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Computational Fluid Dynamics and Wind Tunnel Determination of the Aerodynamic Characteristics of an Axi-Symmetric projectile with a Conical Tail Flare

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The evaluation of axial force was the main request during the design process of a training sub-caliber artillery projectile with a conical tail flare. To this end, a model of the projectile was tested in the T-38 trisonic blowdown wind tunnel of the Military Technical Institute (Vojnotehnički institut-VTI) at airspeeds up to Mach 4. The required test conditions and an unusual form of the model indicated the need to use the prototype of a new, very stiff wind tunnel balance with semiconductor strain gauges and also required a prediction of aerodynamic characteristics using FLUENT CFD software. The experimental and CFD results were compared after the tests, and a good agreement was found. Te flow field around the model was visualized during the tests using Schlieren method and corresponding numerical flow visualization images were also obtained by FLUENT

Key words: **projectile aerodynamics, artillery projectile, sub-caliber projectile, aerodynamic testing, aerodynamic load, axial force, fluid dynamics, wind tunnel.**

Introduction

A usual form of kinetic energy (KE) ammunition is a long, slender body with stabilizing fins. Training areas for firing KE ammunition are restricted in both range and lateral dispersion. In order to meet these requirements the fins section of a training KE ammunition projectile is replaced with a perforated cone. The functional range safety is obtained by the selection of the cone angle, the diameter and the number of the holes [1-3].

The effects of variations in the choice of the cone angle, the diameter and the number of holes on the conical flare on the aerodynamic characteristics of the training KE ammunition can be investigated by numerical aerodynamics. The FLUENT CFD software package widely used for calculating projectile aerodynamic coefficients is a suitable tool for this task.

The determination of the aerodynamic characteristics of a training KE projectile project design called for both a CFD calculation and an experimental verification in a wind tunnel test. After determining the correspondence between the computed and experimental results of an initial model configuration, CFD could be used for further optimizations of the projectile shape. Therefore, based on a selected aerodynamic configuration, a wind tunnel model was produced and tested, and CFD calculations were performed.

The model was tested at Mach numbers up to 4 in the T-38 trisonic blowdown wind tunnel in the VTI. As large transient aerodynamic loads and large axial force were expected in the wind tunnel test at high Mach numbers, the use of a very stiff six-component wind tunnel balance with a suitable load range and a large overload capability was indicated [4].

Because of a relatively unusual model configuration and the introduction of a new type of the wind tunnel balance, a prediction of aerodynamic loads was required in the test preparation, so the CFD computations were performed before the test.

The purpose of this paper is to analyze the slender body projectile with the perforated conical tail section based on both wind tunnel measurements and CFD calculations, since there is no data of the aerodynamic characteristics of a similar projectile in the available literature. Steady state calculations by FLUENT 6.2 software were used to compute the aerodynamic coefficients of the projectile. The results of CFD calculations are verified by comparing them to the wind tunnel measurements. The results for the axial force coefficient of the initial training projectile configuration are emphasized as its evaluation during the design process of the sub-caliber projectile had an extreme importance.

Sub-caliber projectile with the conical tail flare

The main characteristic of the conical tail flare of the sub-caliber arrow-shaped projectile is a resistance-stabilizing effect. The tail flare of the projectile has a larger exterior diameter than the projectile itself.

The perforated cone of the stabilizer is supposed to exhibit an increasing drag at speeds below a certain Mach number, thus performing the range-limiting function essential for a training artillery projectile.

Wind tunnel testing

Wind tunnel model

A wind tunnel model of the projectile was designed using CAD/CAM Unigraphics NX software, Fig.1. An

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appropriate model scale was selected with respect to the recommended values for the T-38 wind tunnel model size, expected loads and available wind tunnel balances. The model was produced in the workshop for models and prototypes of the VTI. The model mounted on the tail model support (sting) in the T-38 test section is shown in Fig.2.

