10th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2019-033**
18-20 September 2019 - METU, Ankara TURKEY

EFFECTS OF VARIOUS DESIGN PARAMETERS ON THE PERFORMANCE OF A CRUISE MISSILE WING

Burak Ertürk[1]
TÜBİTAK-SAGE
and
Middle East Technical University
Ankara, Turkey

Yavuz Yaman[2]
Middle East Technical University
Ankara, Turkey

ABSTRACT

The design of a cruise missile wing is a multidisciplinary work because the wing has to provide enough aerodynamic forces while being structurally in safe. Various parameters of the wing are investigated during the design phase in order to meet the design goals and achieve a successful design. In this paper, the effects of different parameters on the lift force and flutter speed of a cruise missile wing are presented. The aerodynamic analyses for predicting the lift force are performed by using FLUENT and the aeroelastic analyses for the determination of the flutter speed are conducted by using ZAERO.

INTRODUCTION

A cruise missile wing design involves fundamental tradeoffs between aerodynamic and structural considerations. These fundamental tradeoffs can have complex interactions, especially as the wing design problem includes additional design parameters [Ning and Kroo, 2010]. For some cases, the number of design parameters can be more than 50 [Gonzalez, Walker, Srinivas and Periaux, 2007]. Furthermore, the lower and upper limits of each design parameters should be determined. In this complexity, predicting the effects of these design parameters to estimate the geometric constraints is highly important. The purpose of this study is to raise awareness about both the aerodynamic and structural effects of various parameters on a cruise missile wing. Several parameters are worthy to be examined; some of these geometrical parameters are the sweep angle, the taper ratio, and the aspect ratio.

Wings may have forward or backward sweep angle. The swept wings are commonly seen in high-speed cruise missiles since they reduce the effective flow speed below the critical speeds at which shock waves form on the upper wing surface. The backward sweep reduces the drag effect. Moreover, by moving back the center of pressure, it increases missile

[1] Researcher in Aerodynamics Division, Email: burak.erturk@tubitak.gov.tr
[2] Prof. in Aerospace Engineering Department, Email: yyaman@metu.edu.tr

longitudinal stability. In addition to the aerodynamic effects, the sweep angle also affects the aeroelastic characteristics of the wing.

The tapered wings have a span-wise chord variation. These wings are better than the rectangular wings structurally and aerodynamically. Structurally, because the root section is stiffer than the tip section and aerodynamically because it is the nearest wing shape to the elliptical wing which gives the optimum aerodynamic lift distribution [Mahran, Negm and Elsabbagh, 2015].

The aspect ratio defines the ratio of the square of the wingspan to the projected wing area. For the cruise missile wings, change of aspect ratio affects the aerodynamic and aeroelastic characteristics in a number of ways. It is known that flutter speed is changing with the change of the aspect ratio. Additionally, it was observed from the experimental and numerical studies that the change of the aspect ratio also affects the lift force [Aşkan and Tangöz, 2018].

Wing Properties and Variation of Design Parameters

During the design of the wing, many airfoil alternatives are investigated. Consequently, 10-percent thick supercritical airfoil SC(2)-1010 designed by NASA is selected. A comparison of supercritical flow phenomena for a conventional airfoil and the NASA supercritical airfoil is given in Figure 1. The NASA supercritical airfoil produces expansion waves or waves that tend to reduce pressure and increase velocity starting near the leading edge.

