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VORTEX INDUCED DOWNWASH EFFECT ON STATIC STABILITY OF SUBSONIC AIR TO SURFACE MISSILE

IVAN MARIĆ
Military Technical Institute, Belgrade, ivanmaric094@gmail.com

ANJA GAVRILOVIĆ
Military Technical Institute, Belgrade, agavrilovic213@gmail.com

ILIJA NENADIĆ
Military Technical Institute, Belgrade, ilijanenadic98@gmail.com

GORAN OCOKOLJIĆ
Military Technical Institute, Belgrade, ocokoljic.goran@gmail.com

Abstract: *This paper is an aerodynamical analysis of differences that occur between semi-empirical determination of static stability of subsonic air to surface missile and wind-tunnel data when substantial downwash effect due to vortexes on wing surfaces is present. The existence of vortex downwash is confirmed and displayed by numerical CFD computation, and methods of circumventing its effects are reviewed.*

Keywords: *aerodynamics, semi-empirical, vortex, downwash, CFD.*

1. INTRODUCTION

To sucessfully achieve flight, missiles must be dinamically stable. This can be done in two ways – either by spin stabilisation or by ensuring the static stability of the missile.

The long-term trend in missile design, however, is toward increasing performance and maneuverability. This has most commonly resulted in moderate to high incidence angle flight, in which the most practical solution for stability is a statically stable missile with a desired static margin.

In order to achieve desired maneuverability, the missile must also have the required normal force, which is a function of the incidence angle, and the required control force to reach such desired incidence angle. The total normal force can be increased by increasing the size of, or adding new wing surfaces, keeping static stability of the missile in mind.

Each wing surface creates a downwash effect, thus changing the flow conditions on the wing surafce behind it. In severe conditions, vortex induced downwash can completelly change the desired performance of the wing surface, and result in destabilisation of the missile.

2. MISSILE DESCRIPTION

Coordinate system for aerodynamic coefficients further discussed is shown in Figure 1.

To achieve desired maneuverability requirements for air to surface missile, a canard controlled configuration was selected, and the missile is shown in Figure 2.

Since the deflection of the control surfaces in that case coincides with the desired change in pitch or yaw, the total normal force of the missile should increase with the manouvere. The downside to this design is that the angle of incidence and the angle of control deflection also coincide, which could lead to the stalling effect on the control surface on moderate angles of incidence [1].

To circumvent this, the size of canards was increased accordingly, giving higher control forces for lower deflection angles.

Since the wing position and size were predetermined, and could not change, a third wing section was added to the missile, to increase desired normal force and achieve an adequate static margin.

The body shape, diameter and lenght were also predetermined, with the reference point being chosen to coincide with the starting missle center of mass.

