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NUMERICAL INVESTIGATION OF WING STRAKES AERODYNAMIC INFLUENCE USING MODIFIED SDM MODELS

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Abstract: *Many contemporary jet fighters and combat airplanes are equipped with wing strakes, or leading edge root extensions. Their role is to improve maneuvering characteristics and delay stall of swept low aspect ratio wings. Positioned in front of the airplane's center of gravity, they also generate destabilizing contribution to the longitudinal static stability. Aim of this paper was to perform CFD analyses of several characteristic strake shapes, and investigate their global aerodynamic influence on the lift, moment and drag coefficients and the longitudinal static stability derivative. The adopted calculation algorithm was first implemented on the Standard Dynamic Model (SDM), and the results for two subsonic Mach numbers were verified using experimental data obtained during one of the T-38 wind tunnel calibration tests at the Military Institute in Belgrade. After that, several SDM modifications were made, all generally denoted as the Modified Dynamic Models. The first two have provided a loft where the SDM's original double wedge strakes were removed, and the horizontal tail was modified to obtain inherently stable configuration at all angles of attack. Three assigned strake forms - elliptic, ogive and triangular of the same exposed area were added to it, with intention to generate longitudinally unstable configurations. The elliptic form gave the largest increase in lift coefficient, the best lift to drag ratios at high angles of attack, and the most favorable influence on the longitudinal static stability. Presented analyses will be a starting point for future investigations of more complex, multi segment strake shapes.*

Keywords: *Wing strakes, aerodynamic analysis, modified SDM models, CFD calculations, ANSYS Fluent.*

1. INTRODUCTION

One of very common features on many modern jet fighter aircraft with swept, low aspect ratio and delta wings are the strakes. They were first implemented on the Northrop F-5A „Freedom Fighter“ [1, 2] in 1959, which were proportionally small in size. The advantages of their implementation were recognized both in operational use and through numerous wind tunnel investigations, such as presented in [3]. As a consequence, the 1972's F-5E version was equipped with larger strakes (Fig. 1). Also known as the leading edge root extensions (LERX), strakes were progressively growing in size with time, both on the „western“ and the „eastern“ jet fighter planes [4]. Finally, on some designs their length has practically become equal, or exceeded the wing's root chord (Fig. 2).

The primary role of strakes is to act as vortex generators and improve maneuvering characteristics at moderate, and delay stall at high angles of attack, by energizing airflow on the upper wing surface [5, 6]. Although these vortices contribute to the local drag increase, energized boundary layer delays flow separation on the upper wing surfaces, and the overall effect may even be the total drag decrease.

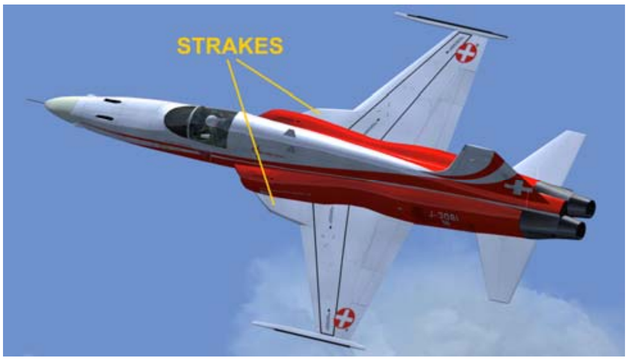

Figure 1. Double wedge strakes on Northrop F-5E (picture @ I. Kostić)

Since strakes are positioned in front of the airplane's center of gravity (CG), in the sense of the longitudinal static stability they are destabilizers, and the amount of this influence depends on their shape, aerodynamic area and distance from the CG.

One of the most comprehensive studies is presented in [7], where vortex breakdown characteristics of 43 strakes were analyzed. They were inspired by the development of the F-16 and F/A-18 lightweight fighters. Many other reports such as [8] and [9], were based on, or derived from these two jet fighters, years after they were put to the operational use.

Figure 2. Strakes on F/A-18C (picture @ I. Kostić)

Purpose of this work is numerical CFD investigation of aerodynamic influence of several wing strake geometries, assuming symmetrical flow conditions. Although some strake analyses in literature have been performed on isolated wing-strake configurations [10], authors of this paper have decided to use the Standard Dynamic Model (SDM, Fig. 3) as starting 3D geometry, which includes the fuselage with canopy, air intake and ventral fins, and the tail surfaces. Although the SDM was originally aimed for wind tunnel calibrations, numerous CFD analyses were performed using this model for their verification purposes, such as [11, 12, 13, etc.].