Figure 1. CAD model of the projectile

Figure 2. Model of the projectile in the T-38 test section

The model of the projectile consists of a cylindrical body, a conical nose and a conical tail section with nine holes coaxial with the model body arranged around the cone. The model is axially-symmetric. The base diameter of the conical tail section is about 3.5 times the cross-sectional diameter of the columnar main body of the projectile and that is about 2.8 times the reference model diameter. The model was tested up to Mach number 4 in the angle of attack range of ±6° [5].

Wind tunnel facility

The T-38 test facility at the Military Technical Institute is a blow-down pressurized wind tunnel with a 1.5m x 1.5m square test section. For subsonic and supersonic tests, the test section is with solid walls, while for transonic tests, a section with porous walls is inserted in the wind tunnel configuration [6].

The Mach number in the range 0.2 to 4.0 can be achieved in the test section, with Reynolds numbers up to 110 million per meter. The Mach number is set and maintained to be within 0.5% of the nominal value by means of a flexile nozzle or sidewall flaps and/or sidewall blow-off, depending on the test speed range.

The stagnation pressure in the test section can be maintained between 1.1 bars and 15 bars, depending on the Mach number, and regulated to 0.3% of the nominal value. The run times are in the range 6s to 60s, depending on the Mach number and the stagnation pressure.

The model is supported in the test section by a tail sting mounted on a pitch-and-roll mechanism by which desired aerodynamic angles can be achieved. The facility supports both step-by-step model movement and continuous movement of a model (sweep) during measurements. The positioning accuracy is 0.05° both in pitch and roll.

Instrumentation, data recording and reduction

The stagnation pressure in the test section was measured by a Mensor absolute pressure transducer pneumatically connected to a pitot probe in the settling chamber of the wind tunnel. The static pressure in the test section was measured by a transducer of the same type (but lower range) pneumatically connected to an orifice on the test section sidewall. The nonlinearity and hysteresis of the transducers used were typically 0.02% F.S.

The stagnation temperature was measured by a RTD probe in the settling chamber. The accuracy of this transducer was approximately ±0.5K.

The pitching angle of the model support was measured by a resolver which is a part of the mechanism. The roll angle was measured by an absolute optical encoder into the drive unit. The overall accuracy of the measurements of the model position, including the calculation of the sting deflections under load, was about 0.05°.

The base pressure was measured by a Druck PDCR42 differential pressure transducer. The typical nonlinearity and hysteresis of the transducer used were 0.05% F.S.

The aerodynamic forces and moments acting on the model were measured by a VTI-produced internal, monoblock six-component strain gauge balance, type BV40 [7], Fig. 3. The accuracy of the balance was approximately 0.3% F.S. for the axial-force component and 0.2% F.S. for other components. This was a prototype of a very stiff wind tunnel balance of a simple construction with semiconductor strain gauges on the axial-load element, so that acceptably large signals could be produced on this component in spite of its high stiffness. The balance was basically a thick-walled cylindrical tube produced of Vascomax 350 steel. A special feature of the used balance, necessary for this particular test, was a large axial-force load range, and significant overload capability on other components, which was necessary in order for the balance to withstand the transient loads at the start of high Mach number wind tunnel tests.

Figure 3. BV40 balance mounted on the sting

The output of a precision digital clock was sampled synchronously with other channels, in order to serve as a time base for the segmentation of data.

The data acquisition system consisted of a Teledyne 64 channel “front end” controlled by a PC computer. The front-end channels for flow parameters transducers were set, with 10 Hz, fourth-order low pass Butterworth filters and appropriate amplification.

In order to minimize the differences in time lags on various channels during the model sweep, the channels for six balance components and the base pressure were set with a relatively high cut-off frequency, 30 Hz low pass filters. These signals were additionally filtered during the data reduction by a 3 Hz non-casual low pass digital filter.

The data from all analog channels was digitized by a 16-bit resolution A/D converter with the overall accuracy of the acquisition system being about 0.05% F.S. of the channel signal range. All channels were sampled with the same 400 samples/s rate.

The digitized data was sent through the network to a Compaq Alphaserver DS20E computer and stored on disk for later reduction.