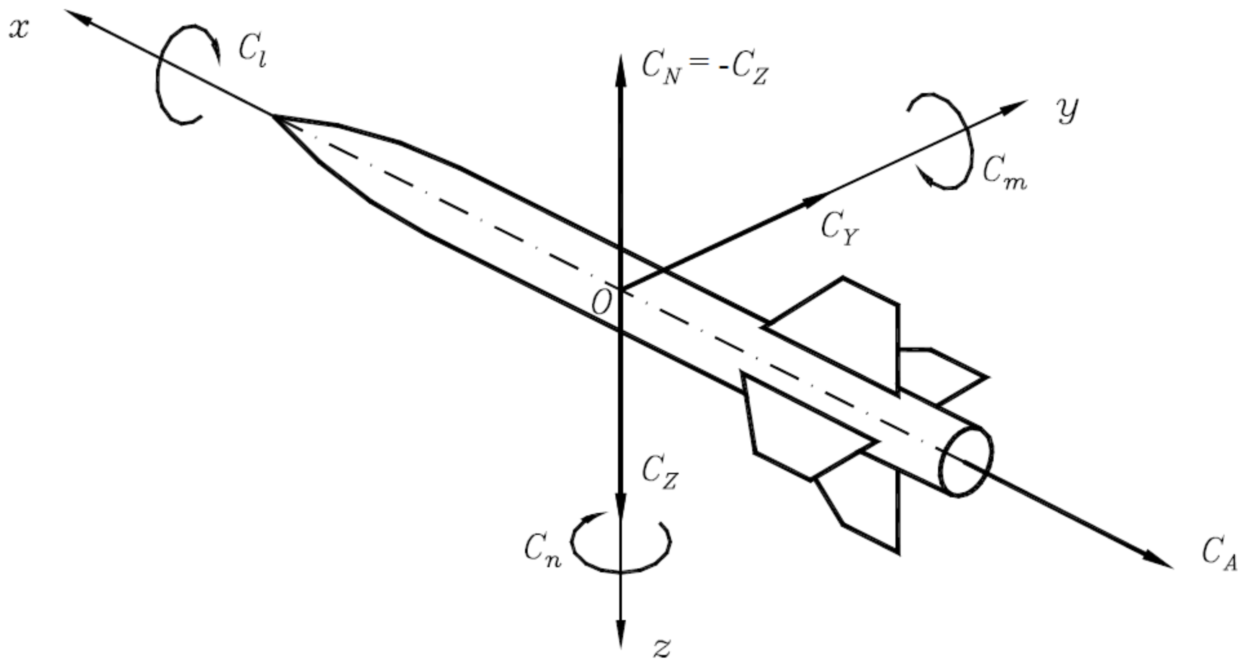

Figure 1. Body coordinate system, where point O is center of mass

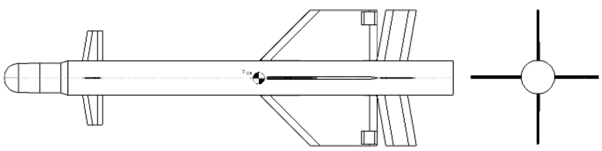

Figure 2. Configuration of subsonic air to surface missile

3. AERODYNAMIC ANALYSIS

3.1. Semi-empirical method

Using semi-empirical aerodynamics [2], preliminary aerodynamic analysis of subsonic air to surface missile was computed. Of note here is the pitching moment coefficient C_m, and namely its derivative C_m^α, which is crucial for static stability.

The missile will be statically stable if the following condition is met:

$$C_m^\alpha < 0 \quad (1)$$

In other words, the slope of $C_m(\alpha)$ must be negative for relatively small values of α, with α being the angle of attack.

The function $C_m^\alpha(M)$ for the missile is presented in Figure 3, where M is the Mach number.

It is evident from Figure 3, that (1) is satisfied, and C_m^α changes little with the Mach number until $M = 0.9$.

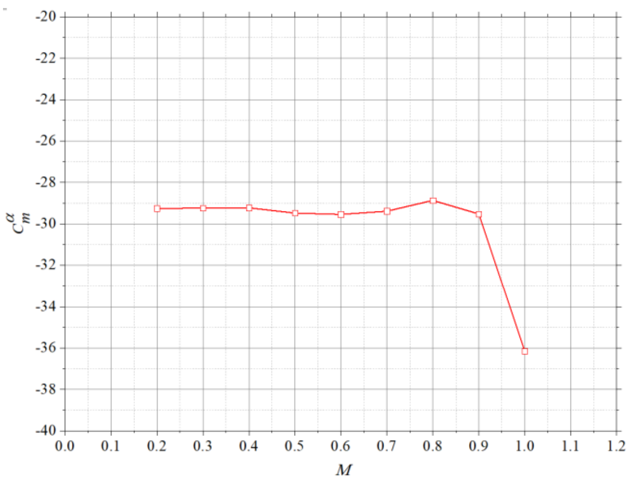

Figure 3. $C_m^\alpha(M)$ as a result of semi-empirical analysis of subsonic air to surface missile, for α in radians

3.2. Wind Tunnel tests and data

After semi-empirical analysis, a model of the subsonic air to surface missile was tested in T-35 Wind tunnel of the Military Technical Instiitute in Belgrade tunnel on $M = 0.4$, and data revealed that the condition (1) was not met, as is seen in Figure 5.

