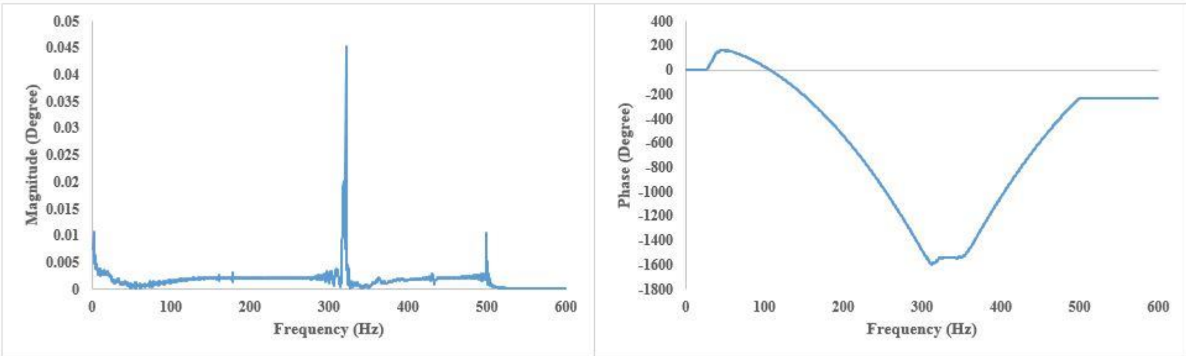


Figure 11: FFT of the pitch angle output shown in Figure 9

As mentioned in Section 2, the aeroservoelastic matrix of ZAERO is combined with aeroelastic state matrix and actuator state matrix. The actuator state matrix is obtained from transfer function of actuator. However, ZAERO uses the transfer function only formulated as a function with no zeros and three poles, as shown in Equation (4) [5]. If the transfer function is presented with higher order denominator and numerator, it must be approximated like as equation (3). Because of this limitation, a certain form of the transfer function is obtained, as in Eq. (5).

$$Transfer\ Function = \frac{a_0}{s^3 + a_2 s^2 + a_1 s + a_0} \tag{4}$$

$$\frac{\theta}{T} = \frac{8.6505\times10^5}{s^3 + 0.0036s^2 + 1.5438\times10^5 s + 554.0032} \tag{5}$$

Although, the above transfer function is expressed as transfer function of actuator, it means the dynamic stiffness between the horizontal stabilizer and the link. Thus, the flutter analysis can be obtained considering above transfer function.

4 CONCLUSION

A horizontal stabilizer controlled by an actuator through link is analyzed in this paper. For verification of the structural analysis by using MSC.NASTRAN, an experiment was conducted. The differences of the modal analyses between the experiment and MSC.NASTRAN were relatively small.In the flutter analysis, the effect of the flexibility of the link was considered. In that, variation of the dynamic torsional stiffness between the horizontal stabilizer and the link due to the flexibility was considered. The flutter boundary was reduced as the torsional stiffness decreased. Furthermore, the dynamic torsional stiffness mainly has a significant influence on the first natural mode. This is due to that the lowest natural mode of the fin is its first torsional mode. Finally, the structural dynamics and modal analysis of the link is conducted by using RecurDyn. As a result, the first natural frequency of the link is very similar to that for the horizontal stabilizer. It implies that in a specific torsional stiffness, flutter may occur due to the merge of the two natural modes. Such dynamic stiffness is vitally considered in the modal analysis and the flutter analysis, because the modal characteristics change as the factor varies as demonstrated in this paper. For the future research on the aeroservoealsticity of the complete horizontal stabilizer, the transfer function will be formulated as the pitch anlgle of the horizontal stabilizer versus torque. From the transfer function, an open loop system considering the elasticity of the link can be set. A closed loop system will be set by adding an controller which adjusts the pitch angle of the horizontal stabilizer to the open loop system. And the closed loop cotrol system analysis for the complete horizontal stabilizer system will be presented as future works.

5 ACKNOWLEDGEMENT

This research was supported by a grant to Bio-Mimetic Robot Research Center funded by Defense Acquisition Program Administration. And this work was also supported by Advanced Research Center Program (NRF-2013R1A5A1073861) through the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) contracted through Advanced Space Propulsion Research Center at Seoul National University.

6 REFERENCES

[1] Seo, Y. J., Aeroelastic Analysis of Missile Fin Considering Multiple Structural Nonlinearities, Doctoral Thesis, Korea Advanced Institute of Science and Technology, 2010, Dae-jeon, Korea.

[2] Raymond, L. B., Aeroelasticity, DoverPublications, 1996.

[3] Nalci, M. O., Aeroservoelastic Modeling of a Missile Control Fin, Master's Thesis, Middle East Technical University, February 2013, Ankara, Turkey.

[4] Chen, P.C., A Damping Perturbation Method for Flutter Solution: The g-Method, International Forum on Aeroelasticity and Structural Dynamics, Hampton, VA, Jun. 22-25, 1999. Also in AIAA Journal, Vol. 38, No. 9, Sep 2000, pp. 1519-1524.

[5] ZAERO Theoretical Manual, ZONA Technology, Inc.

[6] Yehezkely, E. and Karpel, M., Nonlinear Flutter Analysis of Missiles with Pneumatic Fin Actuators, Journal of Guidance, Control, and Dynamics, Vol. 19, No. 3, May-June 1996.

[7] Lee, D.H. and Chen, P.C., Nonlinear Aeroelastic Studies on a Folding Wing Configuration with Free-play Hinge Nonlinearity, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 1-4 May 2006, Newport, Rhode Island.

7 COPYRIGHT STATEMENT