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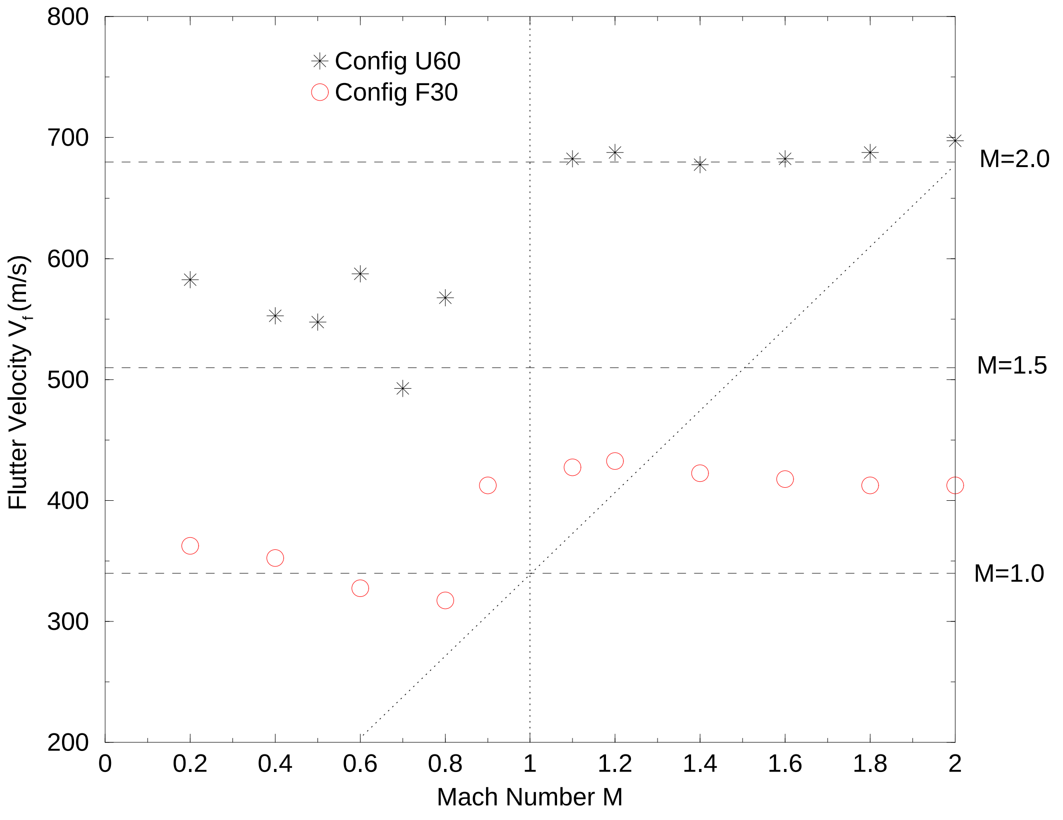
TVÄRTEKNIKPROJEKTET: AEROELASTIC INVESTIGATION OF A MISSILE CONFIGURATION



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Abstract

The objective of the present work is to determine static and dynamic aeroelastic properties for a heavy supersonic attack missile. This work is a part of the project $Tv\ddot{a}rteknikprojektet$ at FFA/FOI. The missile configuration analysed is denoted U60 and has a very low aspect ratio wing.

A presentation of the MSC/NASTRAN aeroelastic model of the missile is given. The model used, consists of a structural shell and beam Finite Element model and a corresponding aerodynamic model with control surfaces enabling the simulation of different steady state flight conditions, $i.e.$ pitch and roll motions.

The objective with the static aeroelastic analysis is to quantify aeroelastic coefficients, such as the elevon aeroelastic effectiveness etc. Finally flutter analyses are performed for subsonic and supersonic speeds at sea level.

The deformations due to the elasticity of the missile has an influence on the flight conditions of the missile. This effect is found to be weak at a Mach number of M = 0.5, where the aeroelastic coefficients $\eta_{C_{N_{\alpha,\delta}}}$, $\eta_{C_{m_{\alpha,\delta}}}$ and $\eta_{C_{l_{\alpha,\delta}}}$ are around 0.9, respectively. However, a decrease of the effectiveness, to about 0.6-0.7 in the transonic range might be critical. Hence, aeroelastic properties in this speed range needs a further analytical or experimental study.

The missile have good flutter qualities in the subsonic speed range and in the low supersonic range $M < 1.5$, while in the transonic range $M = 0.7$ to 1.0, the flutter velocity is reduced. However it is not critical.

Contents

1 **Introduction** 7

2 **The MSC/NASTRAN Aerodynamic Model** 9

3 **The MSC/NASTRAN Structural Model** 11

4 **Mach Number Influence on The Aeroelastic Effectiveness: static aeroelastic analysis** 17

5 **Vibration Analysis: Natural Frequencies and modes** 23

6 **Flutter Analysis** 29

7 **Concluding remarks** 33

References 35

Document information 37

Dokument information 39

1 Introduction

The aeroelastic analysis of a heavy supersonic attack missile reported herein represents a part of a project at FFA denoted $Tv\ddot{a}rteknikprojektet$. The initiative was taken by the Swedish Defence Material Administration (FMV) to start the project. The objective is to increase the capability at FFA to incorporate the available expertise in aeronautical disciplines in projects where multidisciplinary analysis and design are required. The physical object chosen for this study was defined in a dialog with FMV where one goal with this choice was to incorporate the available know how in stealth, flight mechanics, materials and structures, aeroelasticity and aerodynamics into the project. The specifications for the project and for the missile can be found in the document [1].

The technical requirement for the missile may in brief be specified as follows. The missile should carry a heavy and 2.2 meters long warhead a long distance at sea level at supersonic speed, and finally after a reduction to subsonic speed the mission is completed after an advanced manoeuvre. The manoeuvre will, for a conventional missile, cause a very high load factor. The radar and infrared signatures of the missile should also be considered. The engine data, such as thrust to weight, thrust to size and the specific fuel consumption, agreed upon with FMV are such that an engine ready for production satisfying the requirements can not be expected in the near future.

The load factor caused by the advanced manoeuvre was expected to govern most of the structural dimensions. Hence, the work reported in [2] was initiated before the aeroelastic analysis reported here. To gain some kind of early indication in the design process of potential aeroelastic problems, a low aspect ratio rectangular sandwich construction wing, beeing clamped at one side, was analysed with respect to its flutter properties.

At the time of writing this report, it is not yet decided if the wings should be folded and lay flat on top of the fuselage during supersonic cruise or if they should be fixed and used during supersonic cruise. In the former case the speed will be reduced to some subsonic value, probably below a Mach number of 0.5, before the wings are unfolded.

We are concerned with the static aeroelastic and the classical flutter properties of the missile. Aeroelasticity refers to the phenomena of mutual interaction of aerodynamic and structural forces. Aeroelastic analysis is the prediction of the phenomena and it's influence on the design of the missile. Flutter and divergence are examples of such phenomena.

The report contains a general description of the aerodynamic model and the structural model, of the missile used for the aeroelastic analyses, and the interconnection of the structural and the aerodynamic models. Secondly results from static aeroelastic analysis for symmetric and anti-symmetric flight conditions for the missile are described. Finally a subsonic and a supersonic flutter analysis are performed and the results obtained are evaluated.

2 The MSC/NASTRAN Aerodynamic Model

The aerodynamic configuration of the missile used is highly idealized. The Panel method used for the aerodynamics analysis is based on linearized potential flow [6]. One property of the method is that the surface can be represented by segments of planes for the purpose of calculating lift distributions. The surface is divided into small trapezoidal panels in a manner such that the panels are arranged in columns parallel to the free-stream. This method is often considered to be sufficiently accurate for the low subsonic and higher supersonic range of air-speeds, at least for high aspect ratio unswept wings. In the transonic speed range, the method is very inaccurate due to the complexity of the aerodynamic flow field where different phenomena interact [7].

The U60 missile aerodynamic model used here has 887 panels. For the subsonic range of speed the fuselage is divided into trapezoidal panels having different geometries at different locations along the x axis, see Fig 1. The Doublet Lattice Panel method is only applicable for subsonic analysis, therefore, at the supersonic range of speed the fuselage can not be modelled as a lifting body, instead, the fuselage is approximated as a flat surface which is divided into panels as shown in Fig 2. A total of 600 panels represents the wings including the elevons. The wings are considered to be flat plates, without twist, or camber and no incidence angle relative to the fuselage. The interconnection of the aerodynamic model and the structural model is made by a surface spline method [6]. The position and motion of the aerodynamic panels are tied to the corresponding nodes of the structural model.

The fuselage length is $L = 7.5$ [m]. The warhead diameter and cross-section area are used as reference length and area respectively. The reference length is $\bar{C} = 0.35$ [m] and the reference area is $S = 0.0962$ [m^2]. A full-span model is used, which is necessary for the analysis of asymmetric manoeuvers. The origin of the aerodynamic referens coordinate system, X_{ref}, used when moments are calculated is located at the nose tip and the x-axis is parallel to the free stream velocity, se Fig 1.

The control surfaces are elevons at the trailing edge of the wings. The missile is also equiped with a fixed vertical fin for improved yaw stability.

