All Moving Tail Plate Interaction on an Aerodynamic Characteristic of the Rocket Plane in Tailless Configuration

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ABSTRACT

The paper presents results of a numerical investigation for a rocket plane which is designed to suborbital space tourism flights. The vehicle is designed in a tailless configuration. The main goal of the research was to find an influence of the all moving tail (AMT) on rocket plane's dynamic stability. The investigation was done for low and high angles of attack and subsonic speed. Moreover analysis was carried out for altitude equal 15 kilometers. CFD calculations were conducted by Panukl and MGAERO software. The dynamic stability analysis was performed by SDSA package. The analysis included evaluation motion mode as: Dutch roll, short period, roll, spiral and roll-spiral according to MIL regulation. The configuration of the rocket plane which fulfilled all required conditions of the dynamic stability criterion defined by MIL was obtained.

1 INTRODUCTION

Suborbital space tourism flights are in the midst of the most promising branches of aerospace technology. Currently there is a big market demand on suborbital vehicles. So far, only flights of the technology demonstrator were performed but there is no operating commercial spacecraft. However a few companies are working on such vehicles. Following concepts are being developed: a rocket plane lifted by another aircraft (e.g. Space Ship Two & White Knight Two), a one stage horizontal take-off rocket plane (e.g. Lynx), vertical takeoff and landing system (e.g. Armadillo Aerospace). Also at Warsaw University of Technology a concept of a system to space tourism flights is being developed [1]-[3]. The main assumption of the project is two tailless vehicles bonded together which form a conventional airplane configuration, where the second vehicle is used as a tail of the whole system. This system is called Modular Aeroplane System – MAS and is presented in the Figure 1.

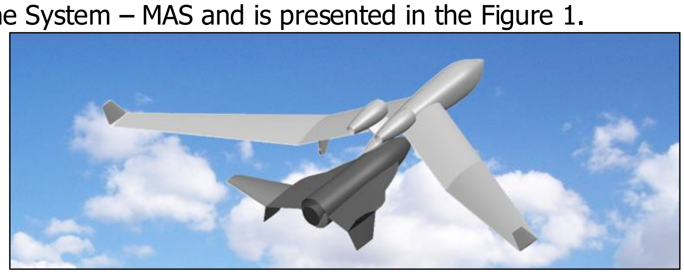

Figure 1: Layout of the Modular Aeroplane system (MAS). The first vehicle -Carrier (light gray), the second one - Rocket Plane (dark gray)

2 BASIC CONSIDEREATION

As was mentioned the rocket plane is part of the MAS. The rocket plane is designed in a tailless configuration and consists of the cylindrical fuselage, main wing, LEX (leading edge extension) and side plates on the wing tips. On board there is a place for two passengers and one pilot. The rocket plane is propelled by hybrid rocket engine. The MAS's mission profile assumes that the carrier lifts the rocket plane above Earth's thick atmosphere layer. Then the rocket plane performs suborbital flight, at the same time the carrier back to an airport. The rocket plane's return flight is a glide. The project assumes that the vehicle is not equipped with a heavy thermal shield but only partial thermal procreation. Therefore the vehicle needs a system which prevent to an excessive acceleration. So, one of the most interesting features of the rocket plane is the LEX. The LEX generates a vortex lift phenomenon which increases aerodynamic forces and in turn reduces the vehicle sink rate and prevents the structure from overheating. The initial return speed of the vehicle should be small, therefore the problem of LEX sharp edge overheating should not occur. Side plates on the wing tips which are used as the all moving tail plane, are applied as a second unique feature of the rocket plane concept. The upper set can be rotated and is used to control of the pitching and yawing channel. The second type of the rocket plane control surfaces are elevons. Deflection of both types of control surfaces ensures flight on high angles of attack during return flight. According to preliminary results of the rocket plane return flight simulation if side plates go back to neutral position (no deflection) at 15 kilometer then generated the G-load which is accepted by [4]. Therefore it was assumed that the 15 kilometers is a boundary between flight at high angles of attack and flight at low angels of attack. The paper presents analysis for flight at low and high (up 36 deg.) angles of attack and results were presented only for one altitude equal 15 kilometers, because decreasing the altitude causes improving dynamic stability only.

2.1 Problem definition

The main assumption for AMT's design was that the upper part of tail should ensure the lateral dynamic stability at low angles of attack. On the other hand, the lower part of AMT should ensure the lateral dynamic stability at high angles of attack. The AMT should be as small as possible due to a lower structure weight and reducing bending moment. Moreover, the size of the upper plates should satisfice the required level of control effectiveness. The initial configuration (Figure 2) was a result of analysis which includes structural, manufacturing, aerodynamic stability and control aspects.

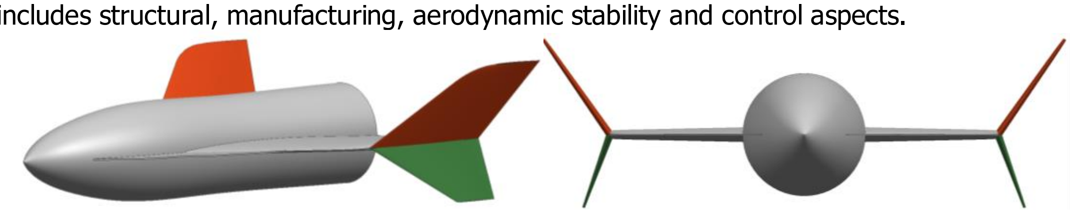

Figure 2: Rocket plane layout - initial configuration of AMT (red and green part)

The main goal of the research is sizing the all moving tail (AMT) to ensure static and dynamic stability for both low and high angles of attack for subsonic speed (up to Ma=0.6). Firstly, the aerodynamic analysis of impact upper and lower plates was conducted to obtain the sensitivity of AMT's geometry on dynamic stability of the rocket plane. The next step of the AMT sizing process was the analysis of the stability at high angles of attack with impact of the Mach number.