The data reduction was performed after each run, using the T-38 standard software package. The processing was done in several stages, and each stage was performed by a different software module. The stages were as follows:

- Data acquisition system interfacing and signals normalization,
- Determination of flow parameters,
- Determination of model position (orientation),
- Determination of aerodynamic coefficients.

Flow field visualization

The test specification for the model included flow visualization by the Schlieren method, which is very convenient for visualization of high-speed airflows. The model size and position in the test section were such that it was completely visible in the viewfield of the Schlieren system, Fig.4 and 5.

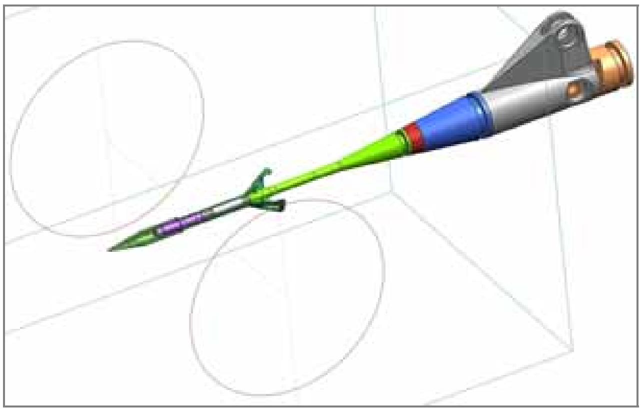

Figure 4. Model position relative to Schlieren windows

The Schlieren method is sensitive to changes of the gradient of density or the refractive index and it can record the angular deflection of the disturbed ray relative to the undisturbed one in a transparent medium with local inhomogenities.

A Schlieren system of Töepler type with parallel rays and a 900 mm light-beam diameter was used. A Phillips SPC-600 digital video camera with 640×480 pixels resolution at a recording rate of 10 frames/s was used to record the flow visualization [8]. The recording was automated and integrated in the wind tunnel data acquisition system.

Computational fluid dynamics

Available software packages for aerodynamic characteristics calculation, based on semi-empirical methods, could not be used for the sub-caliber projectile with the conical tail flare. The numerical calculation was done in the FLUENT package, as it allows calculation of the aerodynamic characteristics of complex aerodynamic shapes.

Figure 5. Large diagonal mirror in the T-38 Schlieren system

Numerical simulation

Because of the limited computer memory that prevented work with a large number of cells, the aerodynamic configuration of the projectile with conical tail section was simplified. The grooves on the part of the body where the sabot is fixed were omitted and replaced by a cylindrical section. The diameter of the cylinder was equal to the maximum diameter of the body. Based on the model dimensions, given in Fig. 6, a solid model of the projectile was generated by the GAMBIT software package.

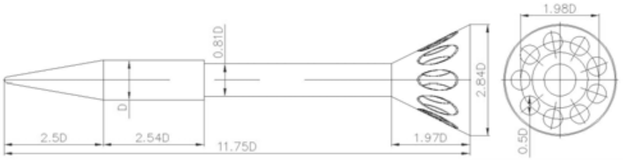

Figure 6. Non-dimensional aerodynamic configuration of the projectile

The computational domain was obtained by subtracting the solid model of the projectile from the solid model of an ellipsoid. The major semi-axis of the ellipsoid was 3 lengths of the projectile body and the small semi-axis was 11 body diameters. The unstructured mesh composed of tetrahedral elements was generated in the computational domain. The total number of the cells was about 2 million. This density of the mesh was selected with respect to available computer memory and convergence of the calculated aerodynamic coefficients and residuals.

The cross section of the mesh in the computational domain is given in Fig. 7. A higher density of the mesh was required in the region of the conical tail flare, Fig.8.

Numerical calculation

The calculation of the aerodynamic coefficients was done by the FLUENT 6.2 software package. The viscous computational fluid dynamic simulations were used to calculate the flowfield around the projectile model in subsonic, transonic and supersonic flows. The computations were performed for Mach numbers ranging from 0.5 to 4.0 at and the angle of attack from –6º to 6º.