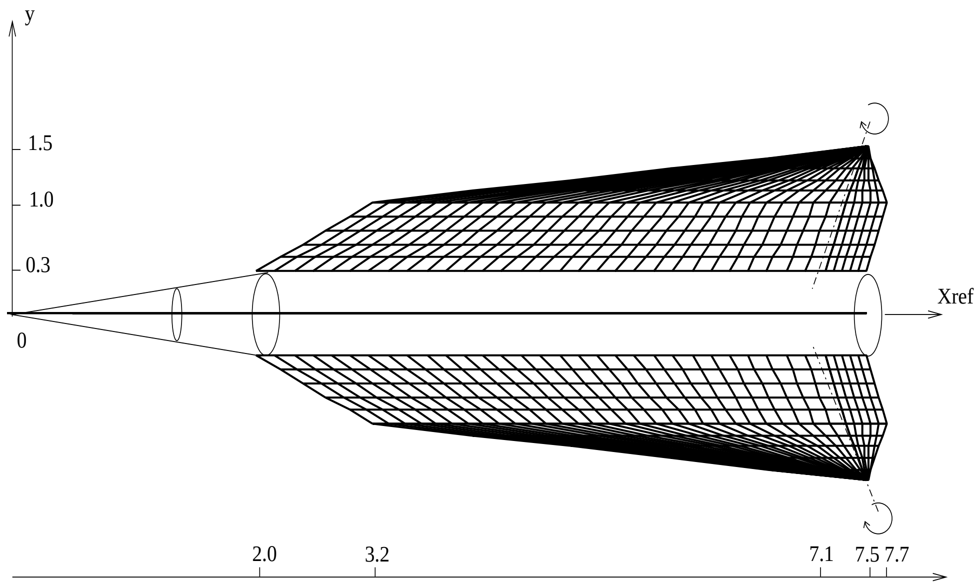

Figure 1. Missile aerodynamic model, showing the wing panels and indicating the lifting body

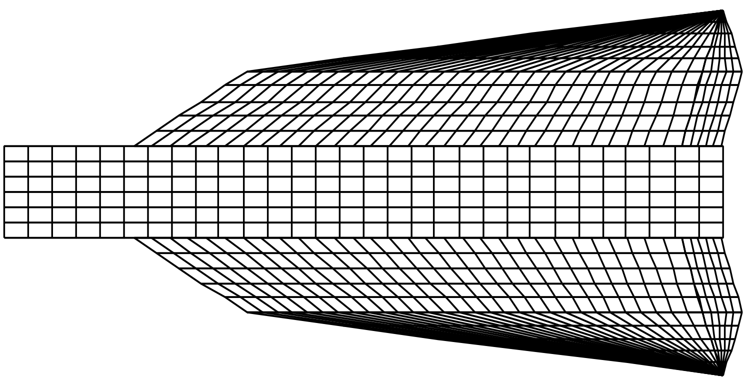

Figure 2. Supersonic aerodynamic model, flat panels are used for the fuselage and wings

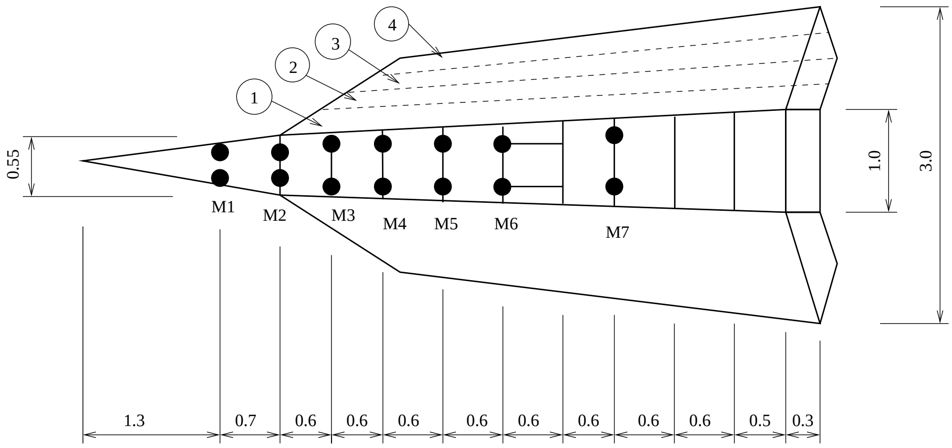

Figure 3. Geometry of the missile showing the locations of concentrated masses and of the eleven fuselage frames. All dimensions given are in [m]

3 The MSC/NASTRAN Structural Model

The structural dimensions used in the finite element analysis where determined as described in [2] so that the structure has sufficient strength for a specified load factor.

The structural discretization is fairly simple, only 4-noded structural shell elements (type: CQUAD4) and beam elements (type: CBAR) are used. The global dimensions of the missile and the location of the fuselage frames are given in the Fig 3.

The mesh of the fuselage and the nose, are illustrated in Fig 4. The material of the fuselage is assumed to be aluminium.

The different dimensions of the beam cross sections in the frame and the skin thicknesses, t_{skin}, forming the fuselage are given in table 1, with notations corresponding to those in the Fig 5. The thickness of the skin at the bottom of the fuselage (No. 10) is varying along the fuselage length as follows: 3mm(0-3m), 30mm(3-6m), 10mm(6-7m), 2mm(7-7.5m), respectively. Beam numbers and locations within a frame refer to Fig 5.

Table 1. Frame cross section and skin dimensions of the fuselage

No.	h[mm]	b[mm]	t_b[mm]	t_{skin}[mm]
1	20	15	4	13
2	20	15	4	5
3	15	15	3	2
4	10	15	2	9
5	10	15	2	2
6	20	15	4	2
7	35	20	6	2
8	35	20	6	1
9	25	15	5	1
10	30	20	8	3,30,10,2