For analysis it was decided that five independent variables were defined: a yaw angle of the upper and lower plate, a height of the upper and lower plate and a position of the complete AMT respect to the wing. Definition of geometry parameters is presented in the Figure 3.

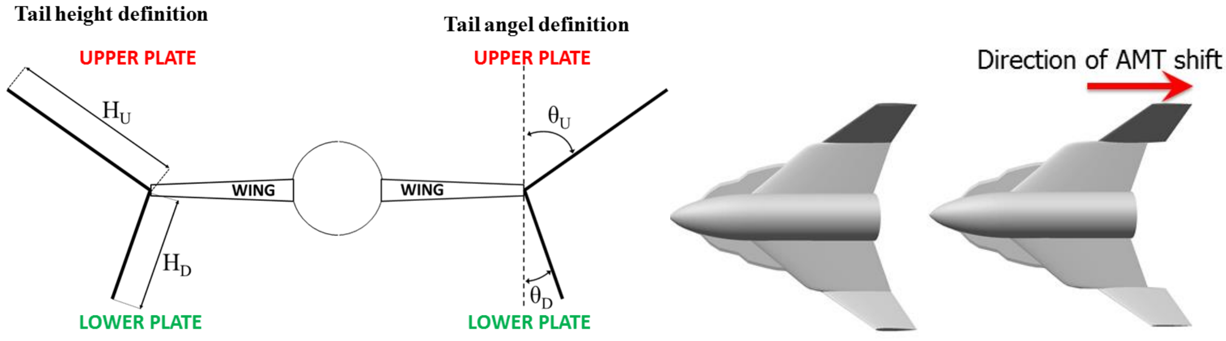

Figure 3: Definition of geometry parameters

3 NUMERICAL METHOD

3.1 Methodology

Numerical aerodynamic analyses were made by using two programs. For simplicity for low angles of attack and low Mach numbers the linear aerodynamic theory (low order panel method) was used [5].The Figure 4 presents a numerical model for the panel method computations. The rocket plane numerical model includes the cone of fuselage's end. It was added because panel method limitation connected with a flow separation at the blunt edge of the fuselage. The pressure form panels on cone are not included in forces and moments coefficients. Numerical aerodynamic calculations for nonlinear aerodynamic were conducted by MGAERO software [6] which based on Euler equations and a multi grid scheme [7]. This kind of method can be used for vortex flow calculations but the LEX's edge must be modelled as a sharp object. Moreover the Euler equations do not consider a vortex breakdown due to inviscid model of a flow. The Figure 5 presents a numerical model for nonlinear calculations.

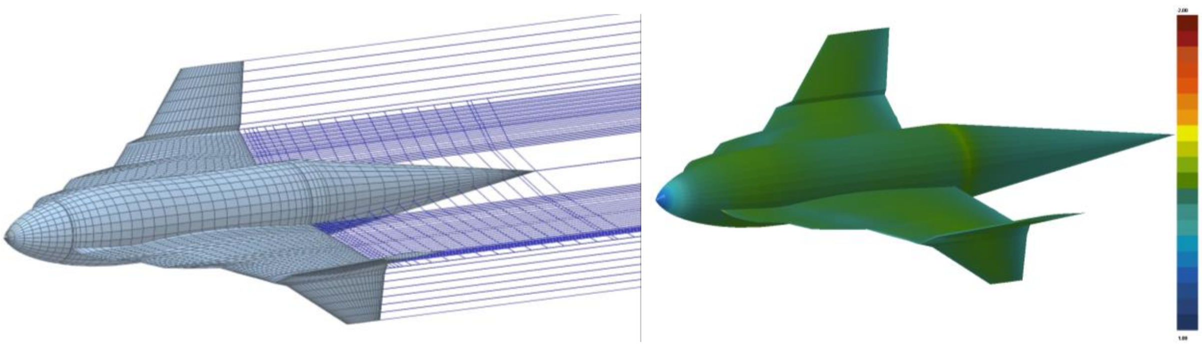

Figure 4: Example of grid and pressure coefficient distribution computed by Panukl

Results of computations by both methods were used as input data for the dynamic stability analysis which was performed by SDSA (Simulation and Dynamic Stability Analysis) package [8]-[10]. SDSA uses six degrees of freedom a nonlinear model of aircraft's motion [11]. The stability analysis can be done by eigenvalues analysis of linearized model. The equations are linearized by Jacobian matrix of stability derivatives for trim conditions [11].