Figure 3. SDM model and pitch/yaw apparatus for wind tunnel calibrations in VTI (photo @ VTI)

In this work, the first obtained CFD results for the original SDM have been evaluated using experimental results from the Military Technical Institute in Belgrade. After that, the SDM model was modified in two steps to obtain longitudinally statically stable configuration. Finally, it was equipped with the new elliptic, ogive and triangular strakes, and their influence on the lift, drag, moment coefficients and the longitudinal static stability characteristics has been calculated. All altered geometries were generally denoted as MDM-s (Modified Dynamic Models).

2. CALCULATION MODEL

CFD calculations presented in this article have been done using the commercial ANSYS Fluent software. For symmetrical flow conditions a half model control volumes were applied. In order to eliminate the influence of the SDM's large end-fuselage diameter on drag results for the new strakes, a "sting" of the same diameter has been added behind all SDM/MDM geometries. By that the base drag has been eliminated, while the contribution of the sting to all coefficients was excluded.

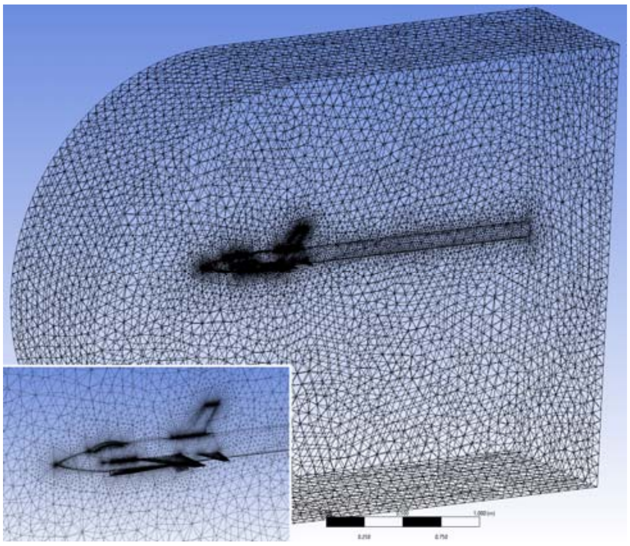

Figure 4. Half-model mesh with 1.1 million elements

Analyses were performed on unstructured meshes with about 1.100.000 elements (Fig. 4), using RANS equations with k-ω SST turbulence model. Applied calculation algorithm is the same as in [14, 15], where more details about it can be found.

3. COMPARISONS WITH EXPERIMENT

The initial CFD results were compared with the wind tunnel test results, obtained for the SDM calibration model at the Military Technical Institute (VTI, serb. Vojnotehnički institut) in Žarkovo – Belgrade [16]. Computational and experimental results for test Mach numbers M = 0.3 and M = 0.61, for the lift coefficient Cl and the moment coefficient Cm, and the derived longitudinal static stability derivative dCm/dCl are presented in Fig's 5 ÷ 8. The drag coefficient Cd values were not provided in VTI report. Computations at this stage were performed twice, first without, and then with the inflation layer implemented in the CFD analyses.

Considering the Cm, obtained agreements are good (Fig's

5 and 6), while for the Cl agreements are fair at small and medium angles of attack. At higher angles of attack, experiments show a slight increase in lift curve slopes for both Mach numbers, while the CFD's slopes remain practically constant. On these graphs, differences in results obtained without and with the inflation layer are hardly recognizable.

