Assessment of the performance of a cruise missile wing depending on design parameters at various flight conditions

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Abstract. The design of a cruise missile wing is a multidisciplinary work, since the wing has to provide enough aerodynamic forces while being structurally safe. In order to meet the design requirements and achieve a successful design, several parameters of the wing need to be investigated at various flight conditions. In this paper, lift forces and flutter speeds are obtained for different wing geometries, at various altitudes and speeds. The design of experiments is constructed by changing the several variables of the wing to have better understanding of the effect of design parameters. 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 package programs.

1 Introduction

The wing may be considered as the most important component of a cruise missile, because it is needed to reach long range. The primary function of the wing is to generate the sufficient lift force and its design involves fundamental trade-offs between aerodynamic and structural aspects.

The wing needs to produce sufficient lift force while being away from flutter problem. The purpose of this study is to indicate the effects of changing various design parameters on the performance of a cruise missile wing at different flight conditions. In order to reach an optimum wing geometry, providing aerodynamic and aeroelastic design goals, predicting the effects of design parameters is very important.

As the wing design problem includes additional design parameters, aerodynamic and structural considerations can have complex interactions. In this complexity, predicting the effects of these design parameters and defining the design parameters to be optimized is highly important. Furthermore, the lower and upper limits for each design parameters should be correctly determined.

In this study, the 10-percent thick supercritical airfoil SC(2)-1010 is used to form 3D wing since the NASA supercritical airfoil produces expansion waves, or waves that tend to reduce pressure and increase velocity starting near the leading edge. Thus, with comparing

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to the conventional airfoils, the shock waves formed on the wing becomes weak. The pressure rise through the shock wave may cause separation of the boundary layer with further increases in drag a well as buffeting and stability problems [1].

The material of the wing is 2014-T6 aluminum alloy which has the density of 2.8 g/cm3. The modulus of elasticity is 73.1 GPa, the shear modulus is 28 GPa and the Poisson's ratio of the 2014-T6 aluminum alloy is 0.33

In order to observe the effect of more than one design parameters and different flight conditions, one of the best methodology is constructing the design of experiments (DOE). DOE is statistical tool deployed in various types of system, process and product design, development and optimization. The number of different geometries in DOE directly depends on the numbers of design parameters. Thereby, determining design parameters to be examined is highly important. All geometries in the DOE must be analyzed in order to generate the response surface. It explores the relationships between design parameters and design requirements.

2 Identification of design parameters

The initial design process begins with a general definition of the mission/scenario desired. This scenario involves the differentiation of flight conditions such as the speed, altitude, angle of attack during the mission. The weapon requirements, trade studies, and sensitivity analysis task provide the high level requirements on the missile such as range, time to target, and other measures of merit [2]. These high level requirements are evaluated by different disciplines and design requirements are identified in this manner.

In order to meet the design requirements mentioned above, several parameters need to be optimized for the wing. Among these parameters; the tip chord, the span, and the sweep angle are worthy to be examined. It should be noted that by changing the tip chord and span, the taper ratio and the aspect ratio will also vary during the design process. Besides, these effects may not be same at different flight conditions on which the cruise missile flying.

Due to the geometric limitations dictated by the missile body, the root chord of the wing is taken as constant. While the root chord of the wing is constant, changing the tip chord of the wing results in the tapered wing which has 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 [3].

Since the aspect ratio defined as the ratio of wing span to its mean chord, varying the wing span is also changing the aspect ratio. For a cruise missile wings, change of the aspect ratio affects the aerodynamic and aeroelastic characteristics in a number of ways. It is known that the flutter speed changes with changing aspect ratio. Additionally, it was observed from the experimental and numerical studies that the changing of the aspect ratio also affects the lift force [4].

As the last parameter, 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. Moreover, the backward sweep reduces the drag effect. In addition to the aerodynamic effects, it is known that the sweep angle also affects the aeroelastic characteristics of the wing.

3 Construction of design of experiments

In order to investigate the effects of design parameters, such parameters as the aspect ratio, the taper ratio, and the sweep angle are differentiated as given in Table 1 [5].

Table 1. Variation of design parameters.

	Minimum	**Maximum**	**Number of Geometries**
Aspect Ratio	4	8	5
Taper Ratio	0.25	1.0	4
Sweep Angle	0°	45°	4

Geometries given in Table 1 are used in aerodynamic and aeroelastic analyses to estimate lift forces and flutter speeds. The lift forces are obtained for different speeds by FLUENT code which has Reynolds-Averaged Navier-Stokes (RANS) solver and the flutter speeds are estimated at different altitudes by ZAERO which is a commercial code having different aeroelastic solution methods.