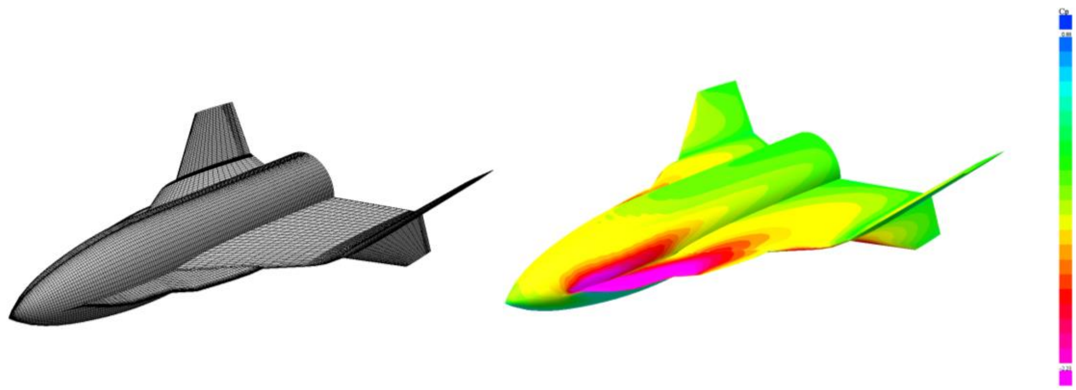

Figure 5: Example of grid and pressure coefficient distribution computed by MGAERO, α=28 deg.

3.2 Derivatives

The dynamic stability by SDSA should be fed by stability derivatives which were calculated based on aerodynamic data computed by mentioned software. All obtained stability derivatives were defined in the velocity axis system. Moreover, all forces and moments coefficients ware calculated in respect to the same area, span and mean aerodynamic chord. Figure 4 presents forces and moments acting on the aircraft.

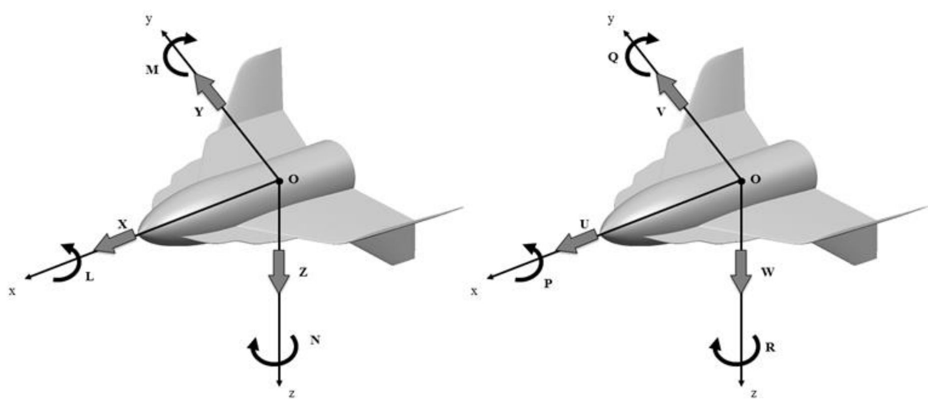

Figure 6: Definition of: forces (X,Y,Z) and moments (L,M,N) -on the left; linear (U,V,W) and angular velocities (P,Q,R) -on the right

The dimensionless angular velocities which were used in calculations of stability derivative in respect to angular velocities are defined as follows:

$$q = \frac{Q \cdot MAC}{2 \cdot V}, \quad p = \frac{P \cdot b}{2 \cdot V}, \quad r = \frac{R \cdot b}{2 \cdot V}. \qquad (1)$$

Where:

P – roll rate; p – dimensionless roll rate;
Q – pitch rate; q – dimensionless pitch rate;
R – yaw rate; r – dimensionless yaw rate;
MAC – mean aerodynamic chord;
b – reference span;
V – velocity.

3.3 Simplified stability analysis

The simplified stability analysis based on eigenvalue (2):

$$\lambda = \zeta + i\eta \tag{2}$$

The undamped Natural Frequency is defined by equation (3) and the damping ratio by equation (4):

$$\omega_n = \sqrt{\xi^2 + \omega_D{}^2}\,, \tag{3}$$

$$\zeta = \frac{\xi}{\sqrt{\xi^2 + \omega_D}}\,. \tag{4}$$

The period of oscillation can be calculated form equation (5):

$$T = \frac{2\pi}{\eta}\,. \tag{5}$$

The time to half and time to double (6):

$$T_{1/2} = \frac{-\ln(2)}{\xi} \text{ for } \xi < 0 \quad T_2 = \frac{\ln(2)}{\xi} \text{ for } \xi > 0\,. \tag{6}$$

3.4 Criteria of dynamic stability

The stability assessment was done according to MIL-F-8785C regulation [12] for the IV aircraft class and B phase of a flight (descent). The stability criteria based on damping ratio, undamped natural frequency for periodical mode and time to half damping for aperiodical mode.

4 NUMERICAL RESULTS

The results are consisting of the AMT geometry influence on stability derivatives and the dynamic stability. Outcomes were presented in two groups. The first one show results for low angles of attack and low Mach numbers, second presents results for high angles of attack and the Mach number up to Ma=0.6.

4.1 Stability derivatives

A few selected results of derivatives computation are presented in the Figure 7. Moreover the influence of yaw angle of the upper plate on the lateral stability derivatives (Cn_β and Cl_β) is presented in the Figure 8.