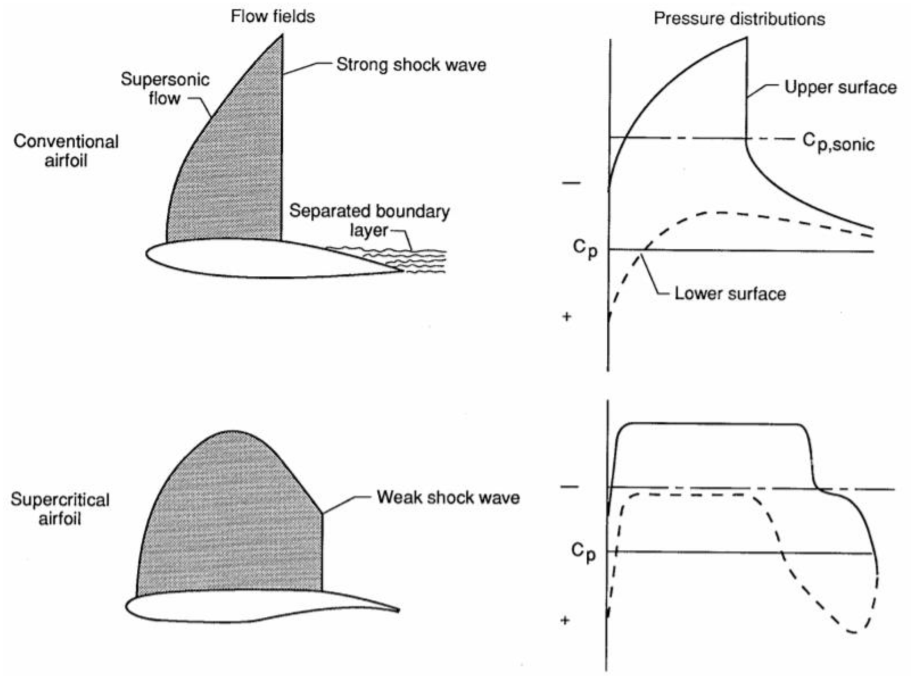

Figure 1: A comparison of the conventional airfoil and NASA supercritical airfoil [Harris, 1990]

In this study, the wing root chord is taken as constant due to geometric limitations dictated by the missile body. Hence, the tip chord of the wing is changed to get variable taper ratio wings. Similarly, the half-span of the wing is changed to get variable aspect ratio wings. Furthermore, the sweep angle represents the quarter chord sweep at 25% line. All examined wing geometries are given in Table 1 [Ertürk, 2019].

Another thing to be considered is the material properties of the wing. It is manufactured from 2014-T6 aluminum alloy. The density of the material is 2.8 g/cm^3. The modulus of elasticity is 73.1 GPa while the shear modulus is 28 GPa. Lastly, the Poisson's ratio of the 2014-T6 aluminum alloy is 0.33.

Table 1: Variation of design parameters

Wing Number	Aspect Ratio	Taper Ratio	Quarter-Chord Sweep Angle (°)
1	4	0.75	30
2	6	0.75	30
3	8	0.75	30
4	10	0.75	30
5	10	0.25	30
6	10	0.50	30
7	10	1.00	30
8	10	0.75	0
9	10	0.75	15
10	10	0.75	45

AERODYNAMIC ANALYSES

In the aerodynamic analyses, the x-z plane at the root chord is defined as symmetry boundary. All external boundaries are defined as pressure far field and wing body is defined as no-slip wall. The computational grids for aerodynamic analyses are constructed by using ANSYS Meshing which is a general-purpose, automated high-performance commercial product. The surface mesh, given for Wing 1 in Figure 2, consists of about 50,000 numbers of triangular elements. Since tetra meshing is not efficient for capturing shear or boundary layer physics, prismatic boundary layer grids are constructed to capture boundary layer effects. The remaining flow domain is meshed with tetrahedron elements. The total volume mesh consists of about 2 million numbers of elements.

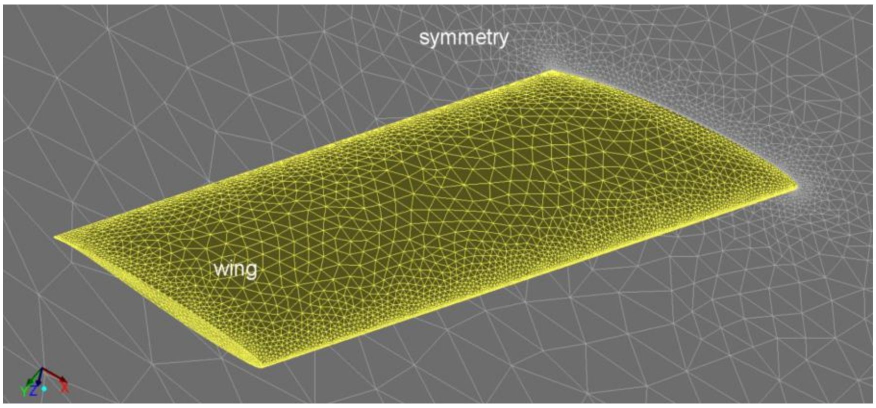

Figure 2: Surface mesh around the Wing 1 for aerodynamic analyses

The aerodynamic analyses to predict the lift forces are performed at cruise condition of the missile by FLUENT code which is a commercial code having Reynolds-Averaged Navier-Stokes (RANS) solver. RANS analyses are conducted assuming fully turbulent flow. In order to represent this condition, the Spalart-Allmaras turbulence model is used in the flow calculations.

Spalart-Allmaras Turbulence Model

The Spalart-Allmaras model is a one equation model solving directly a transport equation for eddy viscosity [Spalart and Allmaras, 1992]. This turbulence model gives acceptable results for a wide range of flow application [Deck, 2002]. In addition, since it uses a single equation, there is no need for excessive computational power and solution converges to steady-state quickly.

AEROELASTIC ANALYSES

In order to perform the aeroelastic analyses, finite element modeling and analyses are conducted. Then, the aerodynamic models are prepared by selecting the number of divisions in chord-wise and span-wise directions in ZAERO input file.