4 Aerodynamic and aeroelastic analyses

The computational grids for aerodynamic analyses are constructed by using ANSYS Meshing. The surface mesh for a selected geometry in DOE, given in Fig. 1, consists of about 50,000 of triangular elements. Since tetra meshing is not efficient for capturing shear or boundary layer physics, prismatic boundary layer grids are constructed in order to capture the boundary layer effects. The remaining flow domain is meshed with tetrahedron elements. The total volume mesh consists of about 2 million numbers of elements.

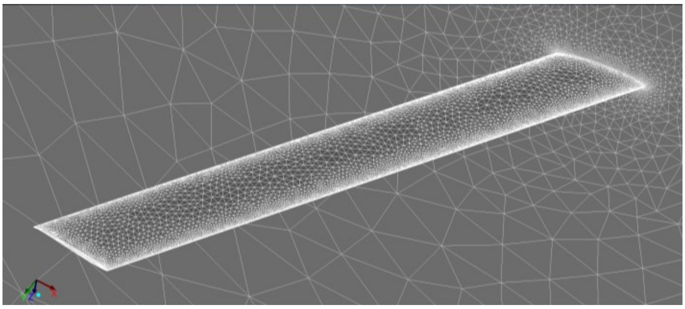

Fig. 1. Surface mesh around wing for aerodynamic analyses.

Aerodynamic analyses to predict lift force are performed for different wing geometries at various speeds by FLUENT code having Reynolds-Averaged Navier-Stokes (RANS) solver. In analyses, x-z plane of Figure 1 at the root chord defined as the symmetry boundary. All external boundaries defined as pressure far field and wing body defined as no-slip wall. RANS analyses are conducted assuming fully turbulent flow by using Spalart-Allmaras turbulence model.

The computational grids and finite element models for aeroelastic analyses are generated by using MSC®PATRAN. The surface element size is selected as the one-tenth of the root chord. Surface mesh is constructed by using triangular elements and solid is meshed with tetrahedron elements. The view of the surface mesh for a selected geometry in DOE is given in Fig. 2.

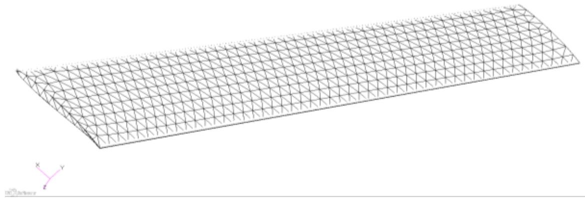

Fig. 2. Surface mesh around wing in finite element model.

The vibrational analyses are performed, for all the geometries existing in DOE, by using MSC®NASTRAN. The modes are calculated for each geometry and the first five relevant modes are used for aeroelastic analyses. The mode shapes for a selected geometry in DOE are given in Fig. 3 as an example.