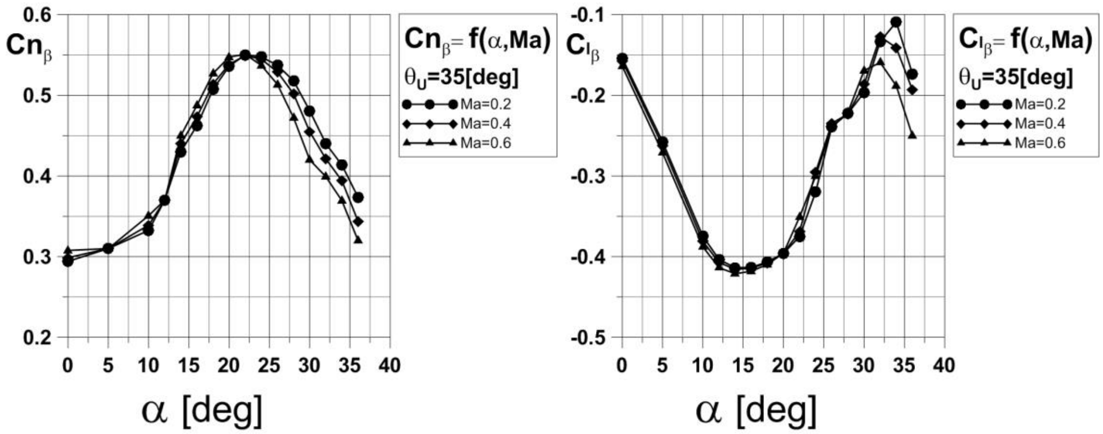

Figure 7: Lateral stability derivatives versus the angle of attack and Mach number (Cn_β – on the left; Cl_β- on the right)

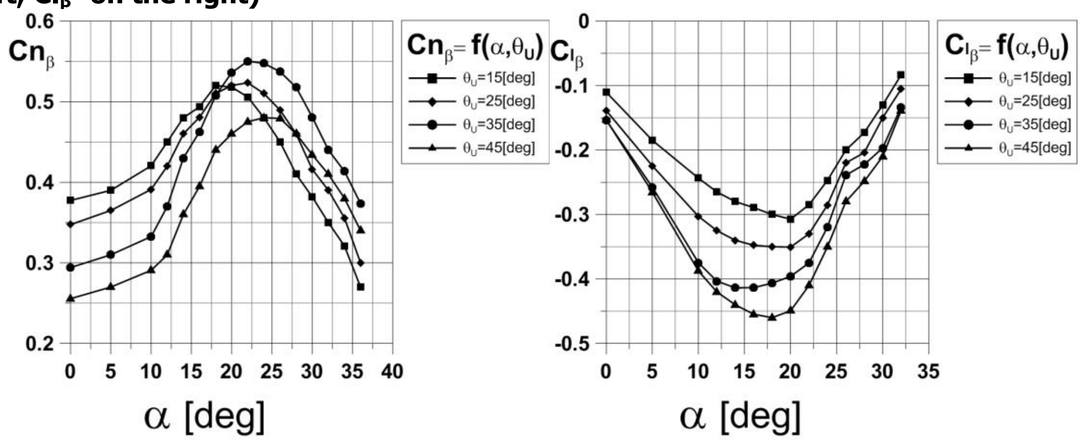

Figure 8: Lateral stability derivatives versus the angle of attack and yaw angle of upper plates (Cn_β – on the left; Cl_β- on the right)

4.2 Dynamic stability evaluation for low angles of attack

Now the evaluation of the dynamic stability of the rocket plane for low angles of attack and Mach numbers was made. Presented results were computed by Panukl package (CFD calculation) and SDSA software (eigenvalues calculation). Outcomes show the impact of different considered parameters (Figure 3) on the dynamic stability of the rocket plane. First, the impact of AMT upper and lower plates was analyzed (Figure 9 to Figure 11). Different configuration of the yaw and height of both plates impact on the Dutch roll and short period modes were analyzed. The last analysis includes the backward shift of the complete AMT (Figure 3).

The yellow curve (Figure 9- Figure 12) defines the minimal level of damping ratio for Dutch roll and short period mode. It means that the configuration of upper plate describe by area above the curve ensure the stable of the Dutch Roll (for the damping ration greater than 0.08) and short period (for the damping ration greater than 0.15) modes. Other modes like the phugoid, spiral and roll are always stable for considered cases

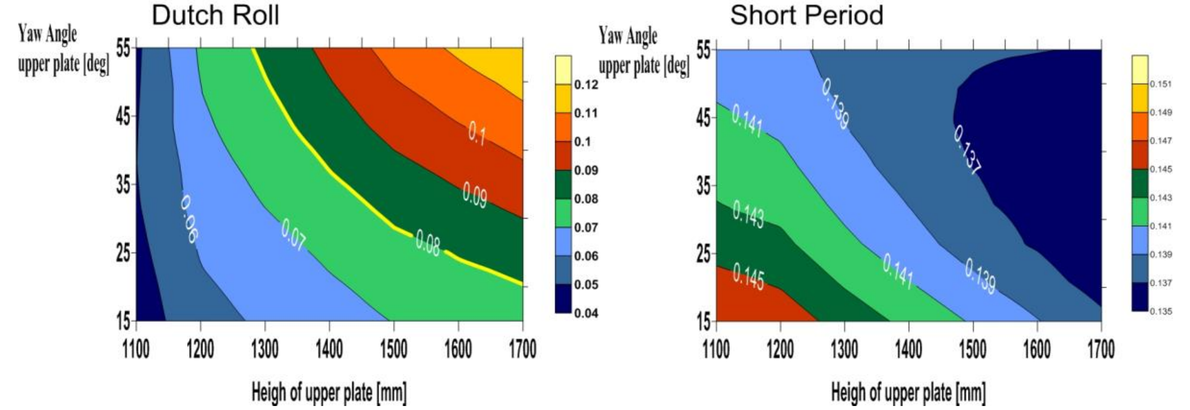

Figure 9: The high and yaw angle of the upper part of AMT influence on the dutch roll (on the left) and short period (on the right)