Since the tests of control effectiveness, shown also in Figure 5, indicate the existence of stalling effect at only $\alpha \approx 9°$, restoring of stability cannot be done by altering canard size, without significant loss of control effectiveness.

Deflection angles are defined in Figure 4.

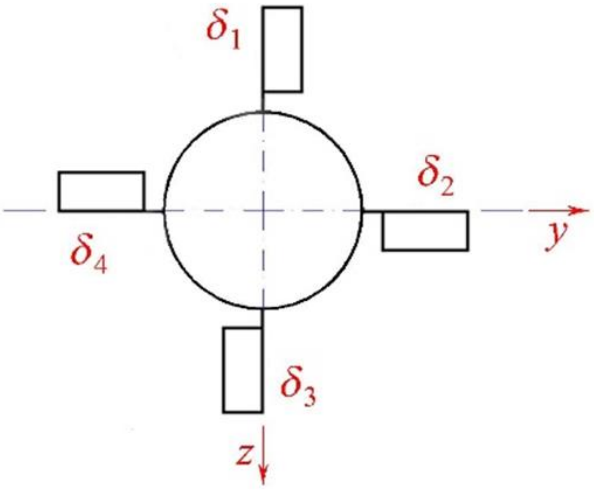

Figure 4. Positive signs of deflection angles

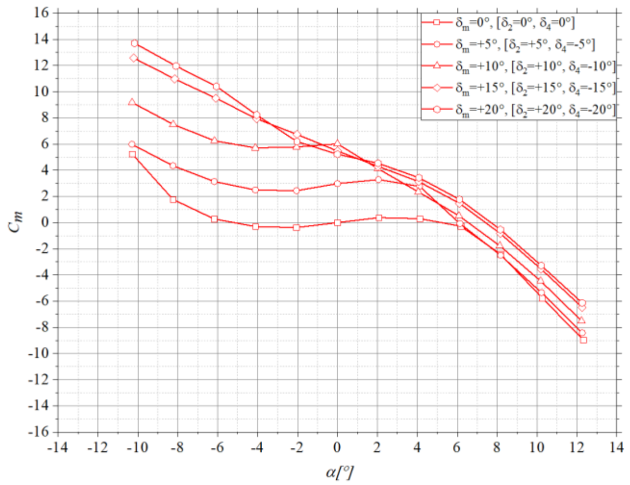

Figure 5. Pitching moment coefficient $C_m(\alpha)$ for different control deflections

In order to determine the cause of instability, and to make the missile stable, several more wind tunnel tests in T-35 wind tunnel were performed [3].

First, two tests in which the third wing section was moved $100mm$ and $200mm$ further back, in order to move the center of pressure behind the reference point of the missile, making it stable. Further, if the loss of stability is due to appearance of vortex induced downwash between second and third wing sections, moving the third section back should remove it from the vortex and increase its aerodynamic characteristics.

The final test was to determine if the downwash from canards was impacting the other wing sections, and decreasing stability [4]. This was done by rotating the canards 45° relative to the second and third wing sections.

The results of these wind tunnel tests are presented in Figure 6.

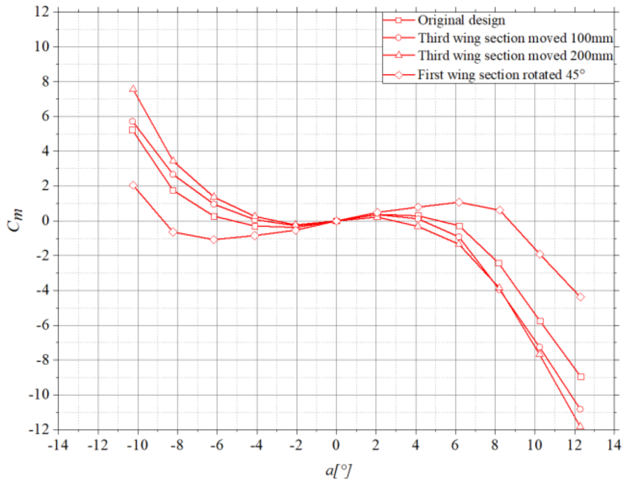

Figure 6. Pitching moment coefficient $C_m(\alpha)$ for different control deflections

As can be seen, rotating the canards 45°, yields the worst results for stability, making it more unstable.