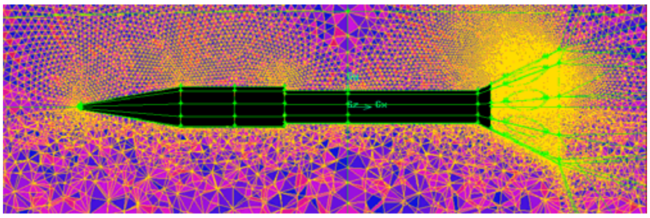

Figure 7. Cross section of the mesh in the body vicinity

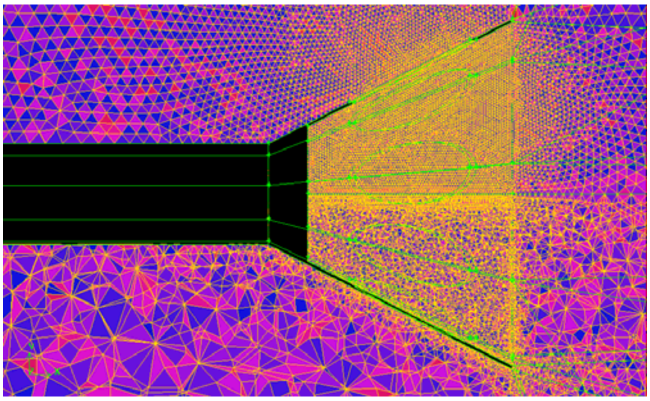

Figure 8. Mesh in the region of the conical tail flare

A personal computer with quad-core 3.2 GHz ADM Phenom II X4 955 Processor and 4 GB RAM memory was used for viscous computational fluid dynamics simulations. The calculations last about 32–35 s of CPU time per iteration and convergence was achieved in about 2000–2500 iterations, depending on the Mach number and the angle of attack.

The 3D coupled explicit solver with the Spalart-Allmaras viscous model was used for the numerical calculation of the flow in the computational domain. The boundary conditions of the outer domain are defined as pressure far field with sea-level temperature (300 K) and free stream pressure (101325 Pa). All surfaces of the CFD projectile model were defined as a stationary wall. The convergence of the numerical calculation of the flow around the body was determined by tracking the change of the residuals and aerodynamic coefficients. The numerical calculation of the aerodynamic coefficients was stopped when the aerodynamic coefficients were changed less than 1% through 50 previous iterations.

The aerodynamic coefficients were obtained as a result of the numerical calculation of the flow in the control domain. The model reference length and the reference area for the aerodynamic coefficients was the diameter (0.044 m) and the cross section (0.00152053 m^2) of the projectile body.

Results and discussion

Aerodynamic coefficients

The experimentally obtained aerodynamic coefficients were fitted as polynomials of the second or third degree order to be compared with those numerically calculated ones [9]. The experimental results of the axial force coefficient are given in the graph in Fig. 9.

The experimentally and numerically obtained results of the axial force, normal force and pitching moment coefficients on Mach numbers 2 and 4 were compared, and the comparisons of the coefficients as a function of the model angle of attack are given in graphs in Figs. 10-13 [10].

The graph of the experimentally and numerically obtained axial force coefficients (at the zero angle of attack) as a function of the Mach number is given in the graph in Fig.14.