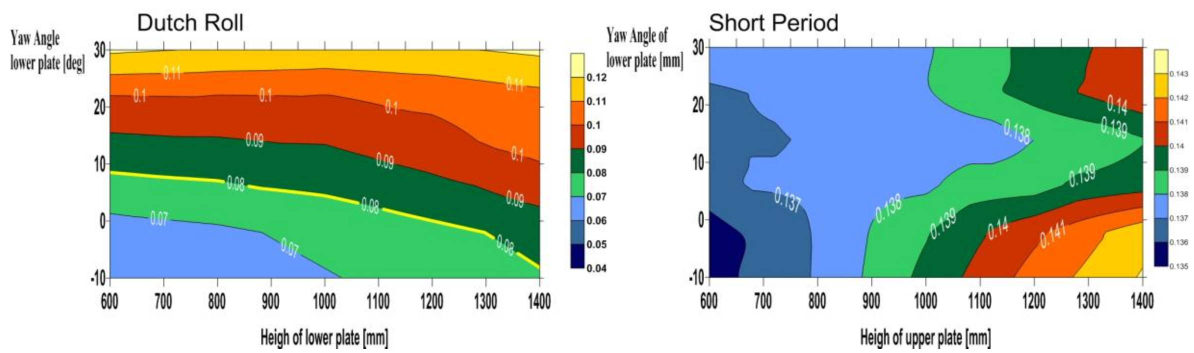

Figure 10: The high and yaw angle of the lower part of AMT influence on the Dutch roll (on the left) and short period (on the right)

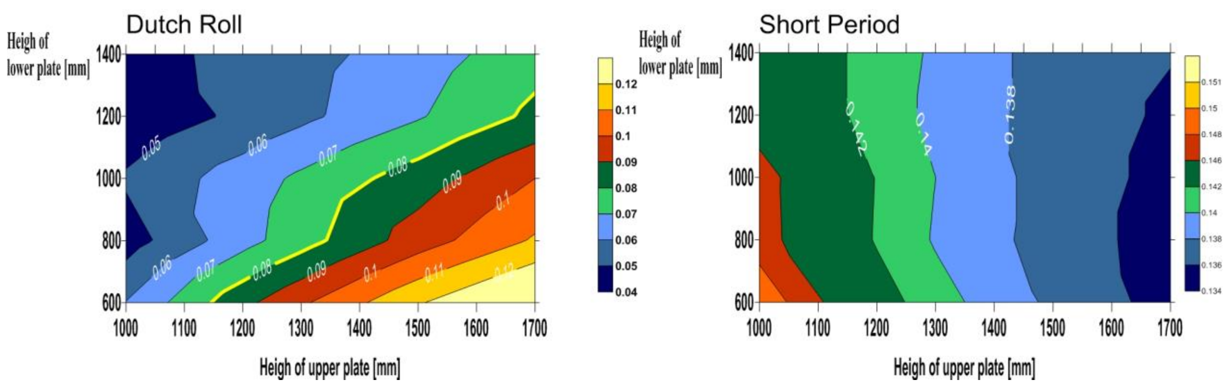

Figure 11: The high the lower and upper part of AMT influence on the Dutch roll (on the left) and short period (on the right)

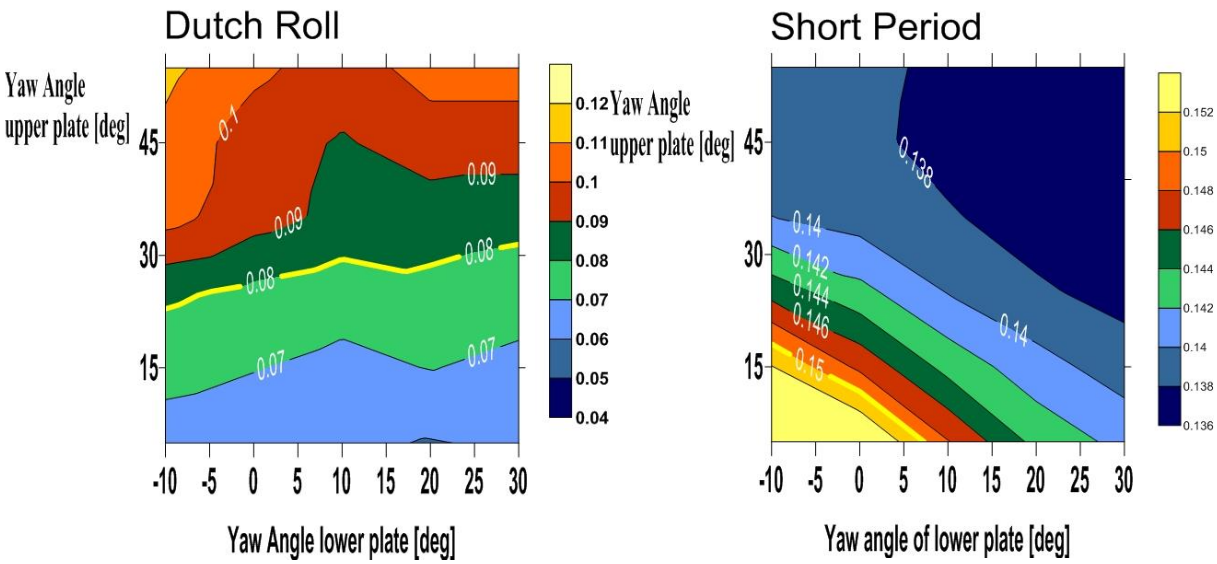

Figure 12: The yaw angle the lower and upper part of AMT influence on the Dutch roll (on the left) and short period (on the right)

Modification of AMT's geometry allow to obtaining the stable Dutch roll mode. The change of the yaw angle and height of the upper and lower plates are not guaranty satisfied criterion for the short period mode (Figure 9 and Figure 10). Simultaneous change of the upper and lower plates' height allow to obtain the stable short period mode (Figure 11). The similar effect is for simultaneous change of the upper and lower plates' yaw angle (Figure 12). Unfortunately results of both mentioned modifications get difficult AMT geometry.