Moving the third wing section does increase the stability of the subsonic air to surface missile, but at an unexpectedly ineffective rate, noticeable only at $\alpha > 2°$.

Because the missile launcher solution makes it impossible to rotate just the second or just the third wing section 45° in order for the vortex induced downwash to avoid the section behind, there will always be interference due to the vortex between the second and third wing sections.

Since the ratio of thicknesses of the second and third wing section is greater than double ($t_{II}/t_{III} = 2.66$), this is the suspected cause of substantial vortex induced downwash interference.

If this ratio $t_{II}/t_{III} = 2.66$ is used as the vortex induced downwash correction coefficient in semi-empirical computation, as is presented in Table 1, a satisfactory value of C_m^α is achieved for the original configuration.

A more accurate correction coefficient for configurations in which the third wing section was moved is obtained if relative distance of second and third wing sections is taken into account. The following semi-empirical formula is sufficiently accurate up to $l = 500mm$.

$$k = \bar{t} - l(0.25 + 5l^2) \qquad (2)$$

Here the ratio of thicknesses is denoted with $\bar{t}$, and l is the distance between trailing and leading edges in meters. The results are listed in Table 1.

Table 1. C_m^α values for semi-empirical and wind tunnel tests

Configuration	C_m^α	C_m^α $100mm$	C_m^α $200mm$
Semi-empirical	−29.23	−35.11	−41.99
T-35 Wind tunnel	10.46	8.97	6.29
k = 2.66	10.51	9.76	9.01
Equation (2)	10.51	8.95	6.30

3.3. Numerical analysis

Existence of vortex induced downwash and interference of second and third wing sections was proven by CFD numeric computation in Fluent [5]. Computations were done for the original configuration, as well as the configuration in which the third wing section was translated 100m to the rear of the missile.

In Figure 7, results from CFD simulations show that the turbulent flow from the trailing edge of the second wing section, completely engulfs the third wing section in turbulent flow, thus diminishing its aerodynamic characteristics substantially.