The computational grids and finite element models for aeroelastic analyses are generated by using MSC®PATRAN. The surface mesh is constructed by using triangular elements and solid is meshed with tetrahedron elements. The view of the surface mesh for Wing 1 is given in Figure 3.

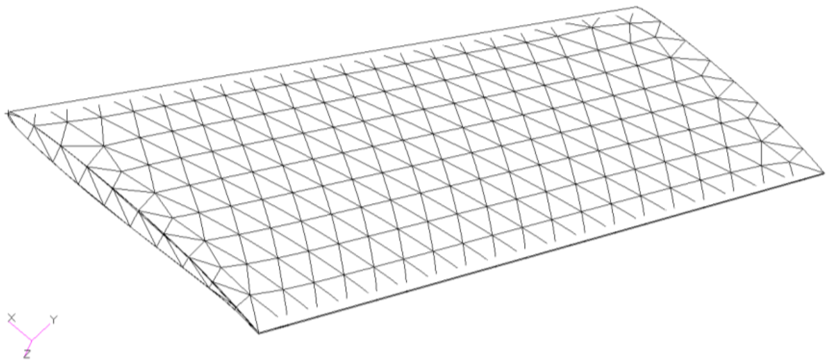

Figure 3: Surface mesh around the Wing 1 in finite element model for aeroelastic analyses

In the finite element models, the boundary condition of the wing is defined as fixed at the root chord and free at the tip chord. Vibrational analyses are performed for all geometries by using MSC®NASTRAN. The normal modes are calculated for each geometry and the first five relevant modes are decided to use in aeroelastic analyses. The mode shapes for the Wing 1 are given in Figure 4 as an example.

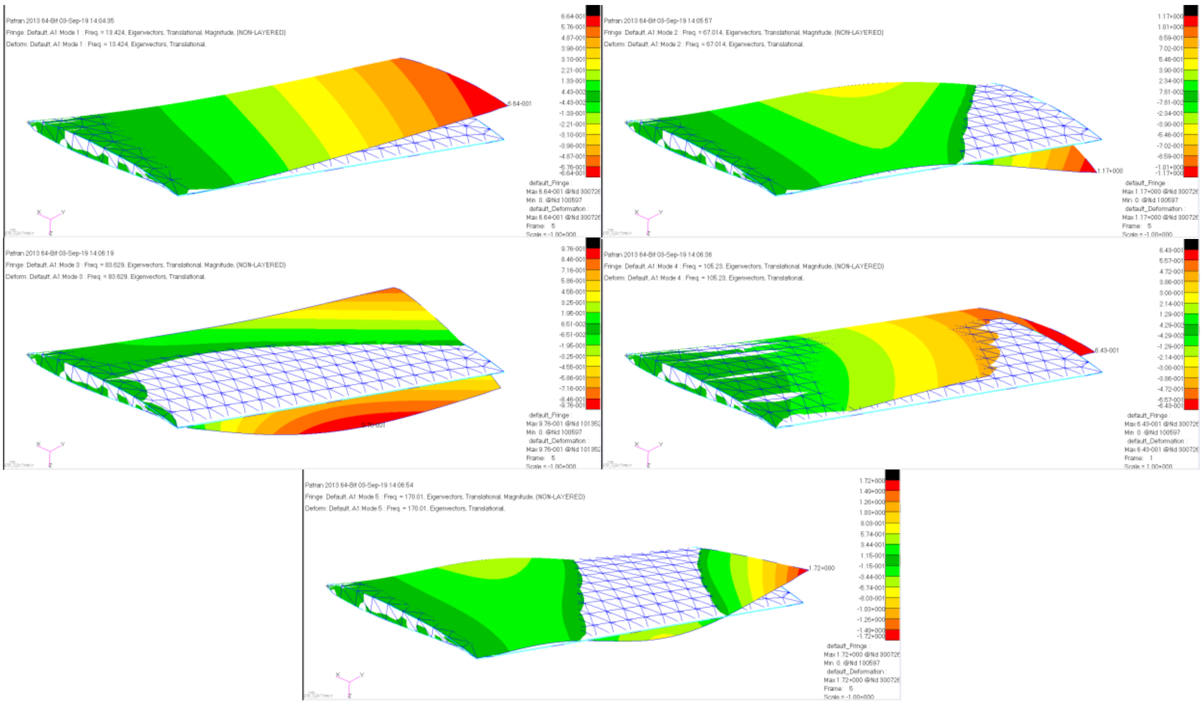

Figure 4: Selected mode shapes for aeroelastic analyses

The aerodynamic model for Wing 1 is given in Figure 5. The element sizes in aerodynamic models are determined by considering the maximum element size formula for a convergent solution [Zona, 2011]. This formula is given as:

$$\Delta x < 0.08 \left(\frac{V}{f}\right) \frac{1}{\left(\frac{M}{\sqrt{|M^2 - 1|}}\right)^2} \qquad \text{(Equation 1)}$$