The last considered geometry parameter is the AMT backward shift. Figure 3 presents the main idea of the geometry modification. The analysis of influence of the AMT position respect to the wing is not easy. It is connected with a centre of gravity (C.G.) the shift causes by the AMT shift. All stability analysis includes the C.G. position respect to the AMT current configuration (Figure 13). Results of influence of the AMT backward shit on the Dutch roll and short period mode are presented in the Figure 14. The time to half for the spiral mode and time constant for roll are presented in the Figure 15. The influence of the AMT backward shift on the dynamic stability is noticeable for the shift up to 0.2 meter.

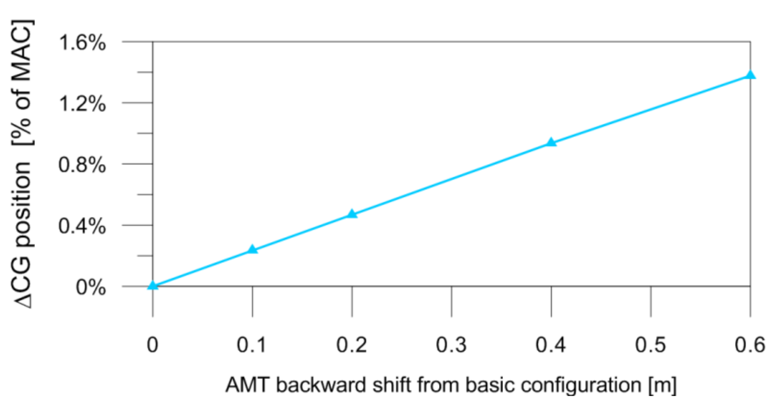

Figure 13: Channing of centre of gravity position causes by AMS shift