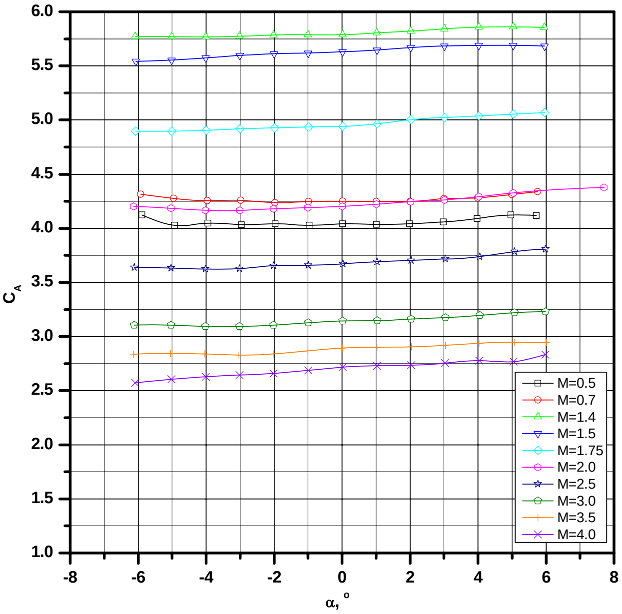

Figure 9. Axial force coefficient ─ T-38 experimental results

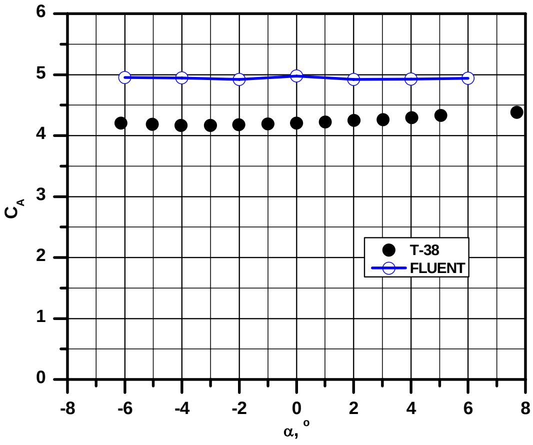

Figure 10. Axial force coefficient ─ Experiment and CFD, Mach 2

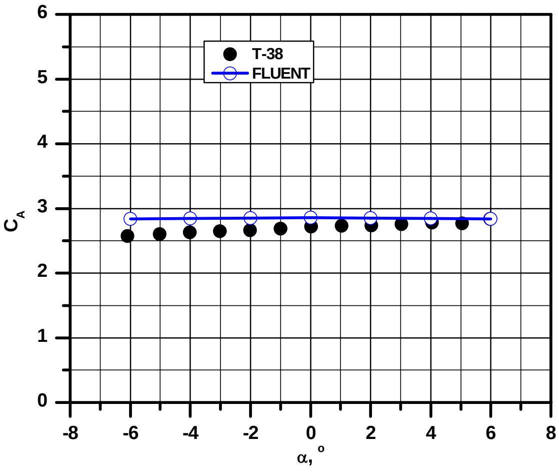

Figure 11. Axial force coefficient ─ Experiment and CFD, Mach 4

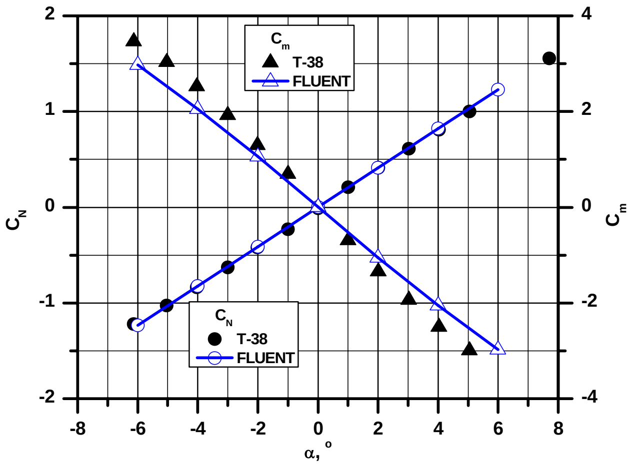

Figure 12. Normal force and pitching moment coefficients ─ Experiment and CFD, Mach 2