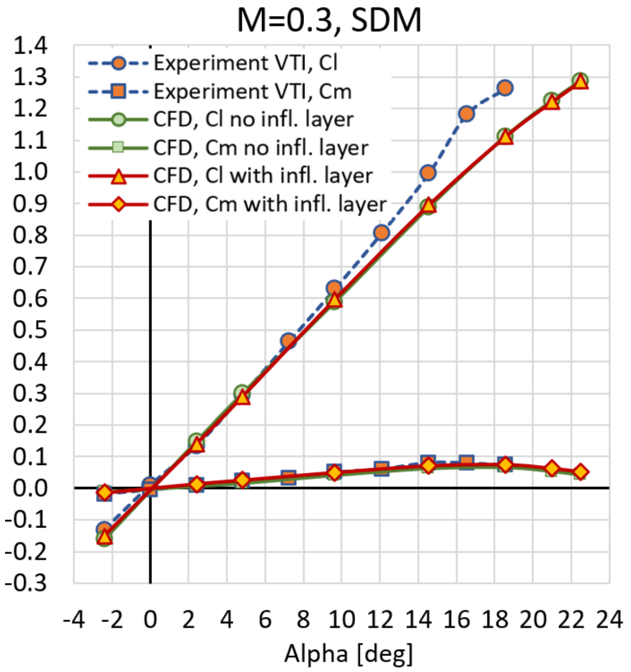

Figure 5. Lift and moment coefficients for M=0.3

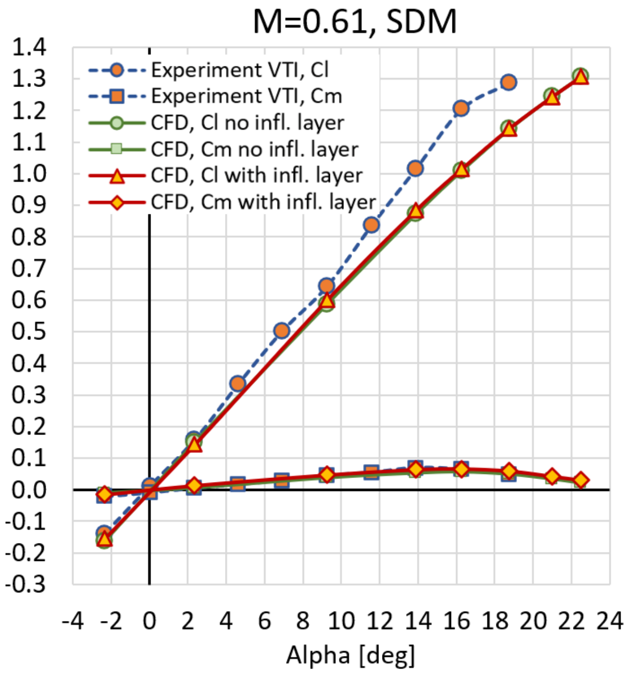

Figure 6. Lift and moment coefficients for M=0.61

Diagrams for the dCm/dCl derivatives at both Mach numbers (Fig's 7 and 8) show noticeable scatter in experimental results at low and medium angles of attack. Such as the numerical calculations, experimental methods are also prone to certain inherent and inevitable faults. In this case, small measurement and averaging errors (hardly noticeable at experimental Cl and Cm curves in Fig's 5 and 6), increase in magnitude when converted to derivatives. In this case, the CFD results have provided quite good "averaging" of the experimental scatters. Both CFD and experiment also show that the original SDM configuration is longitudinally statically unstable at small and medium angles, while at high angles of attack it becomes stable.

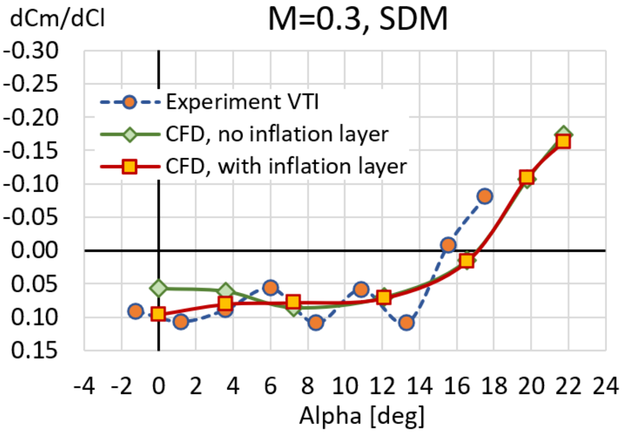

Figure 7. Longitudinal static stability for M=0.3

Figures 7. and 8. also indicate that calculations without and with the inflation layer coincide well, except at small angles of attack. In this domain results obtained with the inflation layer are much closer to the experiment, and this option was applied in all oncoming calculations.