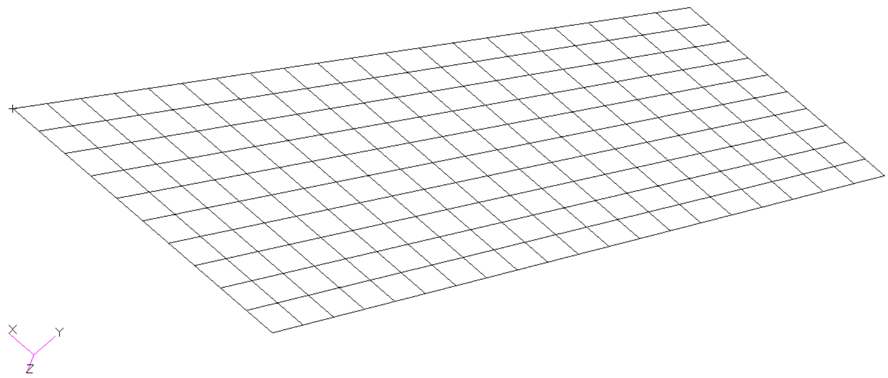

Figure 5: Surface mesh around the Wing 1 in the aerodynamic model for aeroelastic analyses

The aeroelastic analyses to predict the flutter speeds are conducted for different wing geometries by using ZAERO. The structural and aerodynamic models are connected by using the Infinite Plate Spline (IPS) method and analyses are conducted using the P-K method.

RESULTS

The aerodynamic and aeroelastic analyses are conducted at the cruise condition for the missile to be designed. For the aeroelastic analyses, the velocity is increased by 10 m/s until the flutter speed is obtained. The velocity versus damping (V-g) and the velocity versus frequency (V-f) graphs for the Wing 1 are given in Figure 6 and Figure 7. The flutter speed is estimated as calculating the intersection point of the V-g curve with the x-axis. Indeed, this intersection point can be flutter speed or divergence speed. The flutter speed is distinguished from the divergence speed by checking the frequency at this point. If the frequency has non-zero value at this point, the speed at this intersection point is decided as the flutter speed.