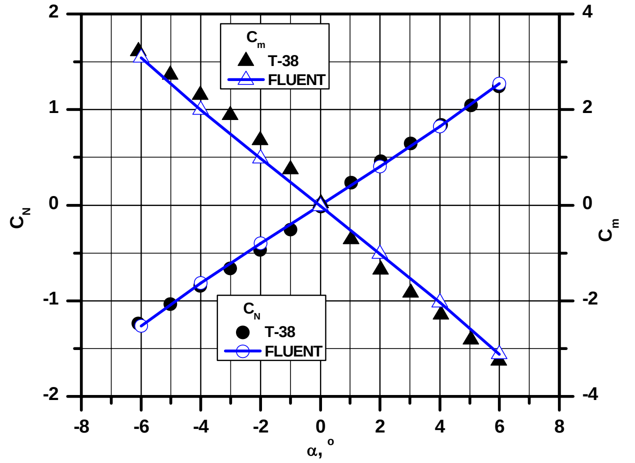

Figure 13. Normal force and pitching moment coefficients ─ Experiment and CFD, Mach 4

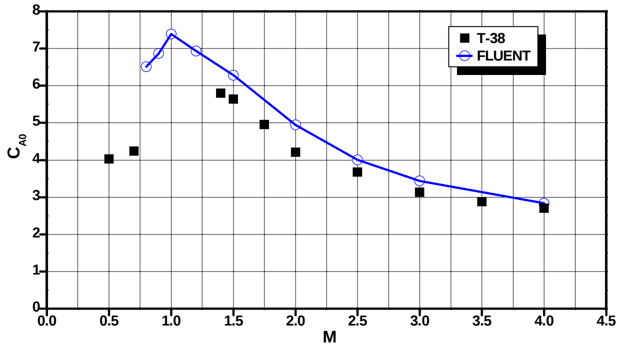

Figure 14. Axial force coefficient, zero angle of attack – Experiment and CFD

The analysis of the aerodynamic coefficients for Mach numbers 2 and 4 showed that better agreements between the calculated and the measured aerodynamic coefficients were obtained at Mach 4 than at Mach 2. The difference between the calculated and the measured axial force coefficients is within 17% at Mach 2 and 5% at Mach 4 (Fig.10 and Fig.11). Practically, there is no difference between the calculated and the measured normal force coefficients (Fig.12 and Fig.13). The comparisons of the calculated and measured pitching moment coefficients (Fig.12 and Fig.13) show better agreement at Mach 4 than at Mach 2 [10].

On the basis of the graph of the axial force coefficients at zero angle of attack as a function of the Mach number (Fig.14), it can be seen that there is better agreement between the calculated and the measured axial force coefficients in the supersonic than in the subsonic region of Mach numbers. With the increase of Mach number values, the difference between the calculated and the measured axial force coefficients at zero angle of attack is decreasing.

Flow field visualization

The photos of the air density distribution in the control domain, obtained from FLUENT and given in Figs.16 and 18, can be compared with the Schlieren-recorded photos of the flow field in the T-38 test section for Mach numbers 2 and 4, given in Figs.15 and 17. It is evident that the computed and the Schlieren-recorded flow fields are very similar.