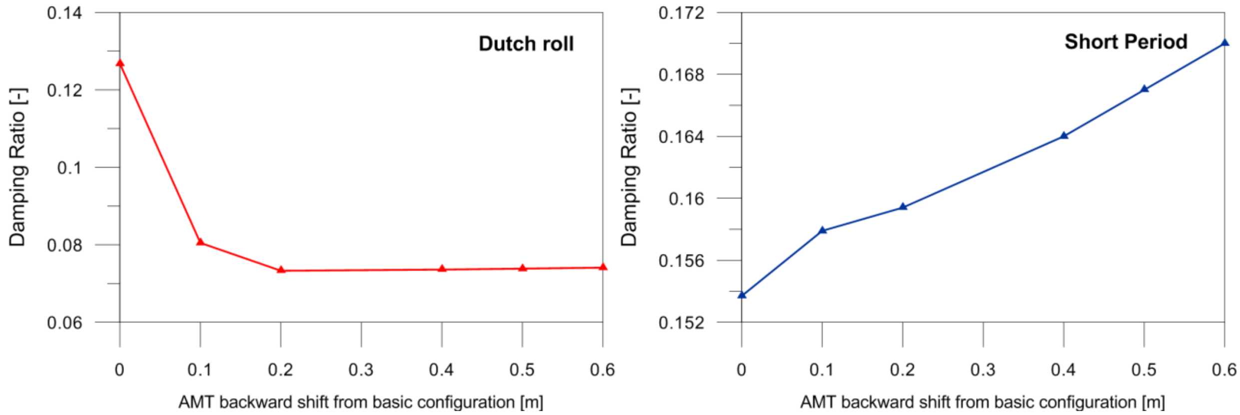

Figure 14: AMT shift influence on Dutch roll and short period mode

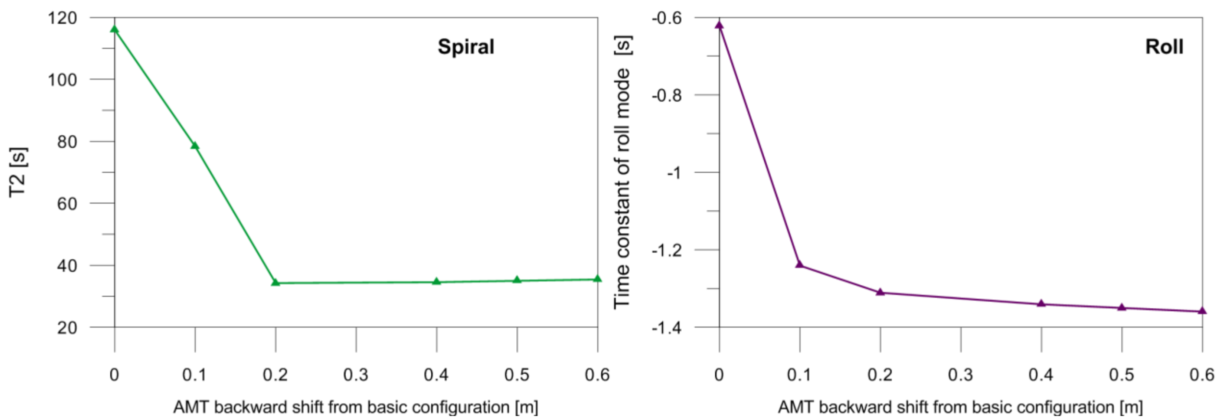

Figure 15: AMT shift influence on spiral and roll mode

4.3 Dynamic stability for high angles of attack

The stability derivatives used to the dynamic stability at the high angle of attack were obtained by MGAERO package. Results of dynamic stability evaluation performed by SDSA package are presented on the Figure 16 to Figure 21 and show the most important aircraft motion modes with the stability criteria.

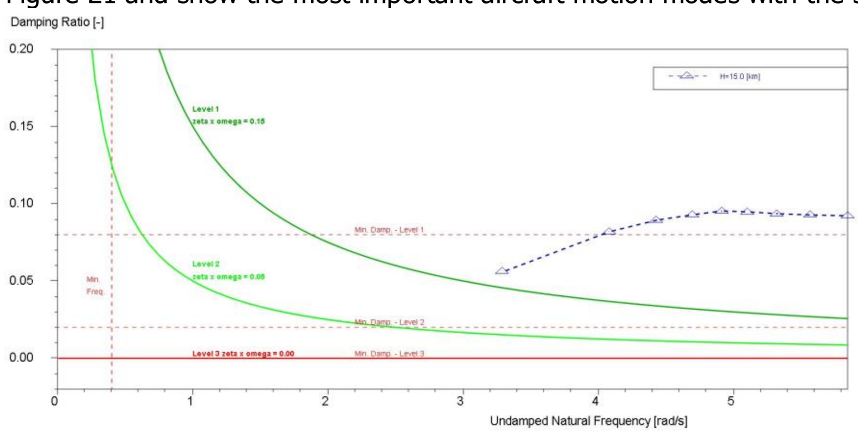

Figure 16: Dutch roll mode

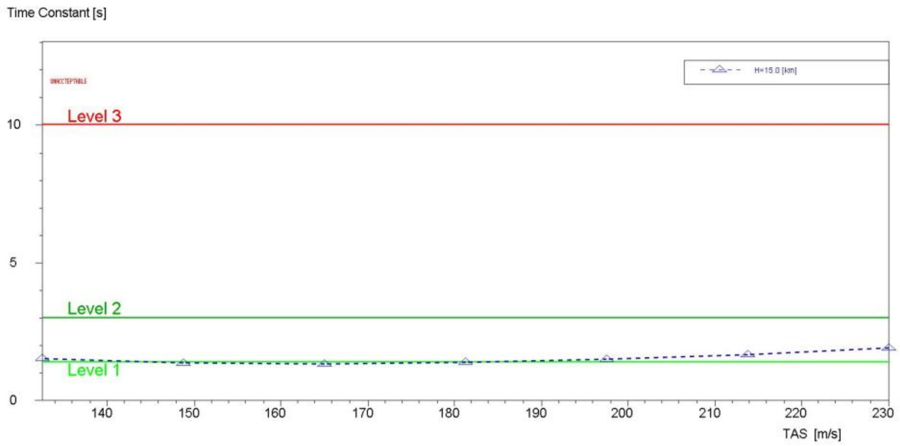

Figure 17: Roll mode

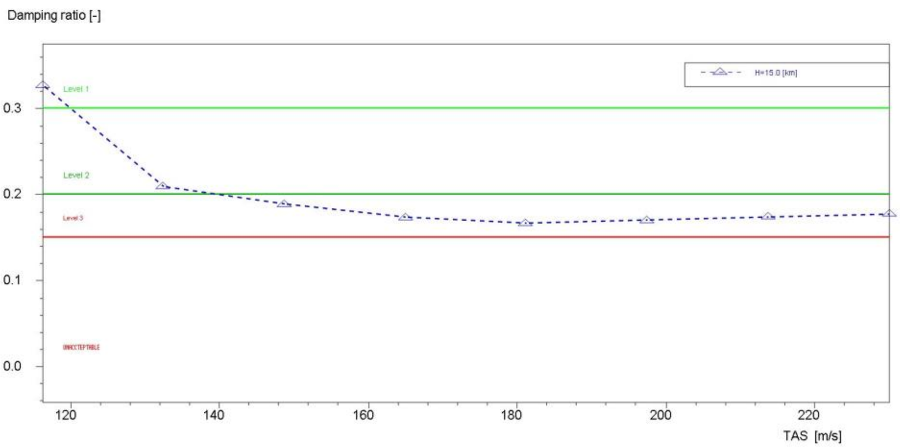

Figure 18: Short Period mode (damping ratio)