The wings and the elevons are modeled as flat plates. The weight and the

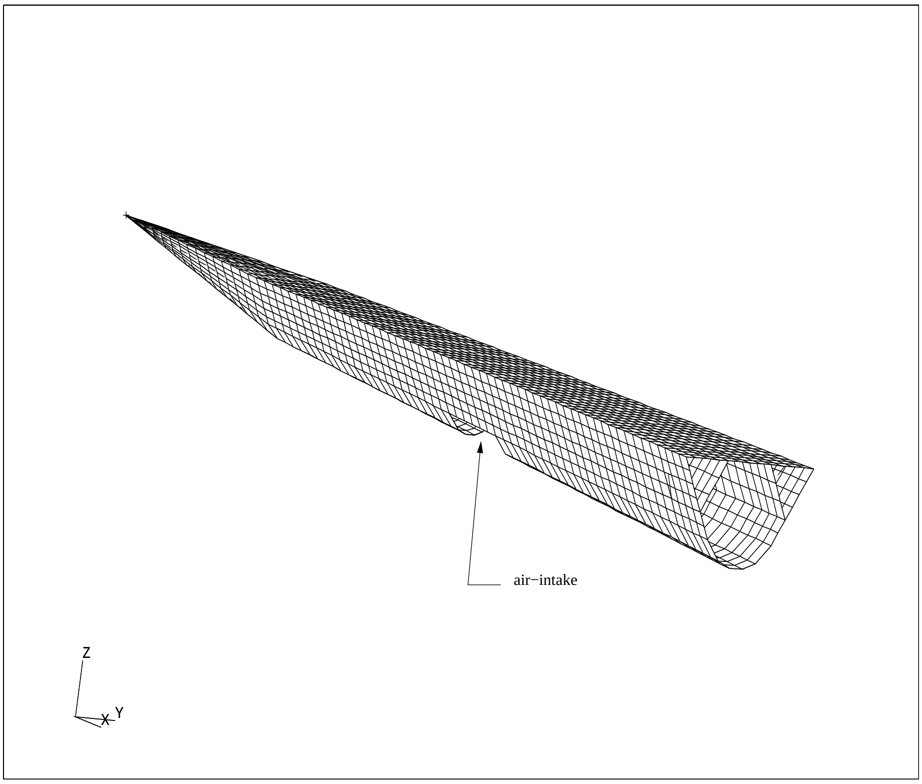

Figure 4. Missile fuselage finite elements mesh

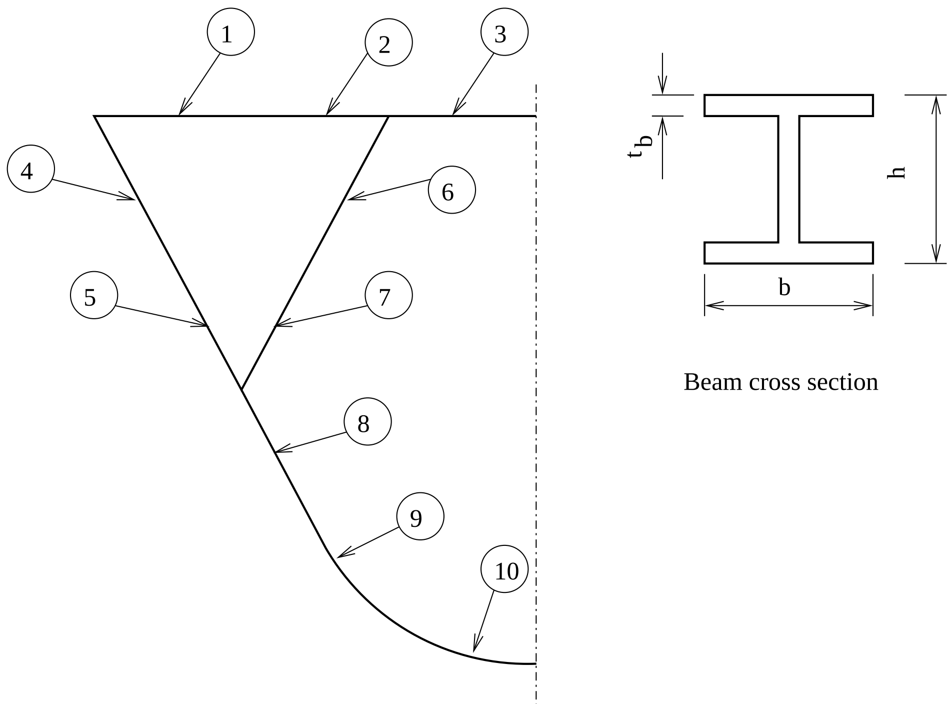

Figure 5. Fuselage section with beam numbers within a frame

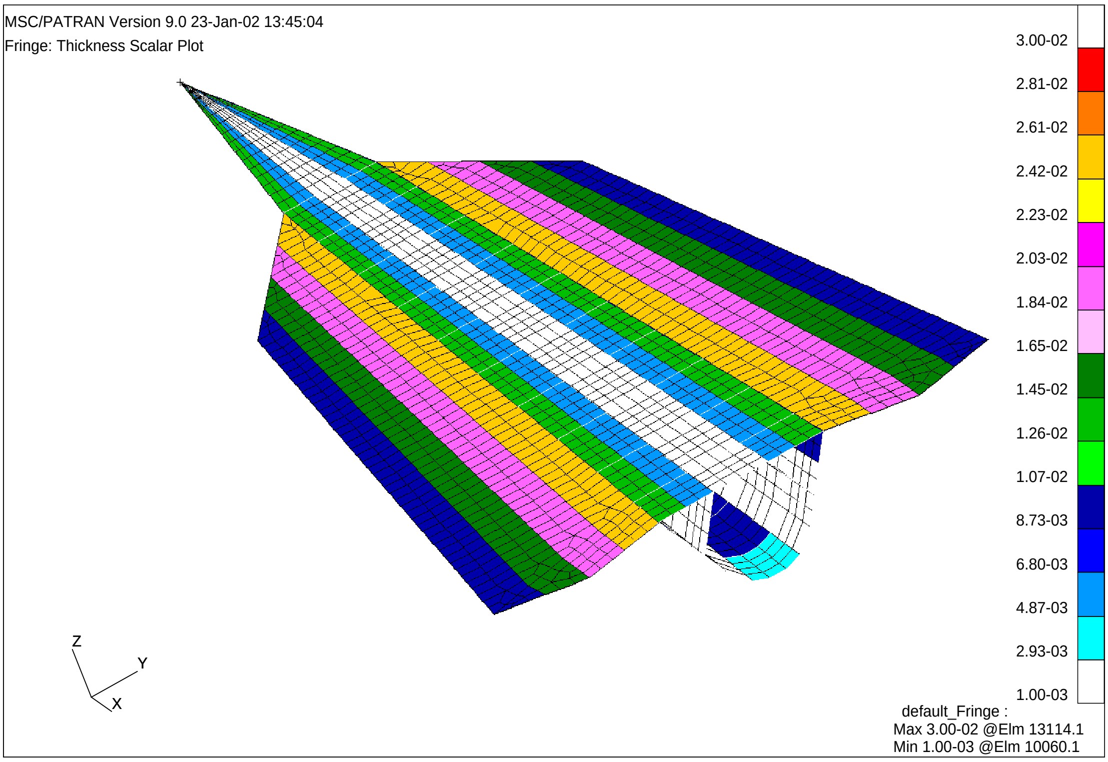

Figure 6. Thickness distribution

bending stiffness of a sandwich-type built-up aluminium wing and elevon structure of a spanwise varying thickness, h is modeled by giving the shell elements the same thickness as for the real wing but artificial Young's modulus, E, and densities. The thickness distribution of different parts of the missile is given in Fig 6 and in table (2), with wing part numbers defined by Fig 3. A rigid connection at the wing root is assumed between the wing and the fuselage. The geometrical discontinuity is taken into account between the elevon and the wing at the hinge line, and between the elevon and the fuselage. The rotation is free at the elevon hinge line and a 336 mm long steel rod with a square cross section of 625 mm^2 is connected from the elevon root spar to the fuselage to simulate the flexibility of an axis and an actuator.

Table 2. Wing thickness distribution and Young's moduli used

Part No.	h[mm]	E [GPa]	Density [kg/m^3]
1	25.37	49.6	662.05
2	20.12	62.6	834.66
3	14.87	42.3	564.50
4	9.62	65.5	874.17

For the calculation of the aerodynamic parameters and derivatives, like the lift and pitch moment coefficients C_N and C_m, a support point is needed to handle rigid body motions. This support point is chosen here to coincide with the center of gravity.

Five rigid body modes for the missile are allowed, and only the horizontal rigid body motion in the wind direction is constrained at the support point.

To compensate for the mass of missing missile components that are not load carrying, the density of the structural model (the density of the skins of the fuselage) are increased to 2.47 times the density of aluminium, and also with the introduction of concentrated masses corresponding to some discrete components, e.g: engine, warhead, fuel and nose, with masses given in table 3, and Fig 3. The total mass of the model was 1385 [kg]. The center of gravity located at: $x_{cg} = 4.11$ [m], $y_{cg} = 0.0$ [m] and $z_{cg} = -0.16$ [m], where the tip of the nose is the origine and also the reference point for moments.

Table 3. Additional concentrated masses for engine, warhead, fuel and nose

Mass No.	Representing	Mass [kg]
M1	Nose, fuel	2 X 20
M2	warhead, fuel	2 X 65
M3	warhead, fuel	2 X 50
M4	warhead, fuel	2 X 50
M5	warhead, fuel	2 X 50
M6	warhead, fuel	2 X 65
M7	Engine	2 X 70

To compensate for the decrease in stiffness of the fuselage due to the presence of the engine air-intake, a frame structure of aluminium was introduced. The frame was modeled with beam elements with the following hollow rectangular cross section of dimensions $20 \times 20 \times 5$ mm. The frame is located in the lower part of the fuselage around the air-intake, as illustrated in Fig 7.

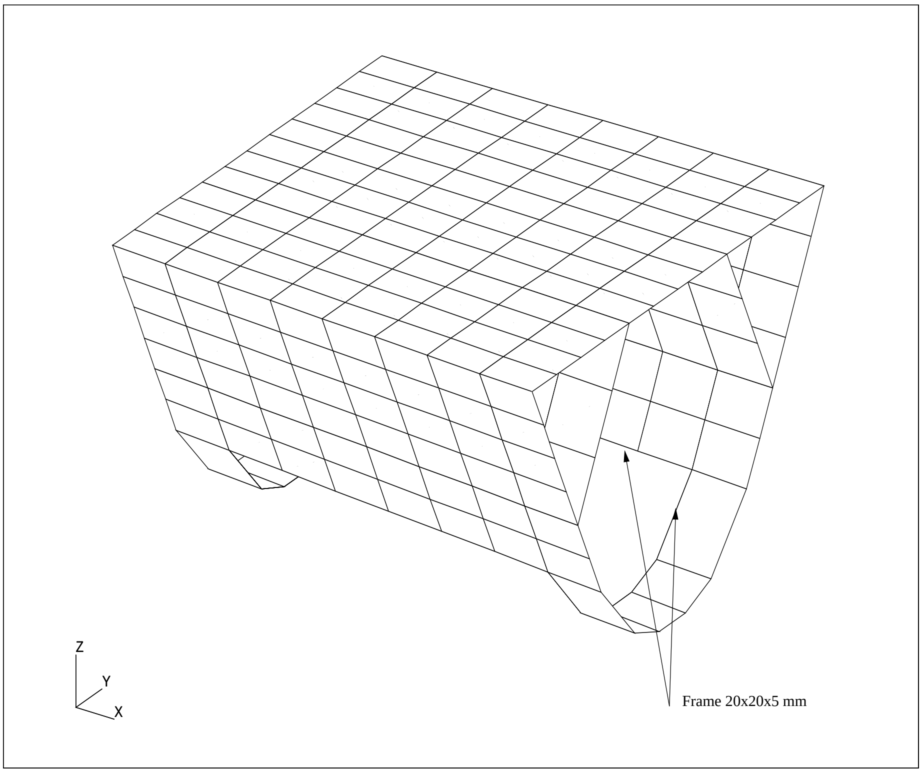

Figure 7. Air-intake, with rectangular box-beam frame

4 Mach Number Influence on The Aeroelastic Effectiveness: static aeroelastic analysis

The static aeroelastic analysis is intended to generate both structural and aerodynamic data. The structural data of interest in our case are deflections, whereas loads, strains and stresses are outside the scope of this report. The aerodynamic data of intrest include aeroelastic derivatives, aeroelastic effectiveness and trim conditions.

The missile is assumed to be flying at sea level at Mach numbers varying from $M = 0.1$ to $M = 0.95$ for the subsonic case and varying from $M = 1.0$ to $M = 1.8$ for the supersonic case. These flight conditions give a dynamic pressure variation from $Q = 0.7$ [kPa] to $Q = 64$ [kPa], and from $Q = 71$ [kPa] to $Q = 230$[kPa], respectively for the subsonic and supersonic cases.

The aeroelastic effectiveness parameter η is the ratio of an aerodynamic quantity for the elastic configuration divided by the same quantity for the rigid configuration,

$$\eta_{C_{x_y}} = \frac{C_{x_y,elastic}}{C_{x_y,rigid}} \tag{1}$$

The index x in equation (1) can denote the force in the vertical direction N for lift, or a moment l for roll, or m for pitch. The index y can be the angle of attack, α, the elevon deflection, δ, or any other state variable. Positive elevon deflection, δ, is defined as downward.

In order to simulate the flight of the missile at constant altitude (constant density) and with varying speed, the dynamic pressure is varied from $Q = 0.7$[kPa] to $Q = 64$[kPa]. The Mach number is fixed at $M = 0.$ for the incompressible case and varies within the range $M = 0.1$ to $M = 0.95$ for the compressible case. The effect of the Mach number M on the aero-elastic effectiveness η is given in Fig 8, and 10, for a unit angle of attack α[rd] and a unit elevon deflection δ[rd], respectively.

The compressibility effect is significant in general, although there seems to be only slight effect on the lift coefficient for the angle of attack, $\eta_{C_{N_\alpha}}$, while it has an effect on the elevon efficiency for lift and pitch control, see Figs 8, 10.