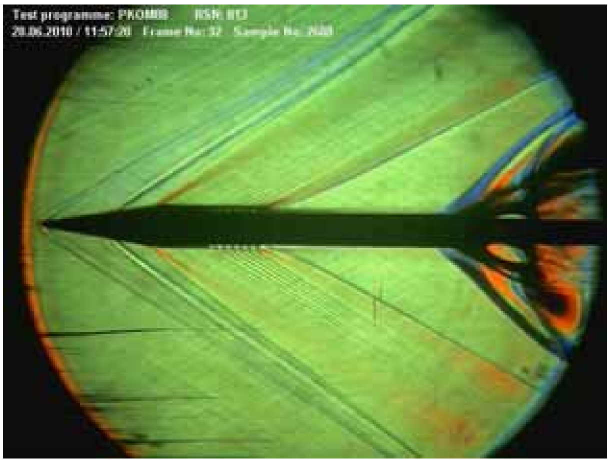

Figure 15. Schlieren-recorded flow field, Mach 2

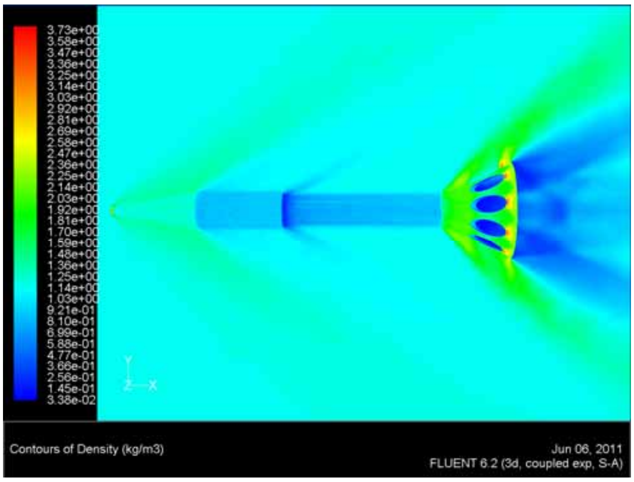

Figure 16. Computed visualization, Mach 2

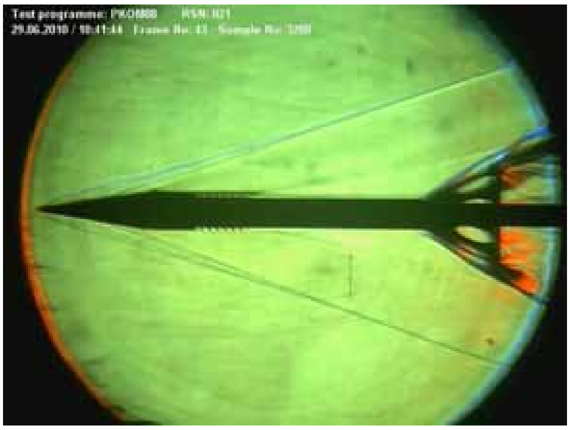

Figure 17. Schlieren-recorded flow field, Mach 4

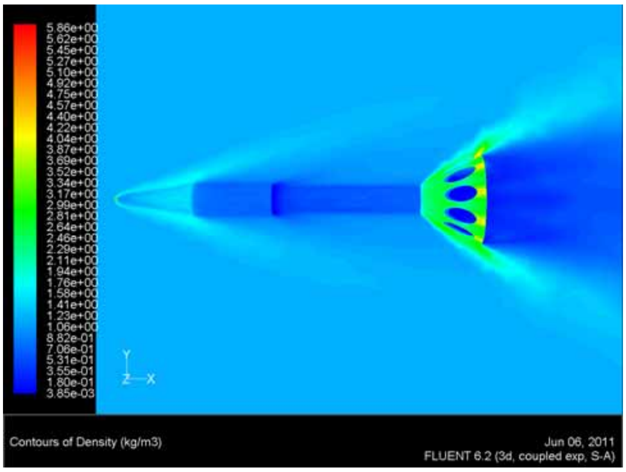

Figure 18. Computed visualization, Mach 4

When comparing the computed and experimentally obtained visualizations, one should have in mind that, while computed images display density distribution, the Schlieren method records density gradients, and also that it integrates the results over the depth of the field of view.

Conclusion

The numerical calculations of the aerodynamic characteristics of the sub-caliber projectile, performed using the CFD methods prior to the wind tunnel test campaign, were necessary in order to estimate expected loads on the wind tunnel model. A specially designed six-component balance showed to be suitable for the experiment and behaved as predicted.

The experimentally and numerically obtained results of the axial force and other aerodynamic coefficients were compared and the good agreement was found, so that the designers of the sub-caliber projectile had correct guidelines.

The difference between the calculated and the measured axial force coefficients are within 5% at Mach 4 and 17% at Mach 2. Practically, there is no difference between the calculated and the measured normal force coefficients. The comparisons of the calculated and the measured pitching moment coefficients show better agreement at Mach 4 than at Mach 2.

The accuracy of the numerical simulation was somewhat impaired by limited computational resources, which necessitated the use of a coarse mesh.

Having obtained an agreement between experimental and numerical results on the initial model configuration, numerical methods can be used in further development of the project.

In the current environment of limited time available for wind tunnel tests, it is important to have both pre-test predictions of aerodynamic characteristics, and test-verified computational codes. This kind of interaction between wind tunnel experiments and computational fluid dynamics is necessary and permanently performed.

