UDK: 621.43.056:620.171.5
COSATI: 01-01, 14-02

Analysis of Bow Shock Waves from a Hemisphere-Cone Nose at Mach Numbers from 1.5 to 4 in the T-38 Wind Tunnel of VTI

Aleksandar Vitić[1)]
Dijana Damljanović[1)]
Đorđe Vuković[1)]

A simple standard model was used for the calibration of the supersonic test section in the T-38 wind tunnel at Mach numbers from 1.5 to 4. The model body was cylindrical, with a hemispherical nose cone. Besides aerodynamic forces and moments measurements, a schlieren flow visualization of the flow around the model was performed. The shape and position of bow waves originating from the model nose was analyzed. The results can be used as a supplement to the existing graphs with shock waves from conical and hemispherical noses that are useful for determining allowable model lengths in supersonic tests with respect to shock waves reflected from test section walls.

Key words: **aerodynamic testing, wind tunnel model, shock wave, flow visualization, Schlieren system, wind tunnel.**

Introduction

SOME of nose shapes of rocket and missile models tested in wind tunnels are a cone, a hemisphere and a combination of the first two: hemisphere-cone. The shape and position of shock waves generated by a model in supersonic wind tunnel tests at particular Mach numbers depend to a large extent on the shape of the nose. On the other hand, the length of a model in a supersonic wind tunnel is limited by the reflections of shock waves from the wind tunnel walls (see Fig.1) [1], as the shock waves reflected from the test section walls must not hit or pass near the rear part of the model. The allowable proximity of the reflected shock to the base of the model depends to a large extent on the model configuration. If the reflected shock passes the model base at a distance of about 1.5 diameters, the only effect will be on the wake behind the model. If the model is equipped with tail fins, the model length would be specified from the consideration of proximity of the reflected shock to the fins.

Application of an exact computational procedure for determining an allowable model length is usually impractical. However, by making a few approximations, reasonable estimations of the allowed model length can be made. The problem is set up as illustrated in Fig. 1, which also gives an estimate of the allowable model length for various model slenderness ratios and model/test-section size ratios. The bow shocks waves are assumed to be reflected from a plane located at a distance equal to the boundary layer displacement thickness inside the wind tunnel walls. Also, it is assumed that the angle of the shock wave reflected from the wall will be identical to that of the incoming shock wave, which is not strictly true. Moreover, the problem becomes more complicated when the model is at a nonzero angle of attack. In such a case, the shape of the bow shock wave cannot be readily determined before the test except by resorting to CFD methods which can be costly and time-consuming (although it may not remain so in the near future, with the rapid increase in availability of powerful computational resources). The assumption that this angle is similar to the shock wave angle on a cone at zero angle attack is reasonable, particularly at moderate angles of attack [2].

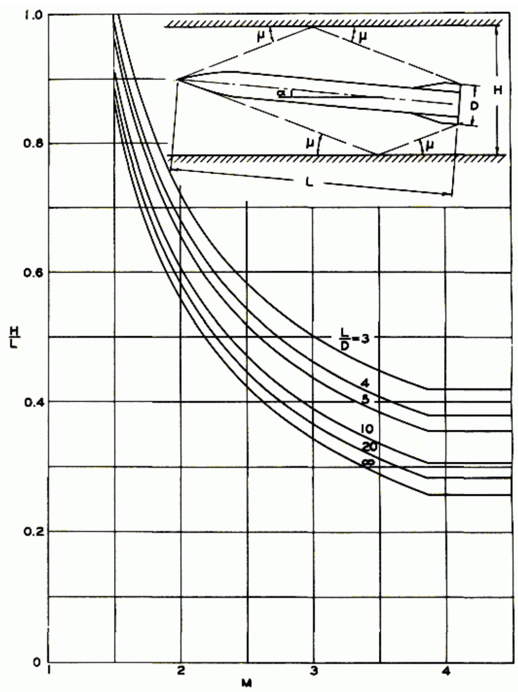


Figure 1. Maximum ratio of the model length and the span of the fins as a function of the free stream Mach number (L=model length, D=maximum model diameter, μ=shock wave angle, H=test section height), [3]

1) Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

It is obvious that the maximum model length, for the condition of no wall interference, depends on the model size relative to the wind tunnel test section. Besides the model length, the important parameters necessary to make an estimate of the allowed length are the span and the location of the wings or fins on the model and the shape of the nose, the last parameter determining the position and the shape of the bow shock wave originating at the model.

There are graphs available [3], Fig.2, in which the positions of the bow shock waves are plotted for the hemispherical and conical nose shapes at a range of Mach numbers and several angles of attack. This paper supplements the graphs [3] which exist only for hemispherical and conical noses, with data for an intermediate hemisphere-cone shape. The data may be of use for quick estimates of the position of bow shock waves generated by a wind tunnel model, and therefore, for the estimates of a permitted model length when supersonic wind tunnel tests are prepared.