The deformations due to the elasticity of the missile has an effect on the flight conditions of the missile, however this effect is weak at $M = 0.5$, where the coefficients $\eta_{C_{N_\alpha}}$, $\eta_{C_{m_\delta}}$ and $\eta_{C_{l_\delta}}$ are around 0.9. Furthermore, the decrease of the effectiveness for the transonic range must be observed and should be considered in the case of a fixed wing that is used at transonic and supersonic speeds as shown in Fig 11.

The angle of attack aeroelastic effectiveness, $\eta_{C_{N_\alpha}}$ and $\eta_{C_{m_\alpha}}$, for lift and pitch respectively, is not verry much affected by the augmentation of the velocity of the air in the supersonic range of speed, see Fig 9, where $\eta_{C_{N_\alpha}}$ and $\eta_{C_{m_\alpha}}$ varies within the range 0.92 to 1.02 for Mach numbers varing from $M = 1.$ to $M = 1.8$. The aerodynamic center of the missile is about $X_{a.c} = 3.6$ [m] and the location is stable in the subsonic range of speed $M < 0.7$ and is not affected by the elasticity of the structure of the missile, see Fig 12. For the supersonic range of speed, the behavior of missile regarding the position of the aerodynamic center is different, se Fig 13. First, a difference between the elastic and the rigid configuration is

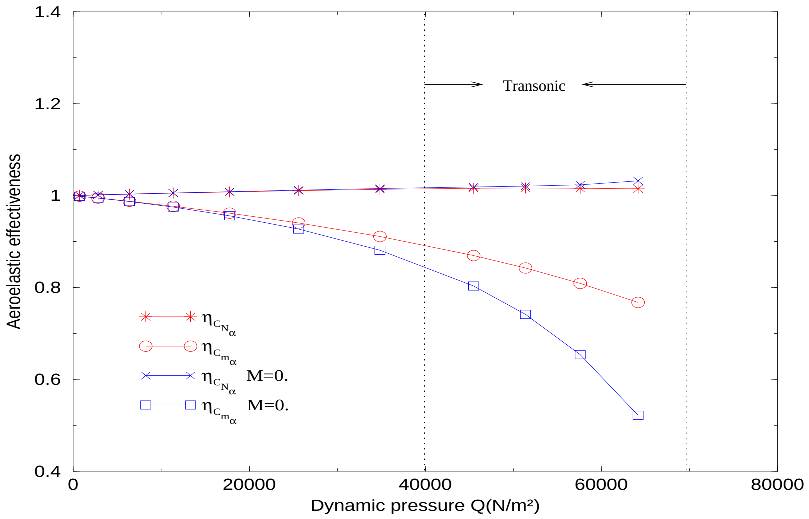

Figure 8. Subsonic angle of attack aeroelastic effectiveness, for lift and pitch

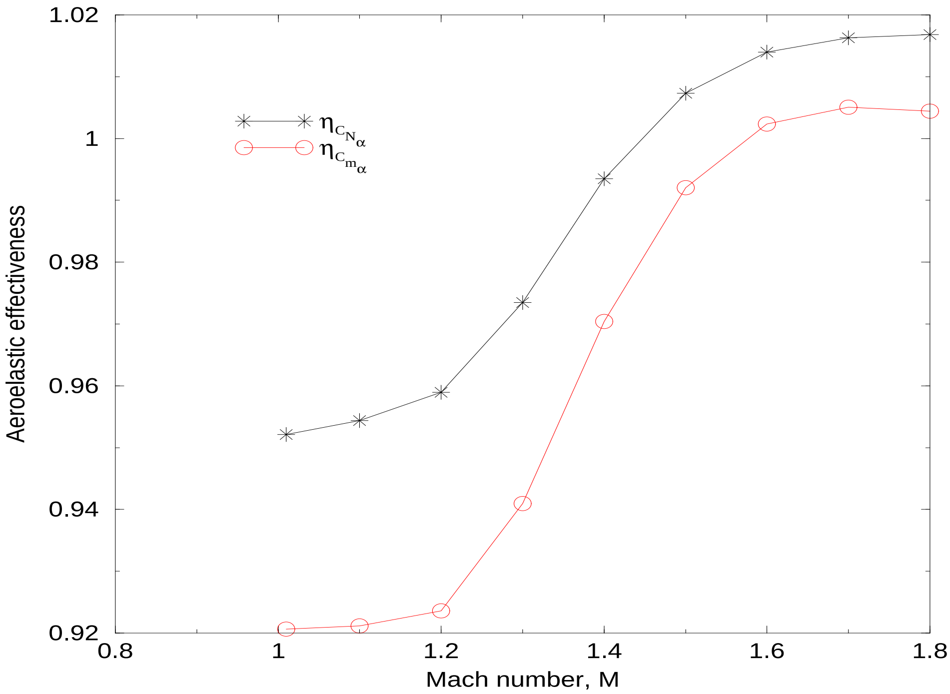

Figure 9. Supersonic angle of attack aeroelastic effectiveness, for lift and pitch

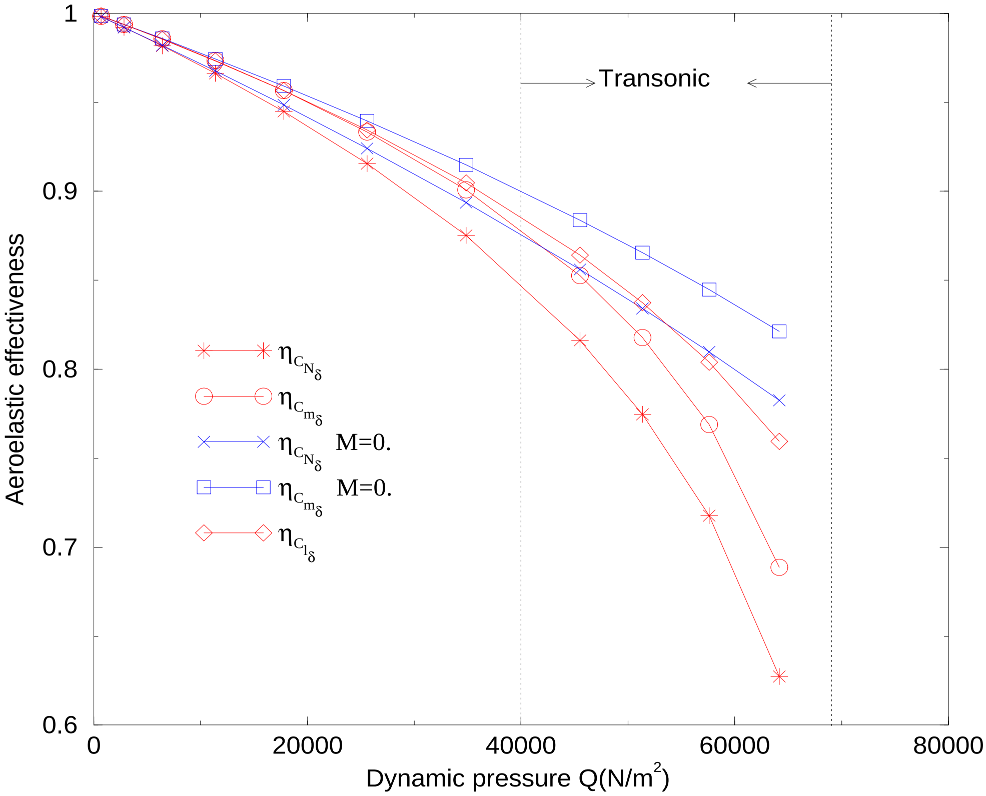

Figure 10. Subsonic elevons aeroelastic effectiveness; for lift, pitch and roll

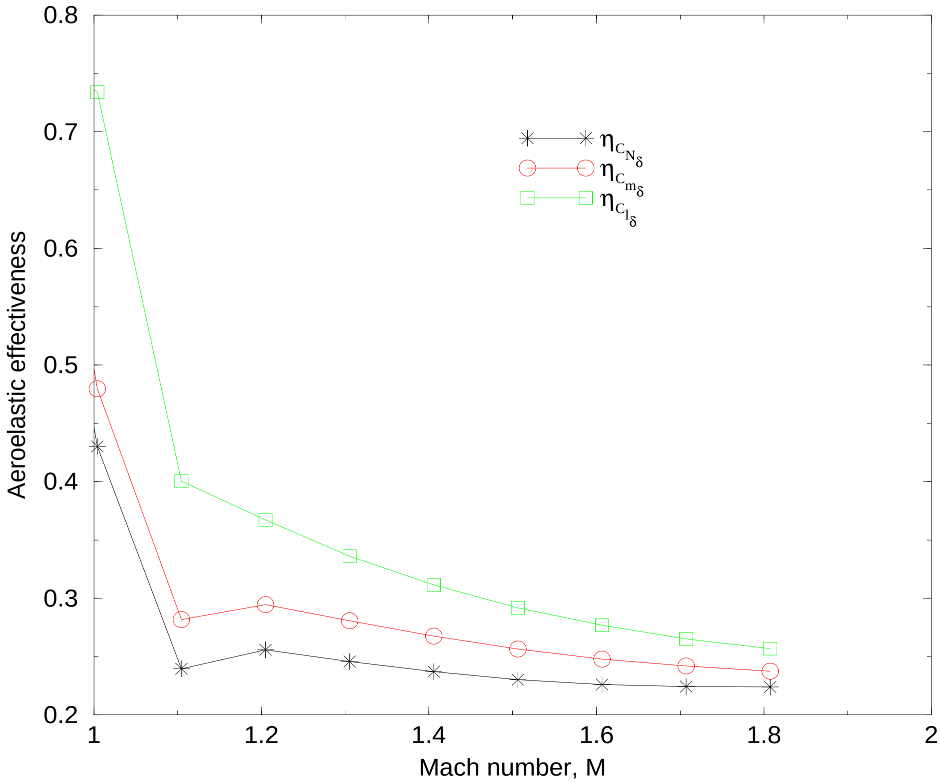

Figure 11. Supersonic elevons aeroelastic effectiveness; for lift, pitch and roll versus