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Proračunsko i aerotunelsko određivanje aerodinamičkih karakteristika aksijalno-simetričnog projektila sa koničnim zadnjim delom

Procena aerodinamičkog aksijalnog opterećanja je bila glavni zahtev tokom projektovanja vežbovnog artiljerijskog potkalibarnog projektila sa koničnim zadnjim delom. Sa ovim ciljem, model projektila je ispitan u trisoničnom aerotunelu T-38 Vojnotehničkog instituta (VTI) do Mahovog broja 4. Zahtevani uslovi ispitivanja i neobičan oblik modela su indicirali upotrebu prototipa nove veoma krute aerovage sa poluprovodničkim mernim trakama i prethodnu procenu očekivanih aerodinamičkih opterećenja softverskim paketom FLUENT za proračunsku dinamiku fluida. Po završenom ispitivanju, izvršeno je upoređenje rezultata iz eksperimenta i proračuna, i dobijeno je dobro slaganje. Strujanje oko aerotunelskog modela je u testovima vizualizirano šliren metodom, a dobijene su i odgovarajuće slike numeričke vizualizacije strujanja pomoću FLUENT-a.

Ključne reči: **aerodinamika projektila, artiljerijski projektil, potkalibarni projektil, aerodinamičko ispitivanje, aerodinamičko opterećenje, aksijalna sila, dinamika fluida, aerodinamički tunel.**

Расчётное определение и определение в аэродинамической трубе аэродинамических характеристик осесиметричных снарядов с коническим хвостом

Оценка аэродинамической осевой нагрузки была одним из основных требований для разработки учебного артиллерийского подкалиберного снаряда с коническим хвостом. Для этого модель снаряда была протестирована в трёхзвуковой аэродинамической трубе Т-38 в белградском Военно-техническом институте (ВТИ) с числом 4 Маха. Необходимые условия исследований и необычной формы модели указывают на использование прототипа новых жёстких аэродинамических весов с полупроводниковыми тензодатчиками и на предыдущую оценку ожидаемых аэродинамических нагрузок программным пакетом FLUENT для обеспечения вычислительной динамики жидкостей. По окончании исследований, проведено сравнение результатов экспериментов и расчётов и в том числе также получено хорошее согласие. Поток вокруг испытанной туннелей модели визуализировано теневым методом, а получены и соответствующие изображения численной визуализации потока с использованием программного пакета FLUENT.

Ключевые слова: **аэродинамика снарядов, артиллерийский снаряд, подкалиберный снаряд, аэродинамическое испытание, аэродинамическая нагрузка, осевая нагрузка, динамика жидкостей, аэродинамическая труба.**

Détermination expérimentale et numérique des caractéristiques aérodynamiques chez le projectile axiale symétrique à la queue conique

L'évaluation de la force axiale aérodynamique était l'exigence principale dans la conception du projectile d'artillerie à calibre réduit à la queue conique et qui est destiné pour l'entraînement. Dans ce but le modèle du projectile a été testé dans la soufflerie aérienne T-38 à l'Institut militaire technique (VTI, Belgrade) jusqu'à Mach 4. Les conditions exigées pendant les recherches et la forme insolite du modèle ont indiqué l'emploi du prototype de nouvelle balance de soufflerie, très rigide, avec les jauges à ruban semi-conducteurs et une estimation préalable des caractéristiques aérodynamiques en utilisant le progiciel FLUENT pour évaluer la dynamique des fluides. Après les tests on a fait la comparaison des résultats des essais et des calculs et on a constaté bon accord. Le courant autour du modèle aérodynamique était visualisé pendant les essais au moyen de la méthode Schlieren et on a obtenu aussi les images correspondantes de la visualisation numérique du courant par le progiciel FLUENT.

Mots clés: **aérodynamique du projectile, projectile d'artillerie, projectile à calibre réduit, essai aérodynamique, charge aérodynamique, force axiale, dynamique des fluides, soufflerie aérodynamique.**