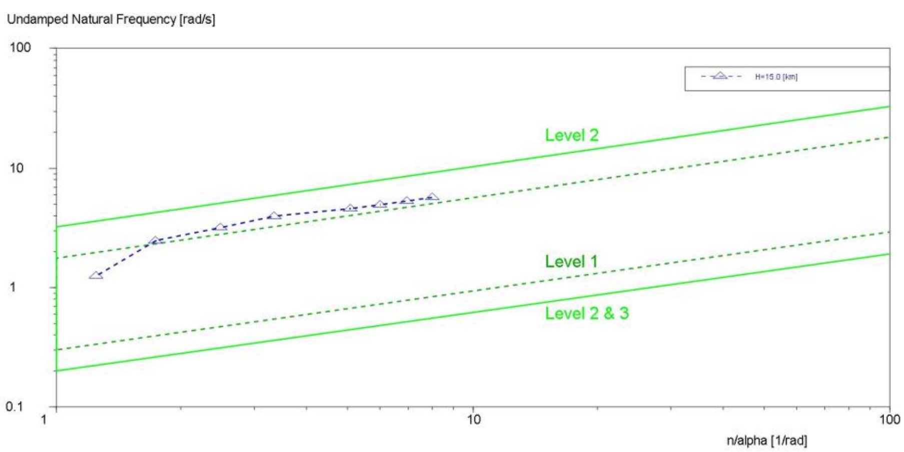

Figure 19: Short period (Undamped Natural Frequency)

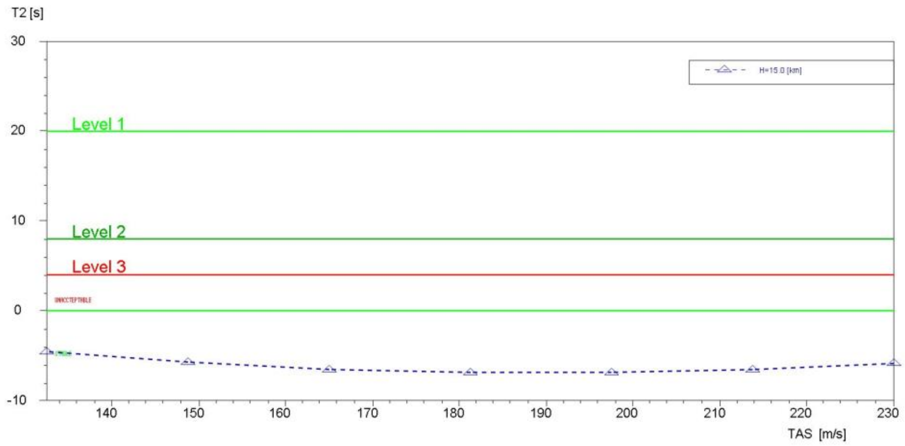

Figure 20: Spiral mode

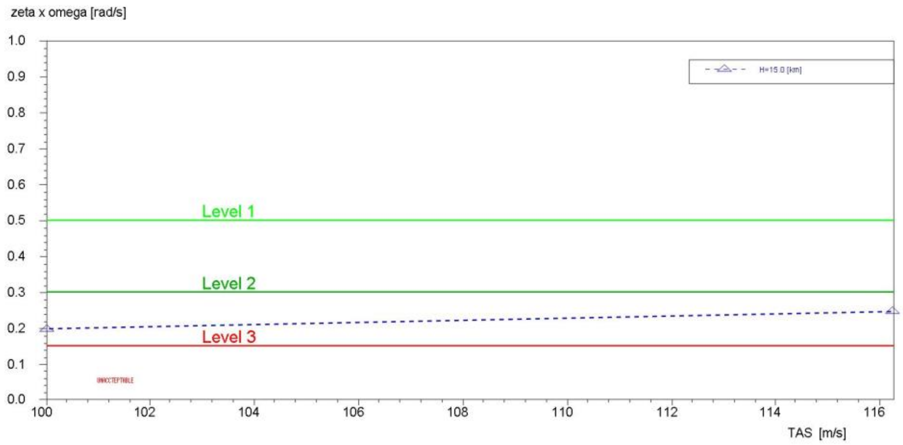

Figure 21: Roll-Spiral mode

The analysis reveals that for high angles of attack (up to the 26 deg.) the rocket plane is dynamically stable. Fulfilled all required conditions of the dynamic stability criterion defined by MIL. However some cases of motion modes satisfied only the 2 or 3 flight quality levels. Moreover, some aircraft modes like the short period satisfied higher requirement level compared to the low angles of attack. However, for higher angles of attack the Roll-spiral mode was observed, which is a kind of lateral pendulum mode [11]. This mode satisfied the stability criterion too (Figure 21).

5 FINAL CONCLUSIONS

Results of presented computation get the interesting information about the influence of AMT's configuration on the dynamic stability of the rocket plane in the tailless configuration. Dynamic stability sensitivity on the yaw angle and height of the upper and lower plate was investigated. Moreover, the position of the AMT respect to the wing was checked. Analysis was made for low and high angles of attack and for different Mach numbers.

The strong coupling was observed between two periodic modes: Dutch roll and Short period. Modification of AMT parameters like the yaw angle and height caused the opposite effect in the damping ration of mentioned modes. Only the backward shift of the complete AMT allows satisfying both modes requirements. Unfortunately it is highly discouraged because of a structural problem with the wing-AMT joint. For the basic configuration at the high angle of attack the Roll-Spiral coupled mode was observed.

The assumed the concept of the upper and lower part of the AMT was checked the area reductions of the lower plate are cause the stability problem at high angles of attack. Therefore the lower part is responsible for the stability at high angles of attack.

6 FURTHER WORK

The dynamic stability for the rocket plane was obtained for subsonic case but the AMT sizing analysis should be expand on supersonic cases because of mission profile assumptions. The further analysis of a trajectory of the rocket plane is needed. To archive this aim the analysis of control surfaces effectiveness should be done too. Moreover both for subsonic and supersonic cases should be investigated.

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