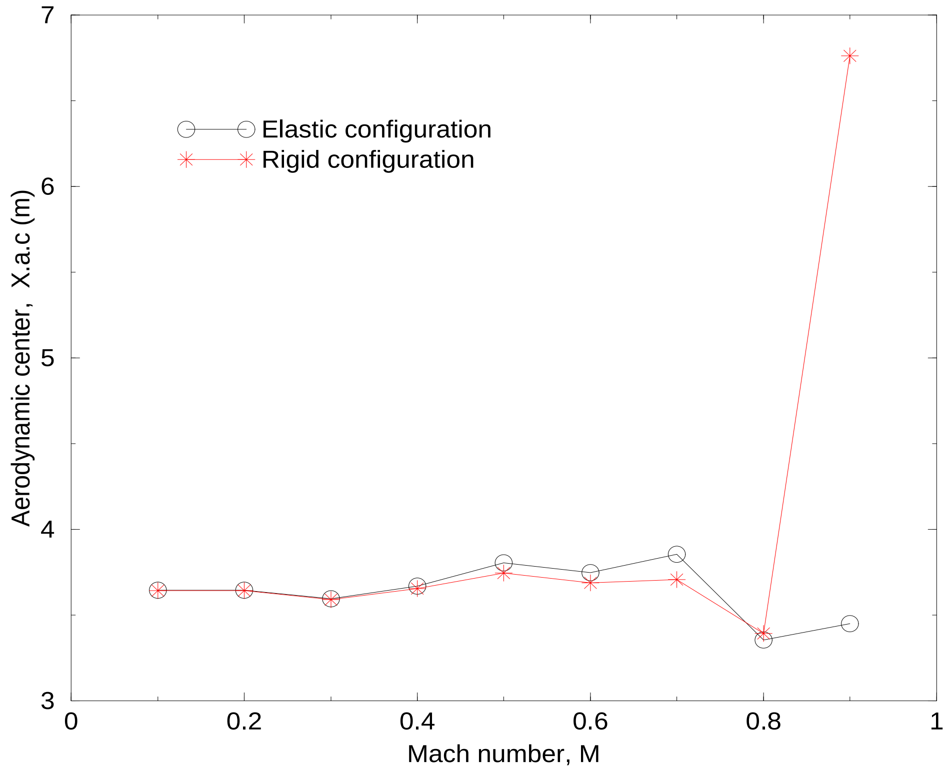

Figure 12. Subsonic aerodynamic center versus Mach number M

observed, especially for the low supersonic range of speed, where the elasticity of the structure moves the aerodynamic center forward on the missile. Secondly, the presence of a minumum at Mach numbers $M = 1.3$ and $M = 1.4$ for the elastic and rigid configuration respectively is observed.

Some missile flight conditions, using symmetric downward deflection or asymmetric aileron deflection of the elevons with $\delta = 10^o$ around the hinge-line, are chosen here to investigate the influence of structural elasticity on the behavior of the missiles flight dynamic properties.

Timmed states are determined for the symmetric and the asymmetric control surface configurations. The rigid body accelerations are set to zero except for the gravity acceleration (9.81 [m/s^2]). The angle of attack is considered as the primary unknown however the sides, roll, pitch and yaw velocities are also free trim variables.

A graph showing the variation of the angle of attack α of the missile at the trim solution, versus the dynamic pressure Q, is given in the Fig 14, for the symmetric deflection of the elevons.

Examples of the deformation of the missile at $M = 0.5$ are given in the Figs 15, 16 for the symmetric and asymmetric cases. Note that the deformations are magnified and that the maximum amplitudes are 29.7 mm and 26.8 mm respectively.

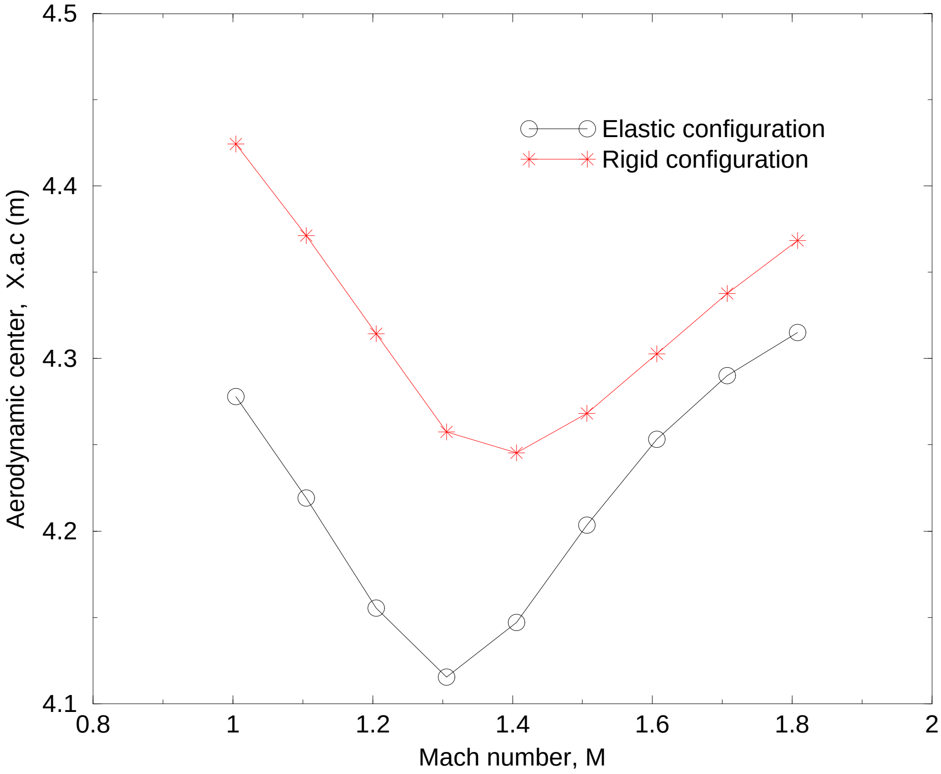

Figure 13. Supersonic aerodynamic center versus Mach number M

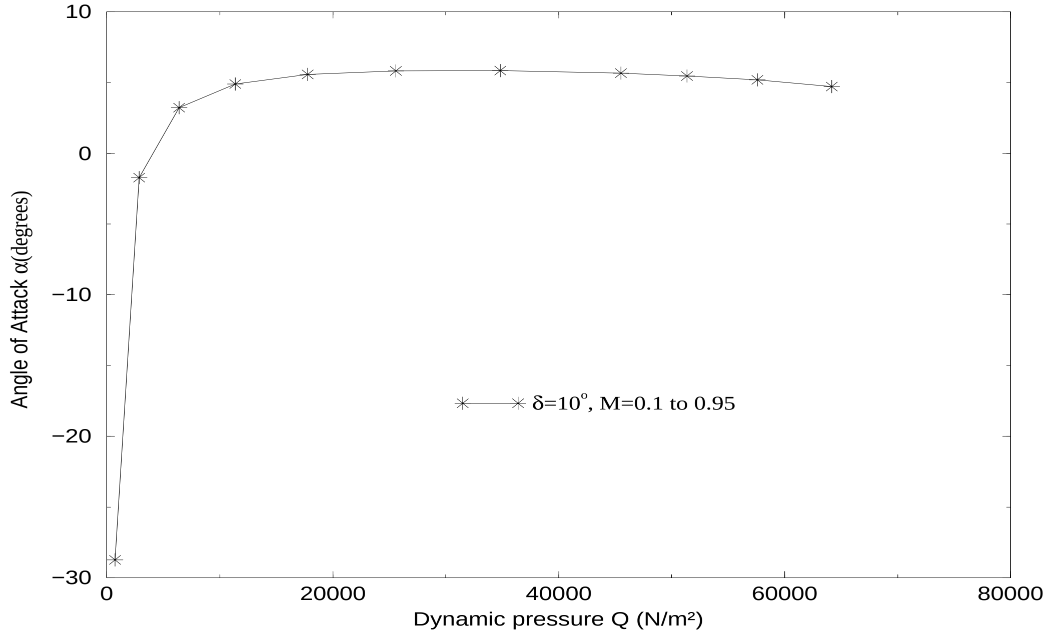

Figure 14. Trimmed angle of attack for 10 degrees symmetric elevator deflection

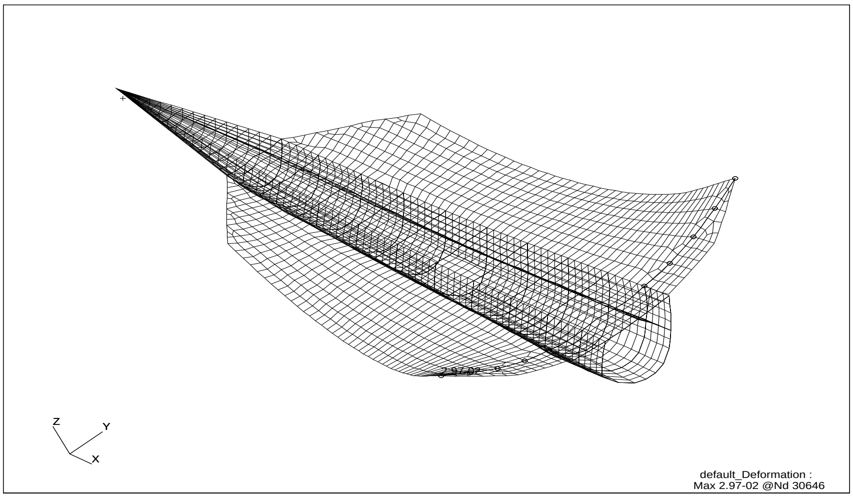

Figure 15. Missile deformation for 10 degrees symmetric elevons deflection at M=0.5 (magnified)