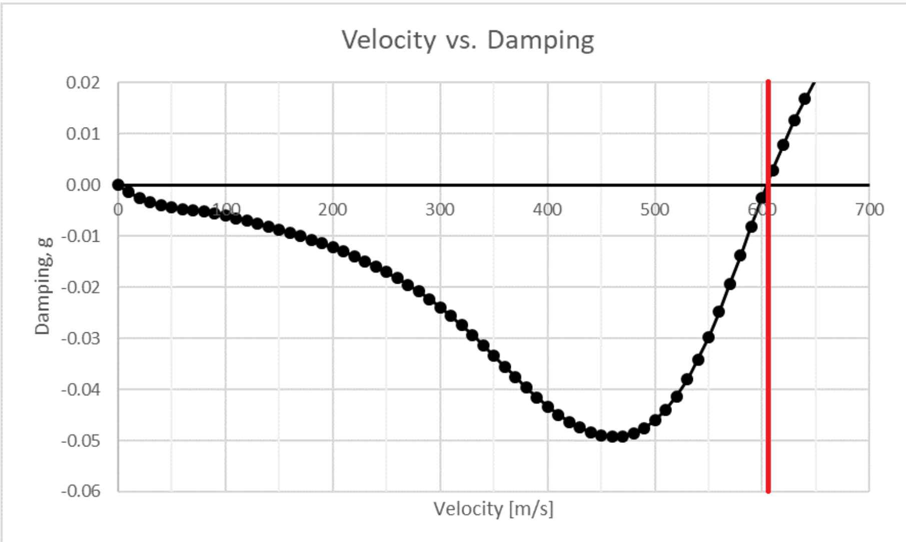

Figure 6: Velocity vs. Damping (V-g) graph for the Wing 1

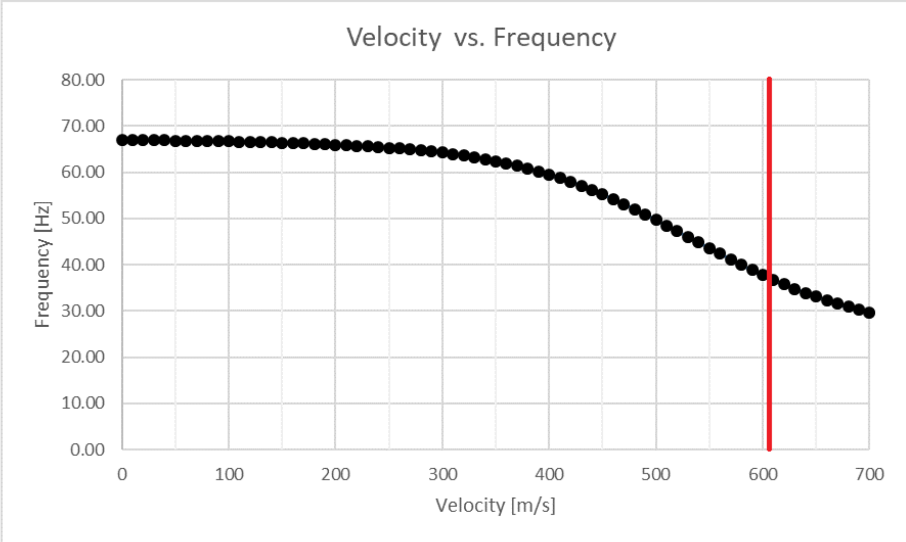

Figure 7: Velocity vs. Frequency (V-f) graph for the Wing 1

Figure 8 represents the relationship between the aspect ratio and the lift force. As expected, due to the increase in the area of the lifting surface, the lift force increases with the increase of the aspect ratio. It can be said that this increase has a linear trend.

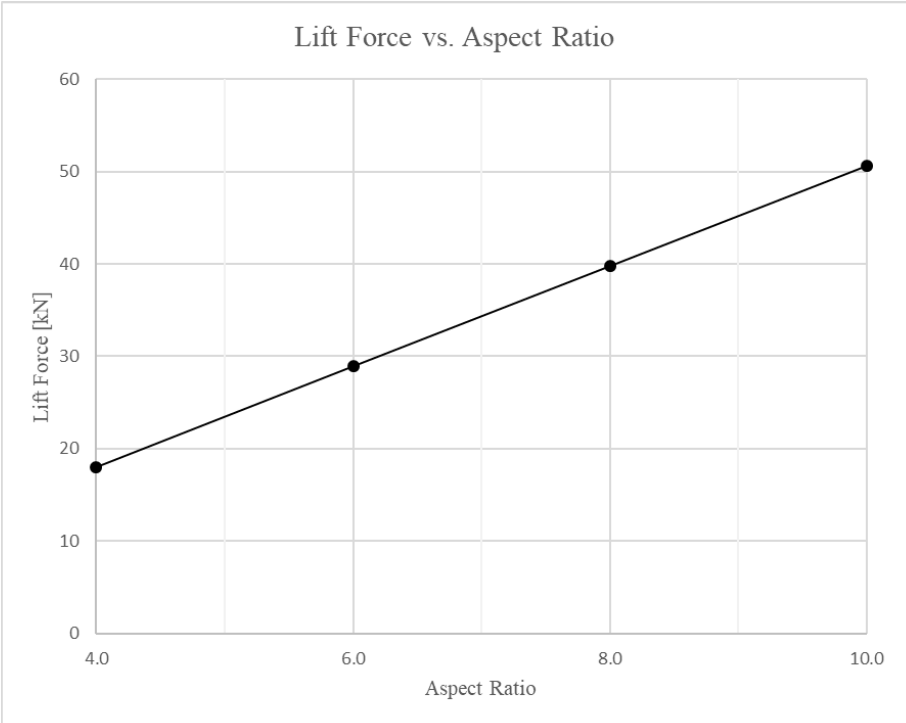

Figure 8: Effect of the aspect ratio on the lift force

Figure 9 gives the results of the aeroelastic analyses to obtain the flutter speeds of different aspect ratio wings. Since the disturbing aerodynamic forces on the wing increased with the increase of the aspect ratio, the flutter speed decreases significantly.