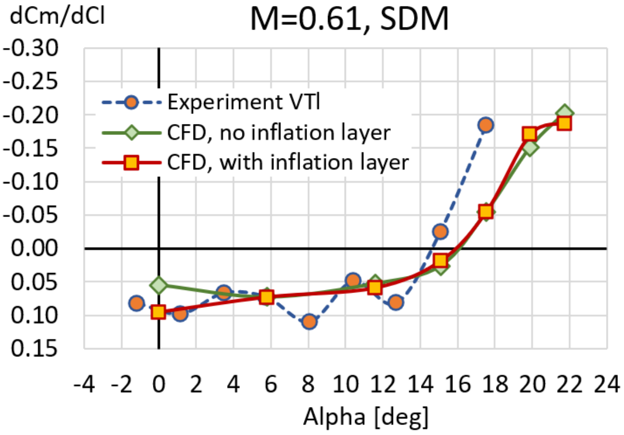

Figure 8. Longitudinal static stability for M=0.61

Presented analyses show that here adopted CFD model can be used for the preliminary comparative numerical investigations of the different strake shapes and their influence on longitudinal aerodynamic characteristics.

4. INITIAL SDM MODIFICATIONS

Since the SDM model (Fig. 9 (a)) originally has medium size double wedge strakes, the next step was to exclude them from the aerodynamic configuration, and provide space for the implementation of new strake shapes. In that sense, the first SDM modification was generated, denoted as MDM-NS (Modified Dynamic Model – No Strakes), shown in Fig. 9 (b). All aerodynamic analyses for this version, as well as for all other configurations presented in this article, were performed only for the Mach number M = 0.61.

Figure 10. shows that the maximum lift coefficient of the MDM-NS is smaller than of the SDM, while the moment coefficient first increases up to Alpha = 7° and then it continues to progressively decrease.

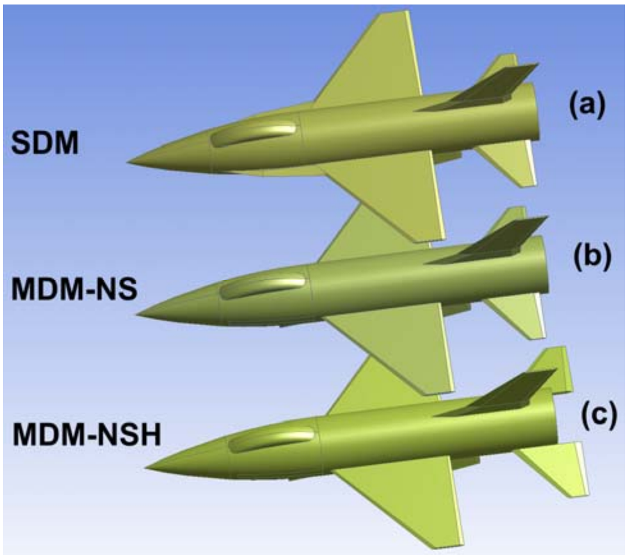

Figure 9. Two initial MDM modifications derived from the original SDM, with strakes removed.

While original SDM is longitudinally unstable up to the calculated Alpha = 16°, the MDM-NS is also unstable, but in a narrower domain, to about Alpha = 9° (Fig. 11).