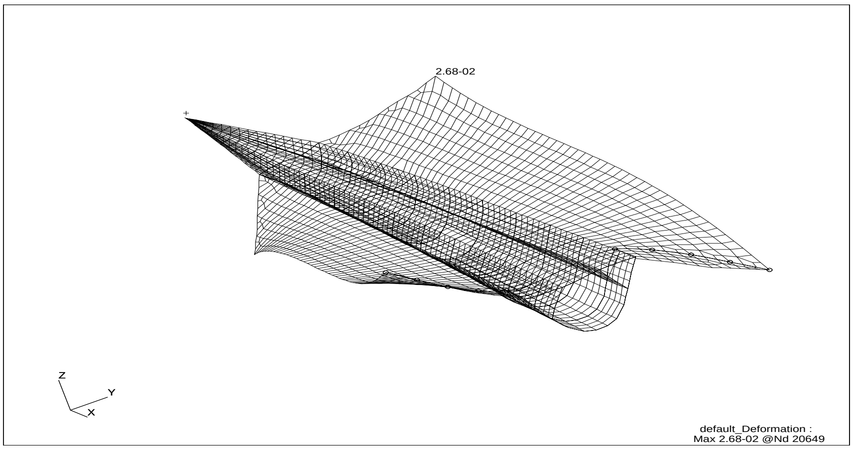

Figure 16. Missile deformation for 10 degrees asymmetric elevons deflection at M=0.5 (magnified)

5 Vibration Analysis: Natural Frequencies and modes

The vibration modes method is used to reduce the number of degrees of freedom in preparation for the flutter stability analysis. A sufficient number of modes must be used to obtain the required accuracy. An aspect of the modal method is the transformation of the aerodynamic influence coefficients into modal coordinates. For computational efficiency reasons, this transformation is carried out explicitly for only a few Mach numbers M and reduced frequencies k (reduced frequency is $k = \frac{\omega b}{V}$, where ω is the structural angular frequency, b is a reference semi-chord, and V is the free-stream velocity). These generalized (modal) aerodynamic forces coefficient matrices are then interpolated to any Mach number and reduced frequency required by the flutter analysis [6].

30 eigenmodes are chosen in the vibration analysis of the missile, thus the vibration analysis is reduced to the first 30 modes and later on, the flutter analysis is based on these 30 modes.

The first 7 vibration eigenmodes are shown in Figs 17 - 23. The first and second modes are typically the fuselage bending and torsion modes at frequencies $F = 19.05$ [Hz] and $F = 23.32$ [Hz], respectively, while the third and the fourth are the first order bending and torsion modes of the wings. We see from the table 4 that many of the frequencies almost coinside. The sixth mode, at a frequency $F = 36.65$ [Hz], is an interaction mode of the fuselage and the wings.

Table 4. Natural frequencies and description of the mode

Mode	Freq [Hz]	Description
1	19.05	fuselage bending
2	23.32	fuselage torsion
3	24.60	symmetric wing bending
4	32.79	anti-symmetric wing torsion
5	34.17	symmetric wing torsion
6	36.65	fuselage torsion + anti-symmetric wing torsion
7	42.11	2:nd order fuselage bending + 2:nd order symmetric wing bending
8	43.14	3:rd order fuselage bending + 2:nd order symmetric wing bending
9	44.23	2:nd order anti-symmetric wing bending
10	52.34	2:nd order symmetric wing bending

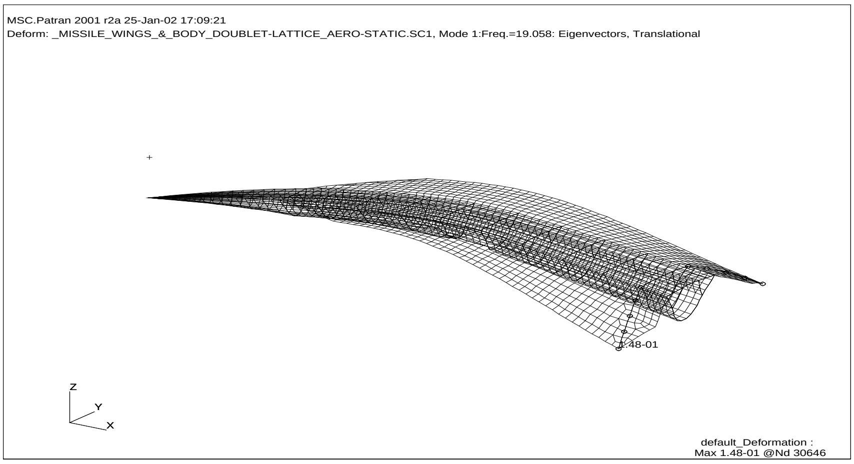

Figure 17. First mode, F=19.05 [Hz]

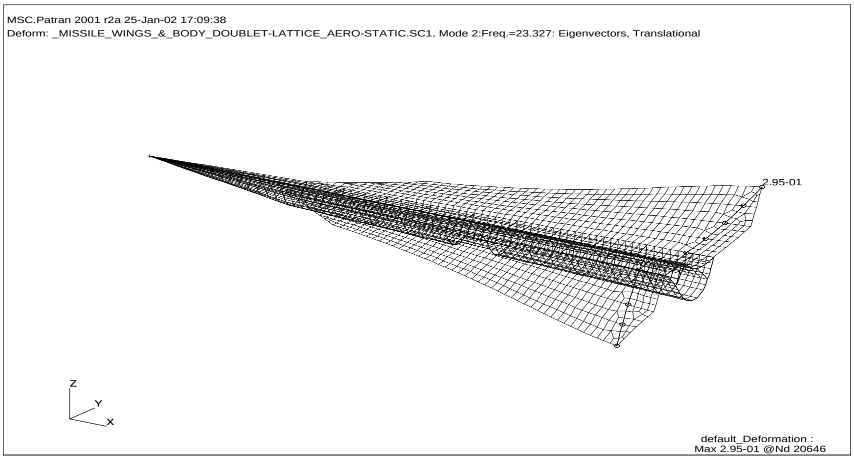

Figure 18. Second mode, F=23.32 [Hz]

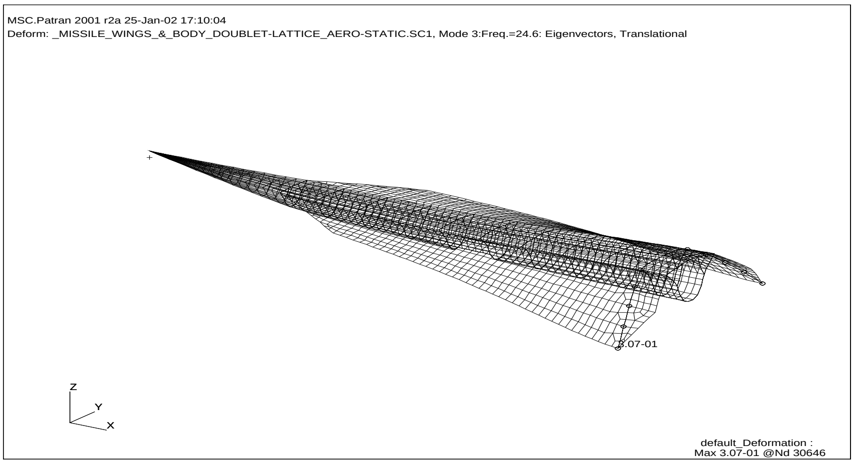

Figure 19. Third mode, F=24.60 [Hz]

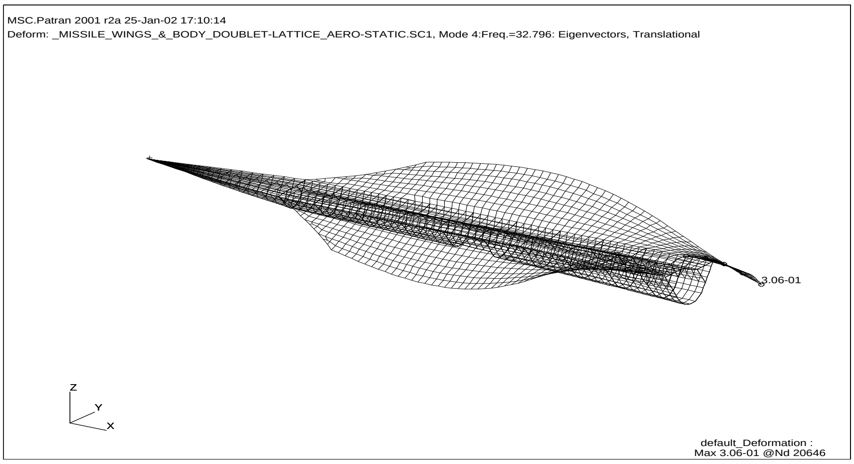

Figure 20. Fourth mode, F=32.79 [Hz]

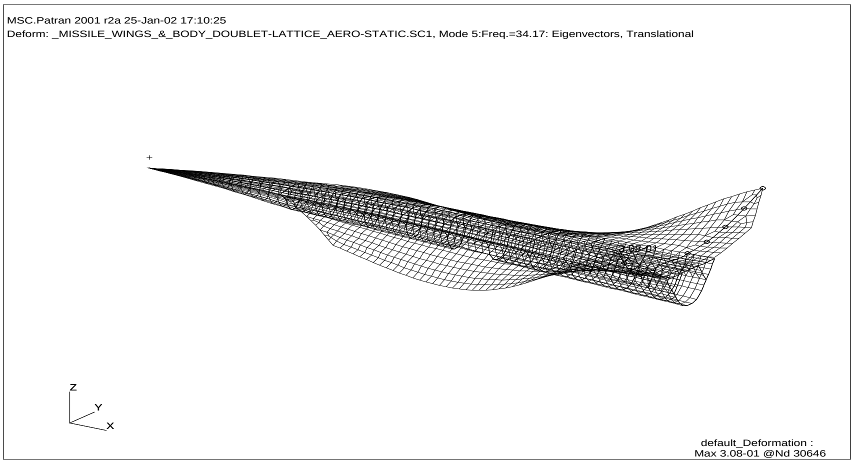

Figure 21. Fifth mode, F=34.17 [Hz]