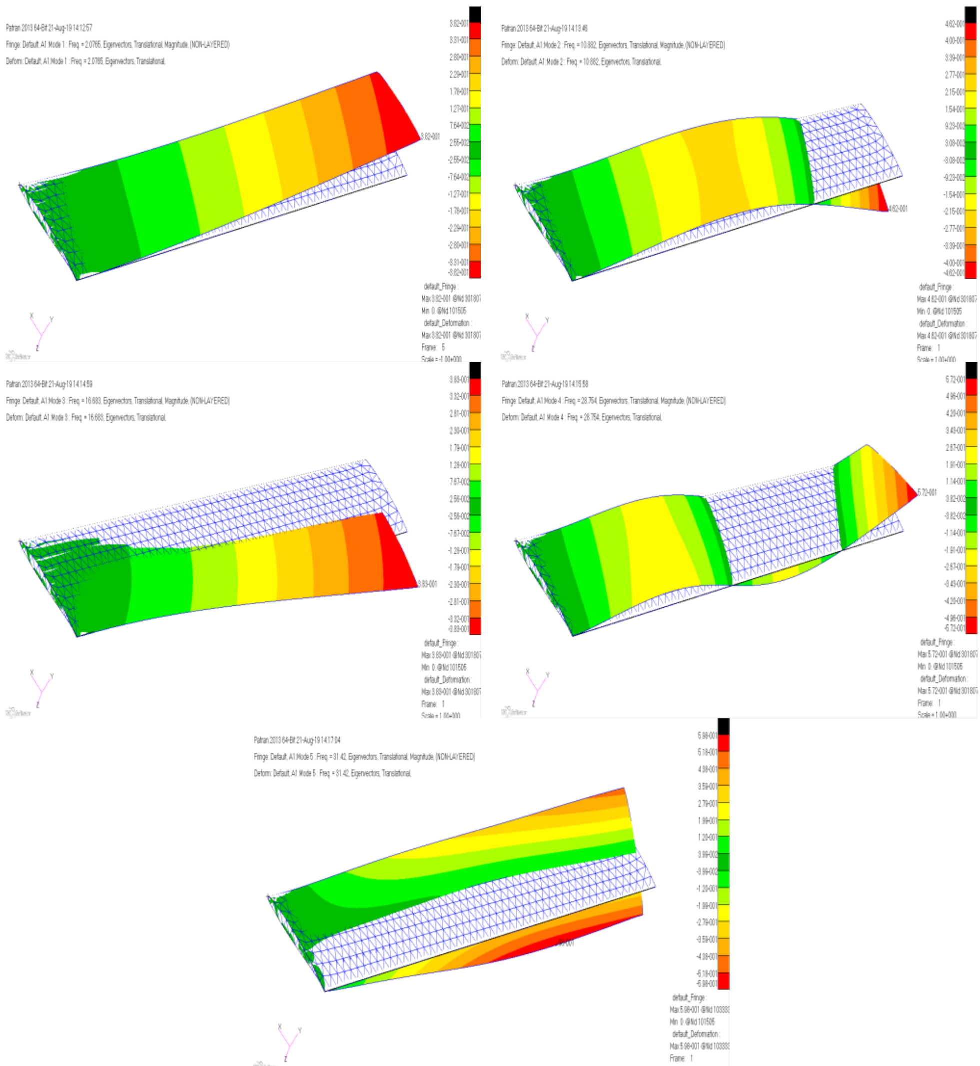

Fig. 3. Selected mode shapes for aeroelastic analysis.

Aeroelastic analyses to predict flutter speed are performed for different wing geometries at various altitudes by using ZAERO. The aerodynamic models for aeroelastic analyses are constructed in ZAERO by inputting the element sizes. Then, structural and aerodynamic models are connected by using the Infinite Plate Spline (IPS) method.

Analyses are conducted using the P-K method which has been widely adopted by aeroelasticians as the primary tool for finding flutter solutions. The P-K method solves the Equation (1).

$$[(V^2/c^2)\cdot\mathbf{M}\cdot p^2 + \mathbf{K} - 1/2\cdot\rho\cdot V^2\cdot\mathbf{Q}(ik)]\{\mathbf{q}\} = 0 \tag{1}$$

5 Results and Discussions

The aerodynamic analyses are conducted for 3 different Mach numbers of 0.75, 0.80, and 0.90. These speeds are possible cruise condition for the missile to be designed. Analyses are performed to obtain lift force at sea level cruise flight condition. Besides, the aeroelastic analyses are performed at 3 different altitudes such as sea level, 10,000 feet and 20,000 feet. For the aeroelastic analyses, velocity is increased by 10 m/s until the flutter speed is obtained.

Fig. 4 represents the relationship between the aspect ratio and the lift force. As expected, due to increase in the area of the lifting surface, the lift force is increased with increasing aspect ratio. It can be said that this increase has linear trend.

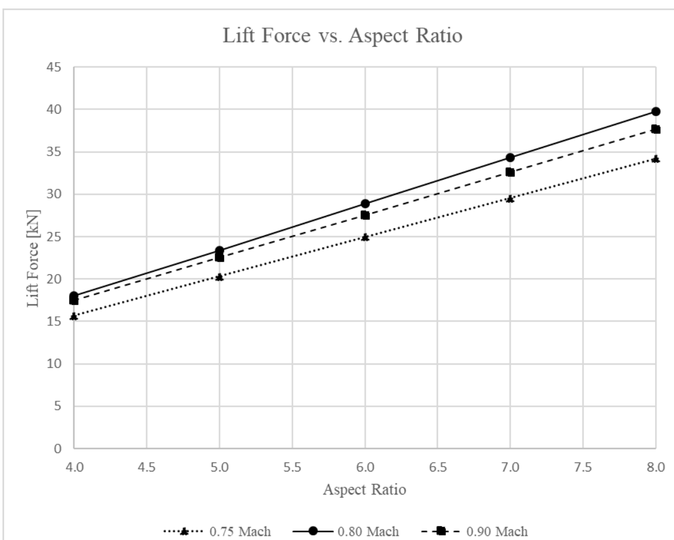

Fig. 4. Effects of the aspect ratio on the lift force.