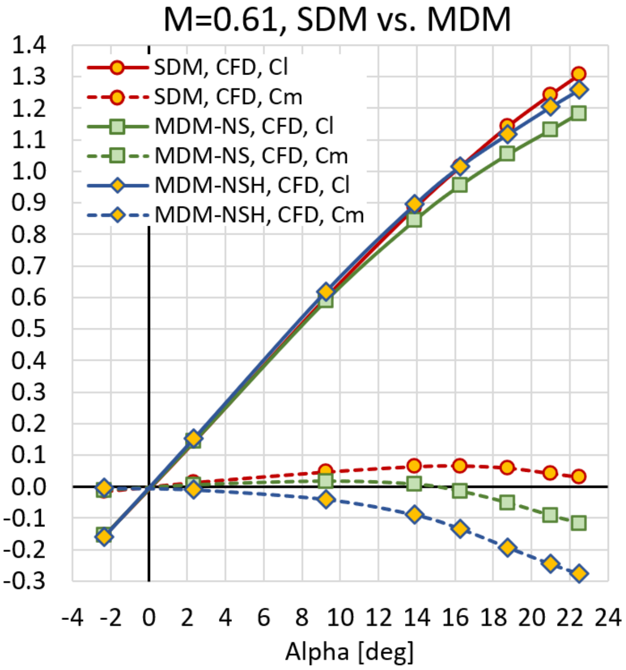

Figure 10. Lift and moment coefficients obtained by CFD

With aim to determine the effective influence of new strakes on the longitudinal static stability, a decision was adopted to modify the MDM-NS and make it longitudinally statically stable in the entire range of angles of attack (still without strakes). After scaling the original horizontal tail by factor 1.2 in chordwise and spanwise directions taking the root leading edge as origin, and then translating it back by 40 mm, the new version has been obtained, denoted as MDM-NSH (Modified Dynamic Model – No Strakes with Horizontal tail modified), Fig. 9 (c))

Figure 10 shows that its entire moment curve has negative slope, while its dCm/dCl derivative (Fig. 11) is also entirely in the negative domain, indicating the posted inherent stability requirement has been satisfied for all angles of attack.

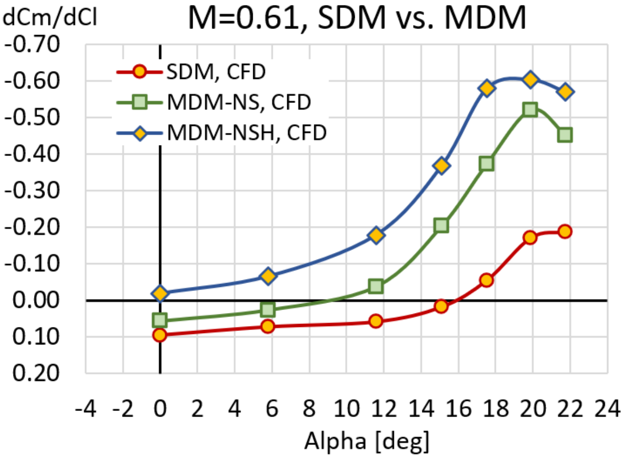

Figure 11. Calculated longitudinal static stabilities

5. RESULTS AND DISCUSSION FOR NEW STRAKE GEOMETRIES

Using the MDM-NSH as a new starting loft, three different strake types were added. The MDM-ST1 was obtained by adding quarter-elliptic strakes, the MDM-ST2 was modeled by adding ogive strakes, while MDM-ST3 was generated by adding triangular, single wedge strakes (Fig's 12 (d), (e) and (f) respectively).

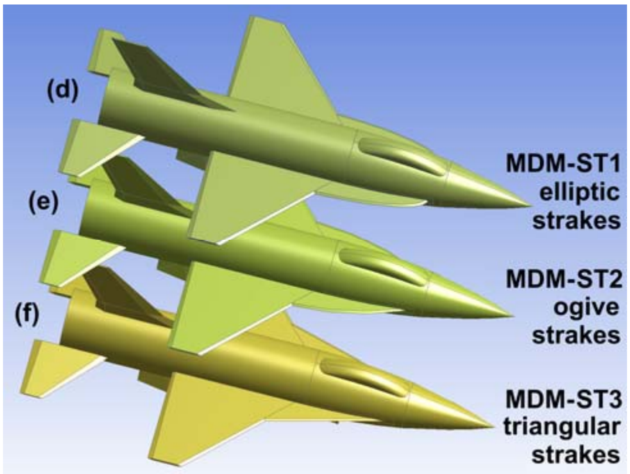

Figure 12. New strake-added modifications, developed from the statically stable MDM-NSH.

They all have the same theoretical planform area of 77 cm^2, while their true area is a bit smaller, i.e. it is the theoretical area reduced by the domains covered by parts of fuselage and wing leading edge, which are practically the same for all three types. This way they have the same area exposed to the air flow, and their comparative investigations can provide useful conclusions considering their aerodynamic efficiency and influence. In this work, analyses were limited only to the strake influence on global lift, drag and moment coefficients, while future work should also include detailed insights in local pressure distributions, vortex pattern influences, etc.

Figure 13 indicates that the elliptic ST1 provides the largest increase in lift coefficient ΔCl with respect to the calculated value for NSH at Alpha = 22.5° (17.3%), while ΔCl contributions of ST2 (16.2%) and ST3 (12.8%) versions are smaller.