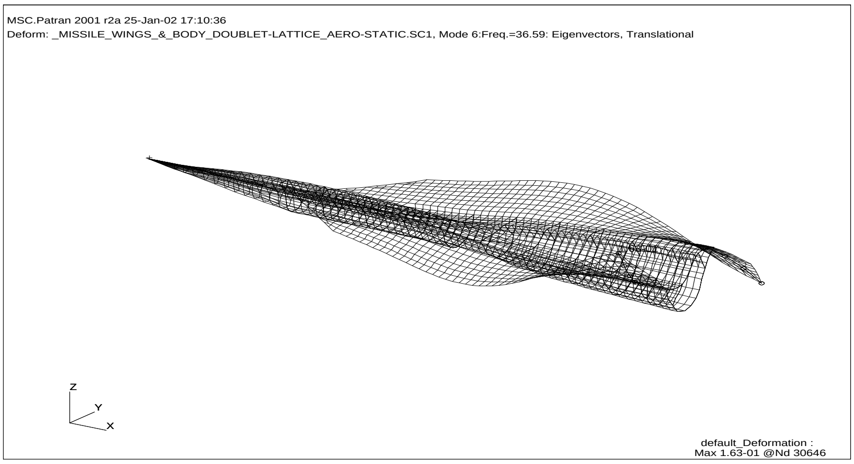

Figure 22. Sixth mode, F=36.65 [Hz]

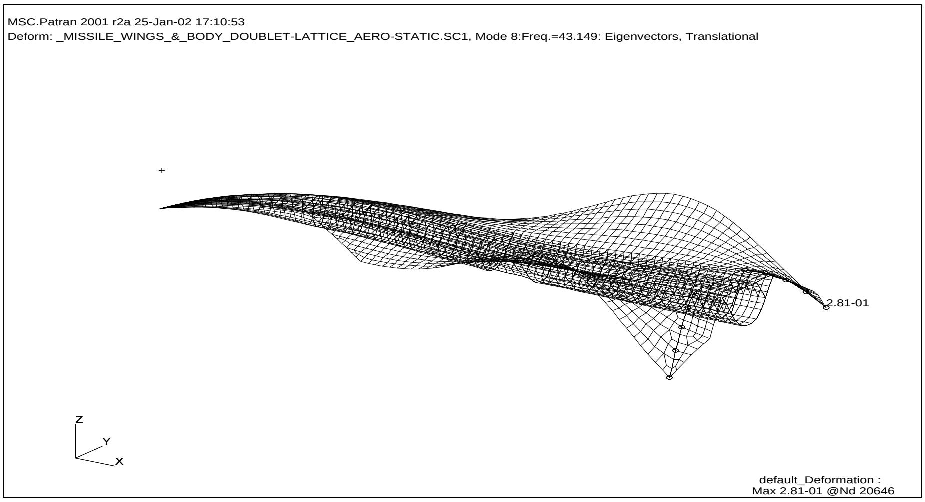

Figure 23. Seventh mode, F=42.11 [Hz]

6 Flutter Analysis

Flutter is a self-excited dynamic instability caused by the interaction of aerodynamic, elastic, and inertial forces. If flutter is present in a structure the overall system damping is negative and energy begins to be added to the system. Any perturbation of the structure will cause an increasing structural oscillation which will grow until limited by nonlinear effects or until the structure fails [5].

There are different types of flutter, each type is described by the type of modes that interact to create the instability. Flutter susceptibility generally increases with air-speed and by designing very flexible structures. The flutter is never entirely eliminated, it is simply delayed to airspeeds beyond the normal flight envelope of the vehicle [3].

The objective of the flutter analysis is to predict under which flight conditions, like altitudes (air density), and air-speeds, the flutter occurs.

The flutter prediction technique used for the study presented herein, involves a series of eigenvalue solutions. The eigenvalue problems to be solved depend on the way in which the aerodynamic loads are included in the equations of motion or whether certain damping terms are included.

Three different approaches are available in MSC/NASTRAN to solve the flutter problem

1. K-method: which introduced the aerodynamics into a vibration analysis as complex inertial terms and the flutter analysis becomes a vibration analysis.
2. P-K-method: in this method, the aerodynamic loads are introduced into the equation of motion as frequency dependent stiffness and damping terms.
3. K-E-method: a simple variant of the K-method, where viscous dampings from all sources, e.g., from structure or control system are neglected.

In this analysis the flutter critical speed variables are determined using the K and P-K flutter methods, assuming cruise at sea level with an air density of $\rho = 1.23$ [kg/m^3] and for the Mach numbers $M = 0.2$ to 1.8.

The flutter velocities and frequencies are summarized in the table 5. The Mach number given in the first column of table 5 is the input parameter needed for the analysis whereas the flutter Mach number M_f ($M_f = \frac{V_f}{a}$, where a is the speed of sound at sea level) is the predicted critical flutter Mach number in this analysis.

The calculated flutter velocities and flutter frequencies are varying from V_f = 500 [m/s] to 700 [m/s] and from F_f = 19 [Hz] to 50 [Hz], respectively for input Mach numbers, M, in the range 0.2 to 1.8. The lowest and possibly the most important critical flutter velocity V_f = 492 (m/s), $M_f = 1.44$ is calculated at the input Mach number $M = 0.7$. Hence the missile has a good safety margin regarding flutter. It is difficult to know exactly which mode or modes are involved in flutter when it occurs, since the flutter frequencies are varying with the velocity. However, the interaction of fuselage bending and wings bending could be the most detrimental flutter mode, since this mode number 7 is present at different air-speeds as seen in table 5.

In order to quantify the influence of the angle of the leading edge sweep on flutter characteristics, a comparison has been made with a missile configuration, here denoted F30, having exactly the same structural model as the U60 missile,

Table 5. Flutter velocity and frequency, configuration U60

Mach	Velocity $V_f[m/s]$	Mach M_f	Freq $F_f[Hz]$	Mode
0.2	582.50	1.71	36.45	7
0.4	552.10	1.62	36.18	7
0.5	547.50	1.60	54.03	9-1
0.6	587.30	1.72	19.24	1
0.7	492.50	1.44	35.30	7-1
0.8	567.50	1.66	24.42	3
1.1	682.50	2.01	43.10	9-1-8
1.2	687.60	2.02	37.22	7
1.4	677.50	1.99	37.60	7
1.6	682.80	2.01	37.89	7
1.8	687.50	1.99	38.14	7-11

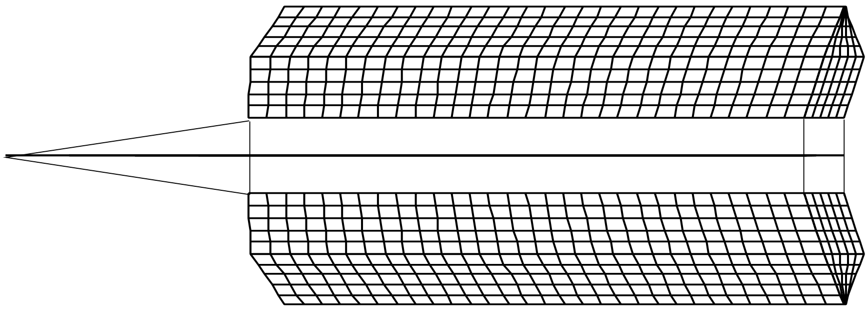

Figure 24. Missile F30 aerodynamic model

while the aerodynamic model has less swept leading edges as illustrated in Fig 24, (compare with Fig 1)

For the configuration F30, the flutter velocities and frequencies are summarized in the table 6. Contrary to the configuration U60, the input Mach number M and the predicted flutter Mach M_f coincide at about $M = 1.3$, and beyond this value the input Mach number is higher than the predicted flutter Mach number, M_f, hence flutter is predicted to occur ($M_f > M_{input}$), see Fig 25.

Figs 25 and 26 shows the variation of the flutter velocity V_f and flutter frequency F_f versus Mach number M. The missile with the wing U60 has a good flutter behavior, in the low subsonic and also in the low supersonic regions, while in the high subsonic and higher supersonic range of air speed $M = 0.7$ to 1.0 and $M > 1.5$, the flutter velocity is reduced. However the latter case is outside of the required fight envelope. The flutter behavior is better for the more swept wing like the one of the configuration U60. By moving the aerodynamic center forward relative to the elastic axis the critical flutter velocity is reduced, see the curve for model F30, in Fig 25. However, one should notice, that the wing surface

Table 6. Flutter velocity and frequency, configuration F30

Mach	Velocity $V_f(m/s)$	Mach M_f	Freq $F_f[Hz]$	Mode
0.2	362.10	1.06	21.96	3
0.4	352.40	1.03	22.02	3
0.6	327.30	0.96	22.07	3
0.8	317.50	0.93	21.52	3
1.1	427.80	1.25	20.63	3
1.2	432.50	1.27	20.51	3
1.4	422.40	1.24	20.46	1
1.6	417.60	1.22	20.40	1
1.8	412.70	1.21	20.34	1