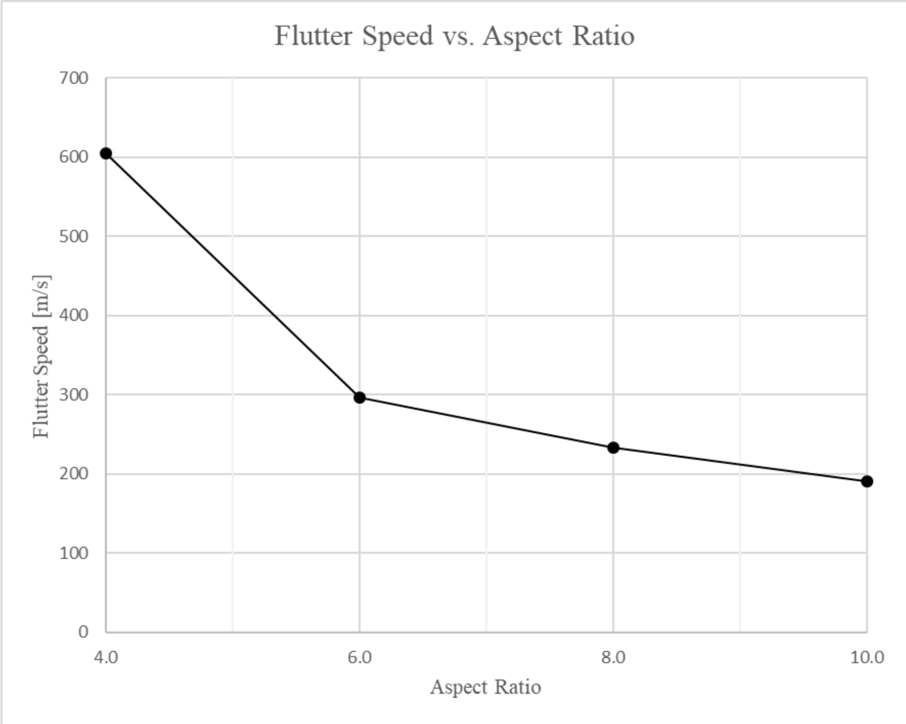

Figure 9: Effect of the aspect ratio on the flutter speed

The effect of the taper ratio on the lift force is presented in Figure 10. While the taper ratio increases, also the area of the wing increases. Thus, similar to the effect of the aspect ratio, it can be concluded that lift increases with the increase of the taper ratio.

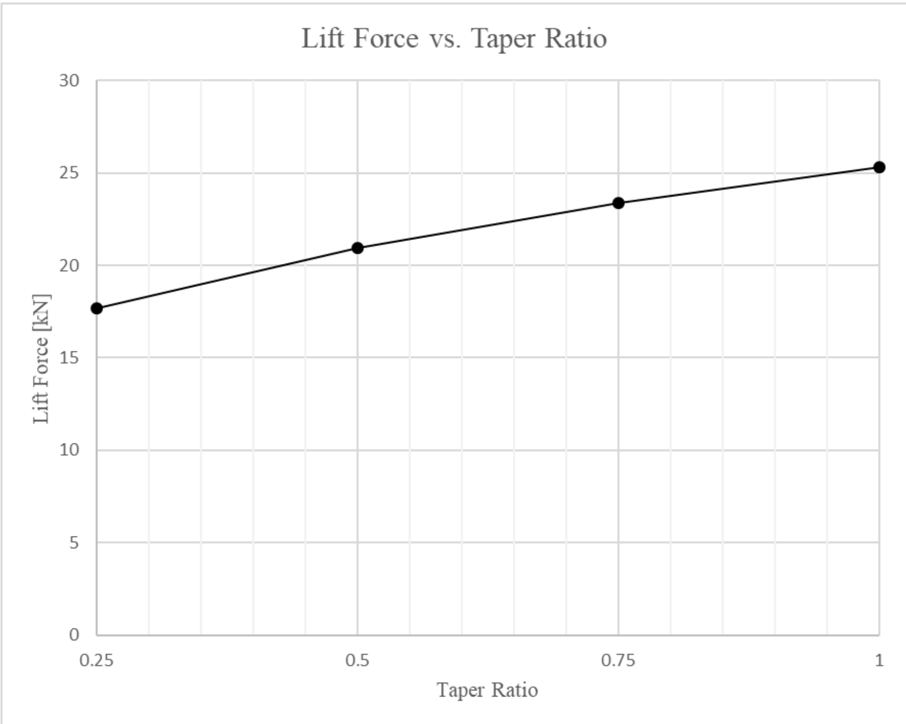

Figure 10: Effect of the taper ratio on the lift force

In Figure 11, the effect of the taper ratio on the flutter speed is given. It shows clearly that with the increase of the taper ratio, the flutter speed decreases. In other words, the tapering increases the flutter speed. This increase is the result of the increase of the bending and torsional stiffness of the structure.