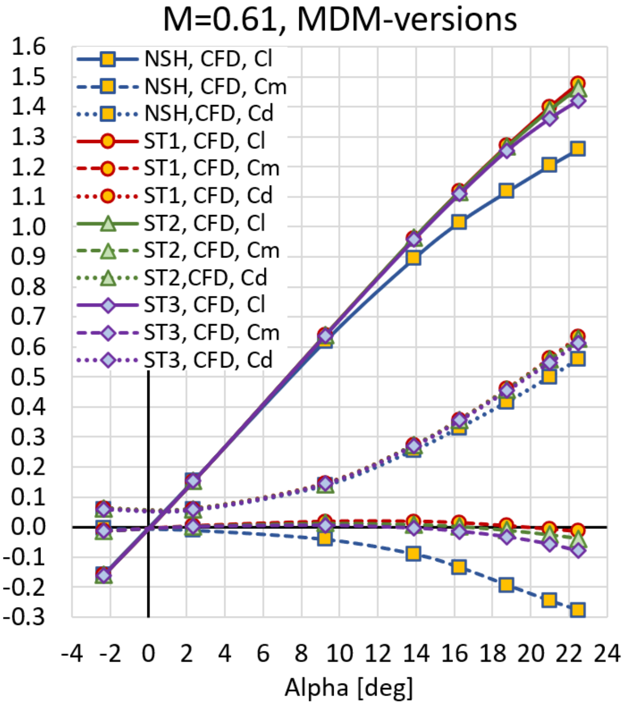

Figure 13. Lift, drag and moment coefficients

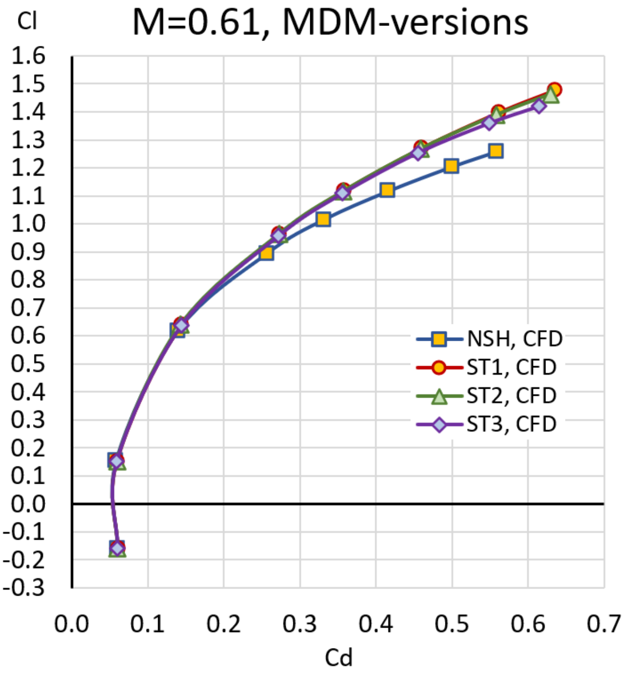

Figure 14. Calculated drag polars

The same generally applies for the drag coefficients at Alpha = 22.5°, where ST1 generates proportionally the largest ΔCd increase (13.7%) with respect to the NSH, while values for ST2 (12.7%) and ST3 (10%) are also smaller. On the other hand, if drag polars are analyzed (Fig. 14) instead of the Cd-Alpha diagrams, the situation is quite different. In the upper half of the Cl domain, the elliptic ST1 version produces the smallest drag coefficient for the same lift coefficient generated (although differences between the three new strakes are hardly visible). So in this Cl domain, all three strake types generate noticeably smaller Cd for the same Cl values, than the NSH version. In fact, the MDM configurations with strakes, due to the enlarged exposed wing area but also owing to their shape, contribute more to the lift coefficient increase than to the increase in drag coefficient at high angles of attack, compared to the Cl-Cd ratios obtained by NSH version. Thus all three strake types, ST1, ST2 and ST3 have increased the configuration's Cd vs. Cl aerodynamic efficiency at angles of attack in the range Alpha = 10° ÷ 22.5°, which is one of the primary roles of the strake implementation. In that sense, the elliptic form has certain advantage over the ogive and triangular versions.