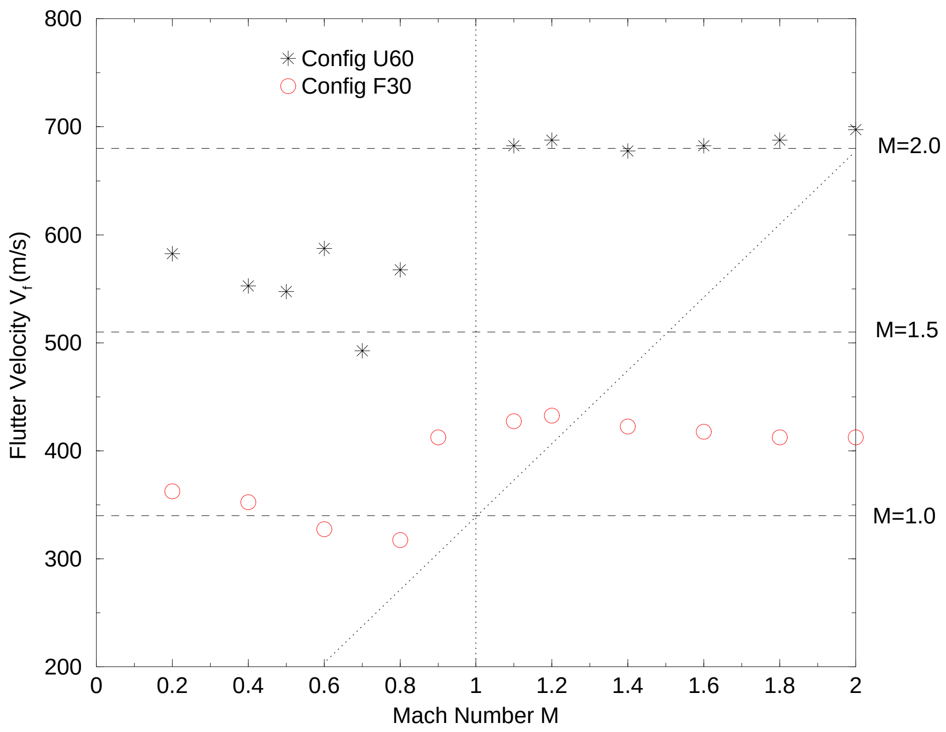

Figure 25. Flutter velocity

area of the F30 model, which has inferior flutter behavior, is bigger than for the U60 configuration.

Some abnormal behavior is observed from the flutter results in Fig 25 and table 5, for to the U60 configuration. At the input Mach number $M = 0.5$, the flutter velocity increases suddenly from $V_f = 547$ [m/s] to $V_f = 587$ [m/s] at $M = 0.6$, then decreases to $V_f = 492$ [m/s] at $M = 0.7$. This behavior is caused by excitation of different modes at different speeds.

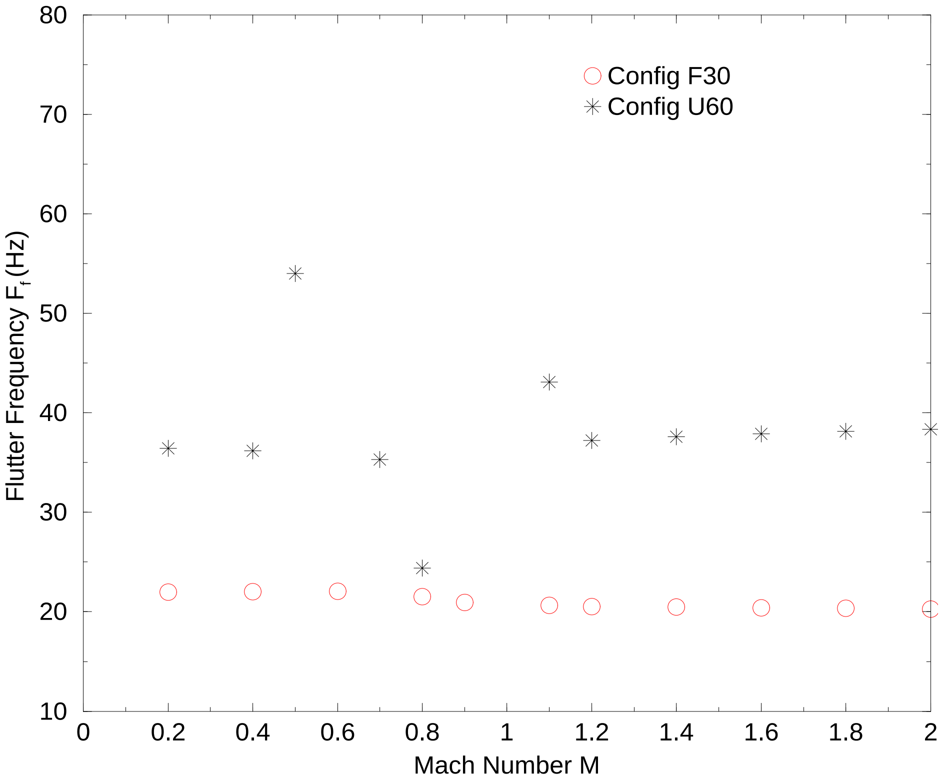

Figure 26. Flutter frequency

7 Concluding remarks

A static and a dynamic (flutter) analysis of a configuration of the missile denoted U60 in the Tvärteknikproject has been made. The work presented, is carried out using a linear Panels method for the aerodynamics analysis and the Finite Element Method for the structural analysis.

Concerning flutter, the missile U60 sems to be properly designed from an aeroelastic point of view for the given mass and mass distribution and for the intended speed range $M < 1.5$.

With respect to aeroelastic effectiveness, specifically elevon effectiveness, the situation is completely satisfying only in the case of a folded wing, beeing used only at Mach numbers below about 0.7. In the case of fixed wing the analysis indicate that it may become impossible to obtain a trimmed flight condition at transonic cruise speeds. Further flight mechanics investigations should be performed in this case. The aileron effectiveness is further reduced at supersonic speeds.

The flutter critical air speed for the U60 configuration is higher than for the less swept F30 configuration. The flutter velocities $V_f = 587$ [m/s] and $V_f = 682$ [m/s] at $M = 0.6$ and $M = 1.6$ respectively for the U60 configuration, drops significantly to $V_f = 327$ [m/s] and 417.6 [m/s] for the F30 configuration.

From an aeroelastic point of view, the results of this study shows a potential for weight reductions if the concept with a folded wing, being used only at Mach numbers below 0.5, is considered. However in that case the flexibility of the hinge must be taken into consideration. An interesting continuation of this work is to make an optimization study regarding the aeroelastic behavior in order to decrease the total mass of the structure. A more realistic model of the servo-actuators than the steel rod model used here may lead to important results conserning the requirement for the stiffness of the actuator system.

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TVÄRTEKNIKPROJEKTET:
AEROELASTIC INVESTIGATION OF A MISSILE CONFIGURATION</td></tr>
<tr><td colspan="3">Abstract
The objective of the present work is to determine static and dynamic aeroelastic properties for a heavy supersonic attack missile. This work is a part of the project $Tv\ddot{a}rteknikprojektet$ at FFA/FOI. The missile configuration analysed is denoted U60 and has a very low aspect ratio wing.
A presentation of the MSC/NASTRAN aeroelastic model of the missile is given. The model used, consists of a structural shell and beam Finite Element model and a corresponding aerodynamic model with control surfaces enabling the simulation of different steady state flight conditions, $i.e.$ pitch and roll motions.
The objective with the static aeroelastic analysis is to quantify aeroelastic coefficients, such as the elevon aeroelastic effectiveness etc. Finally flutter analyses are performed for subsonic and supersonic speeds at sea level.
The deformations due to the elasticity of the missile has an influence on the flight conditions of the missile. This effect is found to be weak at a Mach number of M = 0.5, where the aeroelastic coefficients $\eta_{C_{N_{\alpha,\delta}}}$, $\eta_{C_{m_{\alpha,\delta}}}$ and $\eta_{C_{l_{\alpha,\delta}}}$ are around 0.9, respectively. However, a decrease of the effectiveness, to about 0.6-0.7 in the transonic range might be critical. Hence, aeroelastic properties in this speed range needs a further analytical or experimental study.
The missile have good flutter qualities in the subsonic speed range and in the low supersonic range $M < 1.5$, while in the transonic range $M = 0.7$ to 1.0, the flutter velocity is reduced. However it is not critical.</td></tr>
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Rapporttitel
Aeroelastisk undersökning av en robotkonfiguration

Sammanfattning

Målsättningen med det beskrivna arbetet är att undersöka de statiska och dynamiska aeroelastiska egenskaperna för en supersonisk tung attackrobot. Arbetet är en del av det s.k. Tvärteknikprojektet på FFA/FOI. Den analyserade robotkonfigurationen, vilken benämns U60 inom projektet, har vingar med mycket lågt sidoförhållande. I rapporten beskrivs den aeroelastiska modell som används vid analyser med programmet MSC/NASTRAN. Modellen består av en strukturmodell beskriven med finita element av skal- och balk-typ samt en aerodynamisk panel-modell av robotkroppen, vingar och roderytor. Med denna modell simuleras kvasistatiska flygtillstånd som tipp- och roll-rörelser.
Syftet med den statiska aeroelastiska analysen är att kvantifiera aeroelastiska koefficienter som höjd- och skevroder-effektivitet. Därefter analyseras risken för fladder i underljuds- och överljudsfart vid havsytan.
De elastiska deformationer som uppkommer beroende på robotens flexibilitet inverkar på robotens flygtillstånd. Effekten är svag vid Machtalet, M=0.5, där de aeroelastiska roderverkningsgraderna, $\eta_{C_{N_{\alpha,\delta}}}$, $\eta_{C_{m_{\alpha,\delta}}}$ och $\eta_{C_{l_{\alpha,\delta}}}$ samtliga har värden omkring 0,9. Dessa verkningsgrader sjunker till omkring 0,6-0,7 i det transoniska fartområdet vilket kan vara kritiskt och därför bör studeras mer i detalj. En ytterligare reduktion sker i det supersoniska området.
Robotens fladderegenskaper är goda i underljudsområdet och vid lägre överljudshastigheter, $M < 1{,}5$, däremot är fladderhastigheten reducerad i det transoniska fartområdet, M=0,7 till 1,0 men reduktionen bedöms ej vara kritisk.

Nyckelord
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