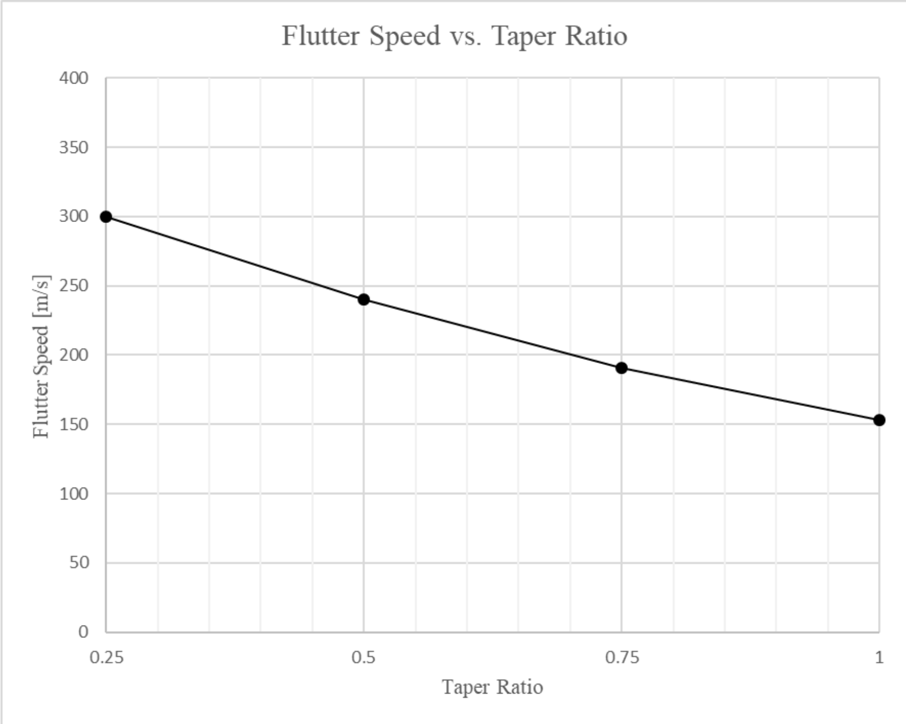

Figure 11: Effect of the taper ratio on the flutter speed

Figure 12 is obtained to investigate the effect of the sweep angle on the lift force. In contrast to the trend seen in the lift force with the change of the aspect ratio and the taper ratio, the flutter speed does not change linearly with the sweep angle. For this wing configuration, it can be concluded that the lift force decreases when the sweep angle exceeds 30 degrees.

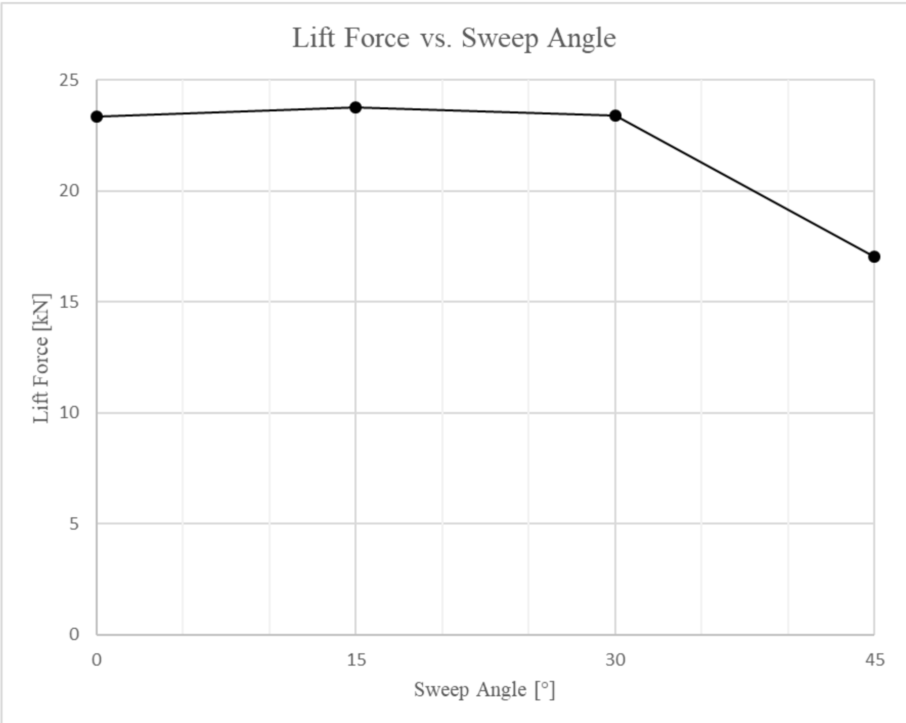

Figure 12: Effect of the sweep angle on the lift force

Finally, the effect of the sweep angle on the flutter speed is shown in Figure 13. Similar to the trend seen in the lift force in Figure 12, the flutter speed does not change linearly with the sweep angle but this time flutter speed decreases when the sweep angle is around 15 degrees.