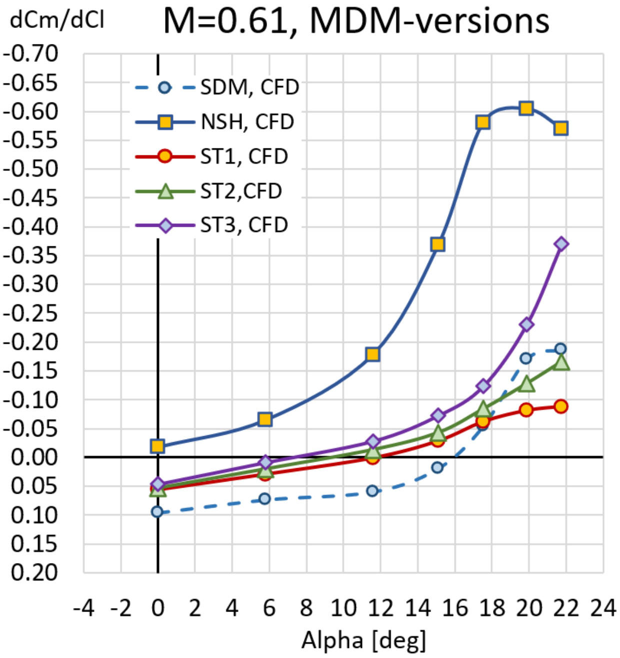

Figure 15. Longitudinal static stability of the SDM, compared to four MDM versions.

Adjusting their shape, size and position, wing strakes on contemporary jet fighters can be used to fine-tune the amount of the desired longitudinal static instability and thus provide enhanced longitudinal maneuverability (but with mandatory use of fly-by-wire controls). Equipped with ST1, ST2 and ST3 modifications, the inherently stable NSH version was converted to unstable at smaller and medium angles of attack. The largest destabilizing influence was achieved by ST1, up to Alpha = 12°, while ST2 and ST3 provided instability up to Alpha = 9° and 7.5° respectively (Fig. 15). So the elliptic strake form proved to be the most efficient „destabilizer“, with the same exposed area.

Another very important aspect is the trend of change of the derivative dCm/dCl with the angle of attack. From Fig. 15 it is obvious that the original SDM, as well as the MDM versions NSH and ST3 show sudden divergence of the longitudinal static stability after a certain angle of attack, from instability (or small stability) at small, to extremely large stability values at high angles of attack. In operational design work, this trend would be very unfavorable.

In that sense, the ST1 version is also the best, with almost linear increasing trend with small gradient. This version would enable, with reasonably small additional length and/or area enlargements, to shift almost the entire dCm/dCl curve in the domain of positive values, and generate unstable configuration in a wide angle of attack domain, with acceptable instability levels for operational use. With ST2, ST3 and the original SDM that would be a very difficult task, since their instabilities at small angles of attack could be unacceptably large.

6. CONCLUSION

This paper presents preliminary investigations of the aerodynamic influence of several characteristic wing strake configurations, implemented to the 3D geometry loft derived from the Standard Dynamic Model. Computational analyses, performed in this work using the commercial ANSYS Fluent software, were evaluated by comparisons with experimental results obtained during the T-38 wind tunnel SDM calibration tests at the Military Technical Institute in Belgrade. The initial modification of the longitudinally statically unstable original SDM model was obtained by removing its double wedge strakes. This gave the first MDM-NS version, which was still longitudinally unstable. In the next step, the horizontal tail was enlarged and shifted backwards, by which the MDM-NSH model was generated. It was longitudinally stable in the entire domain of analyzed angles of attack. This modification was used as the test bed for three wing strake types. The first MDM-ST1 was added with elliptic, the second MDM-ST2 with ogive, and the third MDM-ST3 with triangular strakes. All evaluations were based on the strake influence on global lift, drag and moment coefficients. The ST1 version generated the largest increase in lift coefficient Cl at higher angles at attack, but the same applied for the drag coefficient Cd. On the other hand, since the relative increase in Cl was greater than in Cd compared to the NSH, the elliptic ST1 strakes provided best improvements in Cd vs. Cl aerodynamic effectiveness. When used as longitudinal destabilizing surfaces for modern fly-by-wire combat plane applications, the ST1 version also gave results which appear to be the most suitable. These investigations will provide a starting point for future analyses of more complex strakes, including multi-segment configurations.

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