Fig. 5 gives the results of the aeroelastic analyses to obtain flutter speeds for different aspect ratio wings. Since the disturbing aerodynamic forces on the wing is increased with increasing the aspect ratio, the flutter speed decreases significantly.

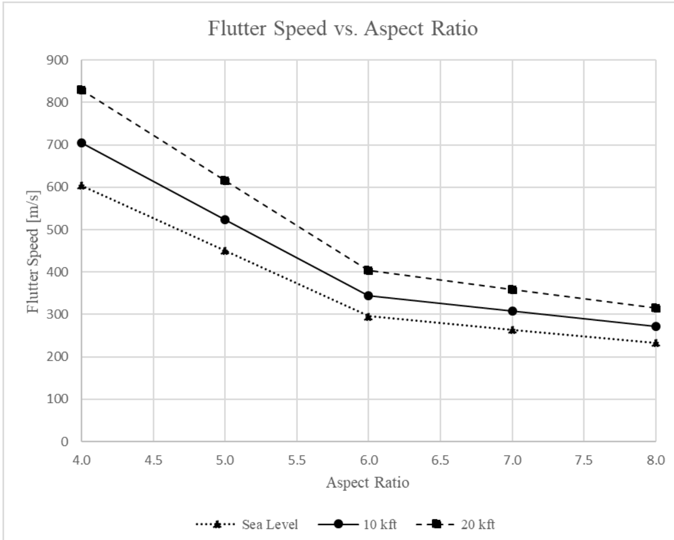

Fig. 5. Effects of the aspect ratio on the flutter speed.

Effects of the taper ratio on the lift force is presented in Fig. 6. While the taper ratio increases, also the area of the wing increases. Thus, similar with the effect of the aspect ratio, it can be concluded that lift increases with increasing of the taper ratio.

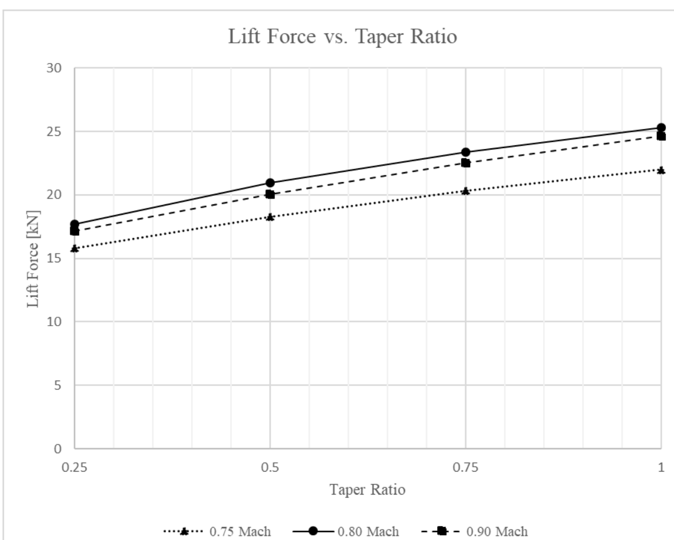

Fig. 6. Effects of the taper ratio on the lift force.

In Fig.7, effects of the taper ratio on the flutter speed is given. It shows clearly that with increasing the taper ratio, the flutter speed decreases. In other words, the tapering increased the flutter speed. This increase is the result of increasing the bending and torsional stiffness of the structure.

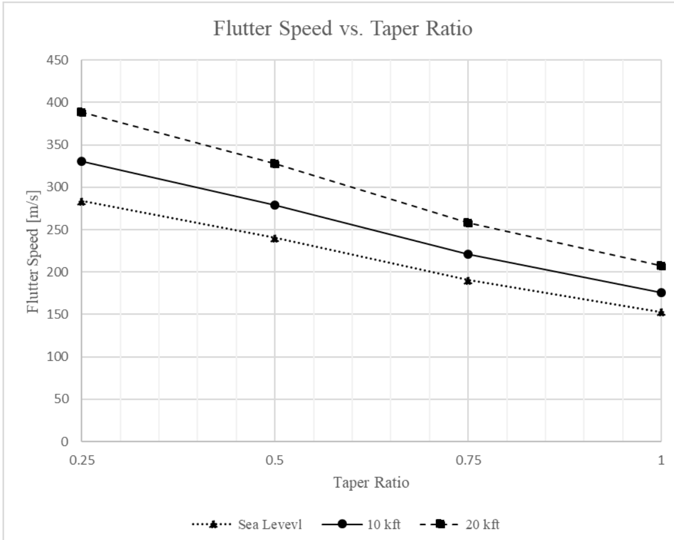

Fig. 7. Effects of the taper ratio on the flutter speed.