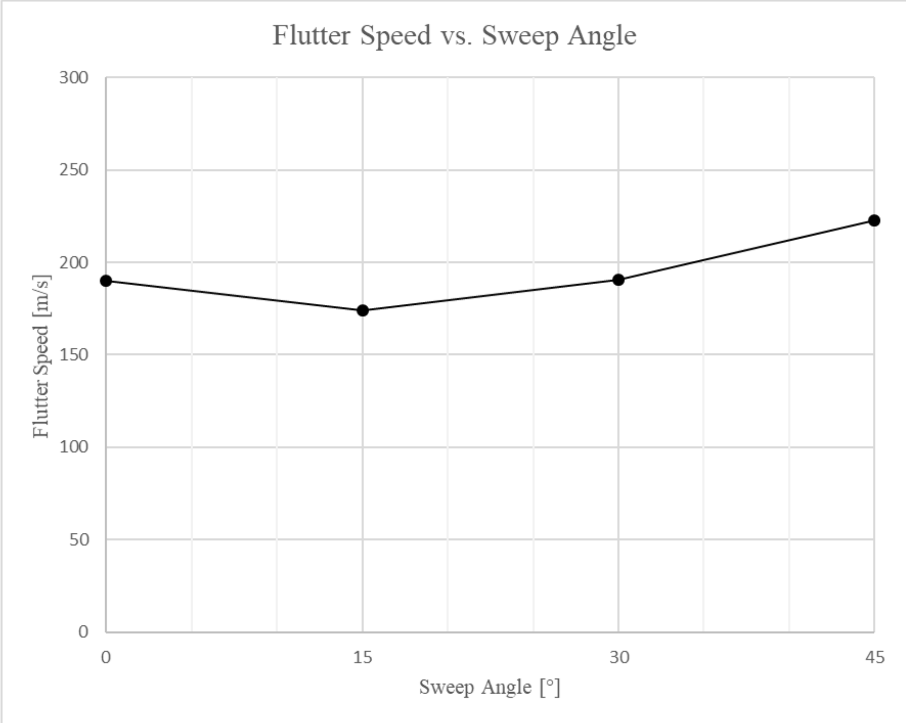

Figure 13: Effect of the sweep angle on the flutter speed

CONCLUSION AND FUTURE WORK

In this study, different geometries are generated by changing the design parameters systematically. The lift forces and flutter speeds are obtained for these different geometries at cruise condition of the cruise missile. Lift forces are obtained for these geometries to examine the aerodynamic effects of design parameters while the flutter speeds are estimated to investigate aeroelastic effects of design parameters.

As a result, this work shows that the aspect ratio and the taper ratio has a substantial effect on the aerodynamic and aeroelastic characteristics of the wing. Furthermore, these effects are inversely proportional to each other. For example, as the lift force increases with the increase of the aspect ratio the flutter speed decreases. The sweep angle shows different characteristics on the lift force and the flutter speed of the wing. Therefore, the design process of the missile needs to be multidisciplinary. In this complex multidisciplinary design process, predicting the effects of individual design parameters is highly important.

This study included the aerodynamic and aeroelastic analyses to obtain the effects of design parameters like aspect ratio, taper ratio and sweep angle. The study may be extended for the other design parameters such as incidence, twist angle, airfoil type, etc. Moreover, this study is performed at cruise condition of the missile. The study may be extended to include these effects at different speeds and altitudes.

References

Aşkan, A. and Tangöz, S. (2018) *The Effect of Aspect Ratio on Aerodynamic Performance and Flow Separation Behavior of a Model Wing Composed from Different Profiles*, Journal of Energy Systems, Vol. 2, p: 224–237, Dec 2018.

Chorin, A. J. (1968) *Numerical Solution of Navier-Stokes Equations,* Mathematics of Computation, Vol: 22., pp:745–762., Jan 1968.

Deck, S. and Duveau P. and D'espiney, P and Guillen P. (2002) *Development and Application of Spalart-Allmaras One Equation Turbulence Model to Three-Dimensional Supersonic Complex Configuration,* Aerospace Science and Technology, Vol.6, pp. 171-183, Jan 2002.

Ertürk, B. (2019) *Effects of Design Parameters on the Aeroelastic Performance of a Cruise Missile Wing*, METU, Aug 2019.

Gonzalez, F. and Walker, R. and Srinivas, K. and Periaux, J. (2007) *Multidisciplinary Design Optimisation of Unmanned Aerial Systems (UAS) Using Meta Model Assisted Evolutionary Algorithms*, 16th Australasian Fluid Mechanics Conference, Dec 2007

Harris, C. D. (1990) *NASA Supercritical Airfoils: A Matrix of Family-Related Airfoils,* NASA Technical Paper 2969, Mar 1990

Mahran, M. and Negm, H. and Elsabbagh, A. (2015) *Aero-elastic Analysis of Plate Wings Using the Finite Element Method*, LAP LAMBERT Academic Publishing, 2015.

Ning, A. and Kroo, I. (2010) *Multidisciplinary Considerations in the Design of Wings and Wing Tip Devices*, Journal of Aircraft, Vol. 47, p: 534–543, Mar 2010.

Spalart, P.R. and Allmaras, S.R. (1992) *A One-Equation Turbulence Model for Aerodynamic Flows,* AIAA-92-0439, Jan 1992.

Zona, T. (2011) *ZAERO User's Manual*, Version 8.5, ZONA 02 – 12.4, Zona Technology Inc., June 2011.