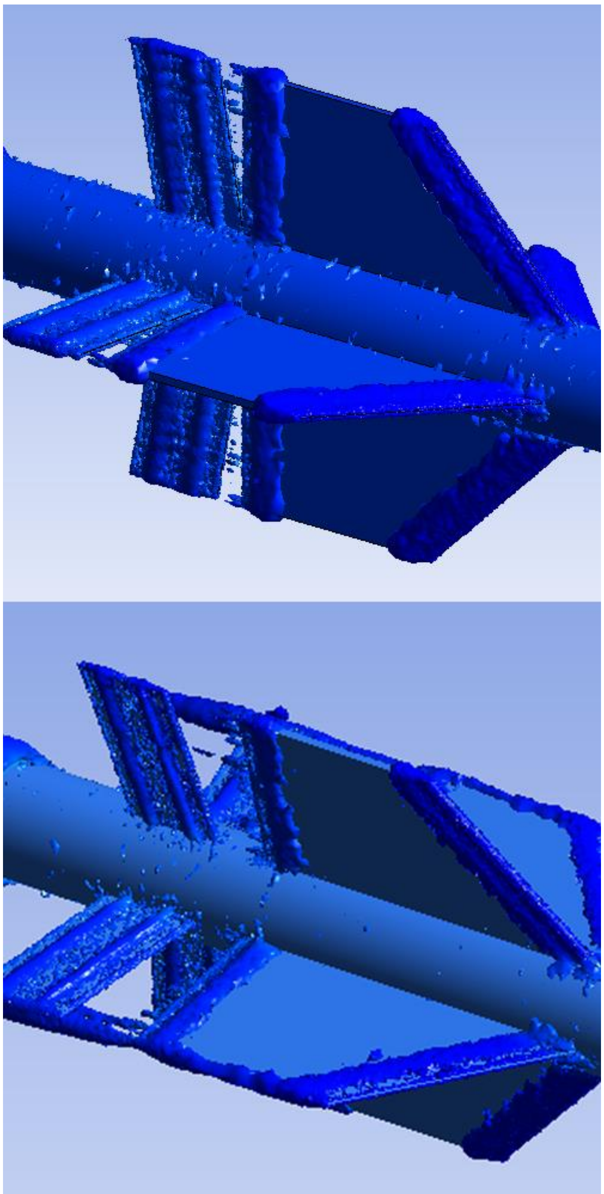

Figure 7. CFD vortex induced downwash interference and turbulent flow on the third wing section

Stability characteristics were calculated for $\alpha = 2°$, and the corresponding pitching moment coefficient C_m is shown in Figure 8, along with wind tunnel data obtained in T-35 wind tunnel. Stability derivative C_m^α for these numerically obtained moments is presented and compared with tunnel data in Table 2.

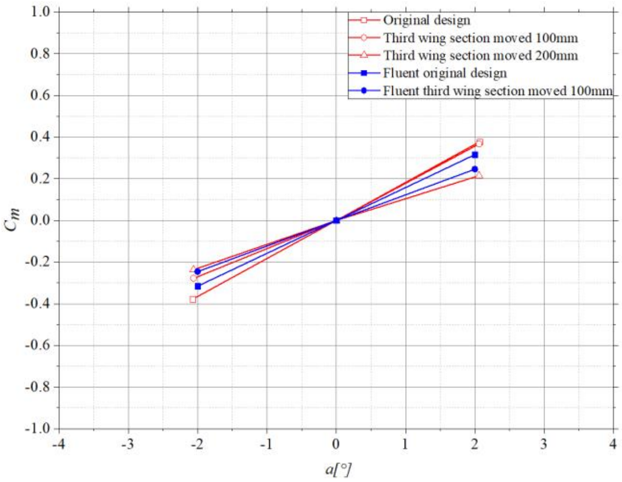

Figure 8. $C_m(\alpha)$ obtained numerically and in T-35 wind tunnel around $\alpha = 0°$

Table 2. C_m^α values for CFD analysis and wind tunnel tests

Configuration	C_m^α	C_m^α $100mm$
CFD	9.05	7.05
T-35 Wind tunnel	10.46	8.97

The numerical simulation, as is evident, provides highly satisfactory results that closely align with wind tunnel data, as well as visual confirmation of aerodynamic phenomena that occur during vortex induced downwash interference.

4. CONCLUSION

Since there is no way to change the size and position of the second wing section, nor rotate the second or the third wing section 45° relative to one another, there will always exist a loss of stability due to vortex downwash interference between the two sections. The missile is subsonic, so disturbances in the flow are spread faster than flight speed.

The canard position is also predetermined, and their size cannot decrease to increase stability due to loss of control effectiveness.

Using equation (2), third wing section will need to move $550mm$ from the second section trailing edged, which is well outside the missile body.

The solution would be to move the control surfaces behind the second wing section, in order to avoid stalling effect, since the angle od incidence and control deflection are opposite. This would result in loss of normal force during control, but the first wing section would be fixed, and could be changed to compensate both stability loss (predicted accurately using equation (2), and confirmed in Fluent) and to reach desired static margin and maneuverability of air to surface missile.

For subsonic missiles, it is necessary to accurately predict and account for vortex effects during preliminary design, which can be done using equation (2) for stability prediction and Fluent for further pre-tunnel corrections.

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