Fig. 8 is obtained to clarify the effects of sweep angle on the lift force. In contrast to the trend seen in the lift force with changing the aspect ratio and the taper ratio, the sweep angle is not changing the lift force linearly.

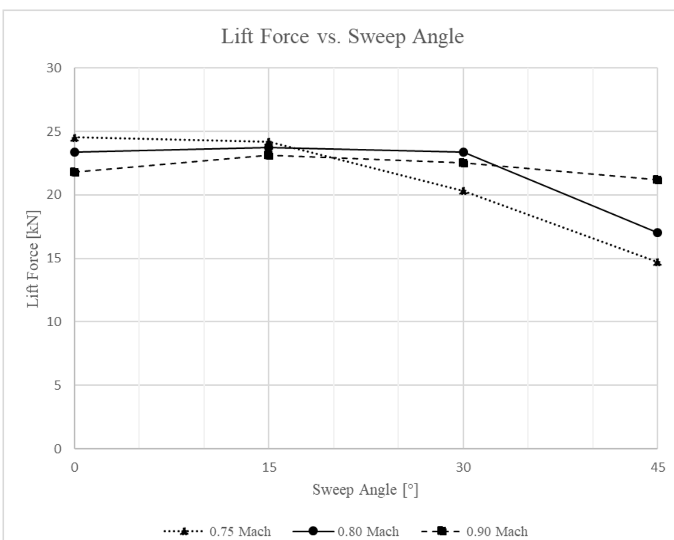

Fig. 8. Effects of the sweep angle on the lift force.

Lastly, effects of the sweep angle on flutter speed is shown in Fig.9. Similar to the trend seen in the lift force in Fig.8, the flutter speed is not changing linearly with the sweep angle but this time flutter speed decreases when the sweep angle is around 15 degrees.

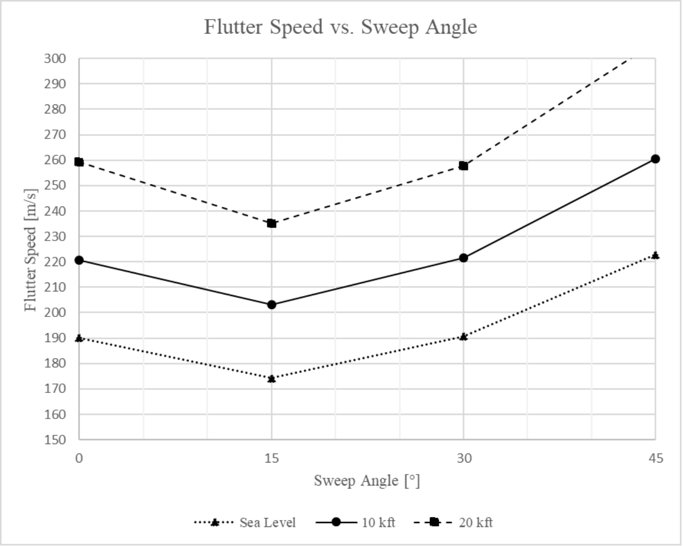

Fig. 9. Effects of the sweep angle on the flutter speed.

6 Conclusion

In this work, the lift forces and flutter speeds are obtained for different geometries in the DOE. In order to obtain the effects of design parameters as the aspect ratio, the taper ratio, and the sweep angle; the different wing geometries are created by changing these design parameters systematically. Lift forces are obtained for these geometries to show the aerodynamic effects of design parameters while the flutter speeds are estimated to determine aeroelastic effects of design parameters.

It can be concluded that the aspect ratio and the taper ratio has substantial effect on the aerodynamic and aeroelastic characteristics of the wing. Indeed, these effects are inversely proportional with each other. For example, as the lift force is increasing with increasing of the aspect ratio the flutter speed decreases. 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.

References

1. Harris, C. D., *NASA Supercritical Airfoils: A Matrix of Family-Related Airfoils*, NASA technical Paper 2969, (1990)
2. Fleeman E. L., *Tactical Missile Design*, American Institute of Aeronautics and Astronautics, (2001)
3. Mahran, M. and Negm, H. and Elsabbagh, A., *Aero-elastic Analysis of Plate Wings Using the Finite Element Method*, LAP LAMBERT Academic Publishing, (2015)
4. Askan, A. and Tangoz, S., *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, (2018)
5. Erturk, B., *Effects of Design Parameters on the Aeroelastic Performance of a Cruise Missile Wing*, METU, (2019)