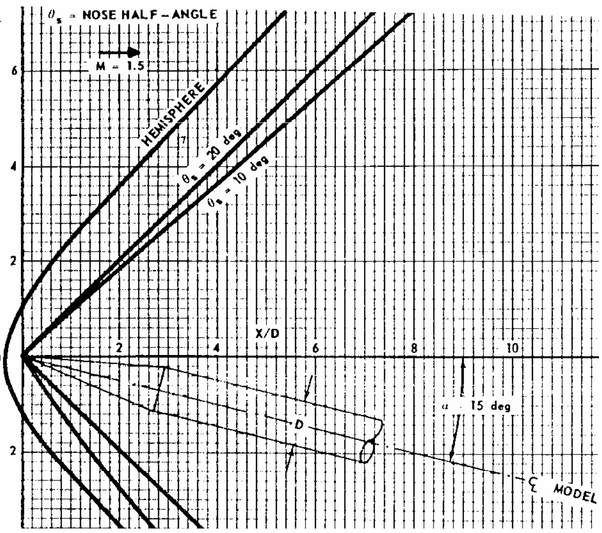


Figure 2. An example of a graph [3] showing the shape and position of the bow shock waves for hemispherical and two conical noses at Mach number 1.5 and 15 angle of attack (D=model diameter, θs=nose half-angle, α=model angle of attack, M=Mach number)

Description of the wind tunnel model

The data on bow shock waves presented in this paper were obtained from routine schlieren recordings performed for logging purposes in wind tunnel tests of a standard model tested in the T-38 wind tunnel [4] of the Military Technical Institute, Beograd (VTI). The configuration of the model was an axisymmetric, blunted-cone-cylinder, [5]. The geometry of this shape is given in detail in Fig.3. The base diameter D was 75 mm. The model was supported by a tail sting support with a diameter of 48 mm. The purpose of the model was to be used as a standard model for verification of the quality of measurements in the supersonic speed range of the T-38 wind tunnel, [6-10].

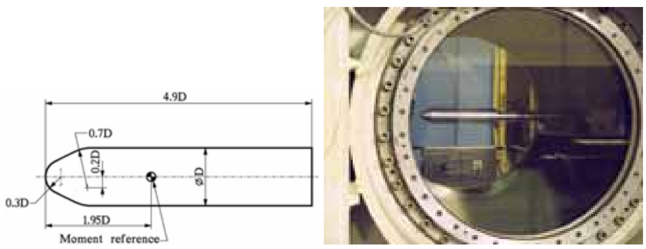


Figure 3. The blunted-cone-cylinder model

The T-38 wind tunnel test facility and the schlieren system

The T-38 test facility is a blowdown-type pressurized wind tunnel with a 1.5m × 1.5m square test section. For supersonic tests, the test section is with solid walls. Mach numbers are set by a flexible nozzle.

The schlieren [11] system for the T-38 wind tunnel is a modified Toepler parallel beam folded "Z" schlieren system. It has a focal ratio f/8 and the general layout of the system is shown in Fig.4. The system can be used with the supersonic test section, for the Mach number range from 1.4 to 4, and with the transonic test section for the Mach number range from 0.7 to 1.4.

The Toepler schlieren system is widely used for investigating high-speed air flow. Its principle is based on refraction of light rays through flow regions of varying density. If a parallel beam of light passes through the air in which there is a density gradient normal to the direction of the beam, the light travels more slowly where the density is grater and hence the beam is reflected towards the region of greater density. The schlieren test is perhaps one of the simplest of the methods in common use today. Schlieren techniques have been used for many years to study the distribution of density gradients within a transparent medium. The schlieren technique is highly sensitive. Its principal limitations are related to dimensions of optical elements.

The light source assembly is housed in a cabinet which is fixed on the floor of the wind tunnel hall (see Fig.5-a). There is a window on the top of the cabinet for leting the light beam pass. The continuous light source is a high pressure 150 W Xenon lamp. The source also comprises a condenser lens system and a beam-shaping slit.

The collimating mirror (first concave mirror) gives a clear aperture parallel beam of 900 mm diameter. The focal length is 7200 mm. It is supported in a rigid mirror cell system capable of accurate vertical and horizontal adjustment. The mirror surface of this and all other mirrors is a vacuum-deposited aluminum film.

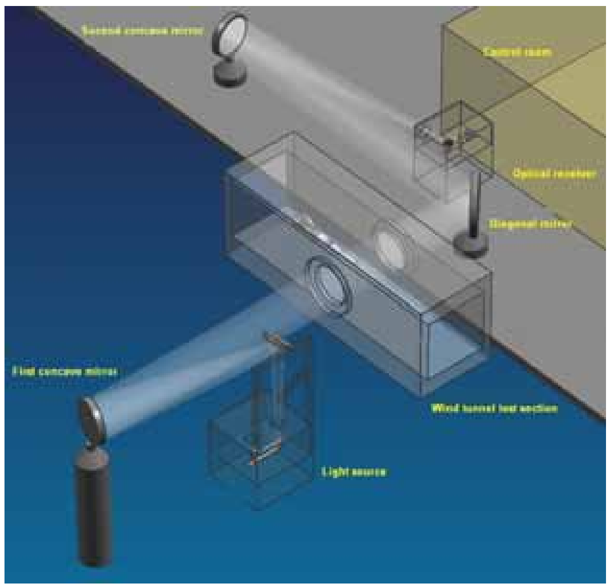
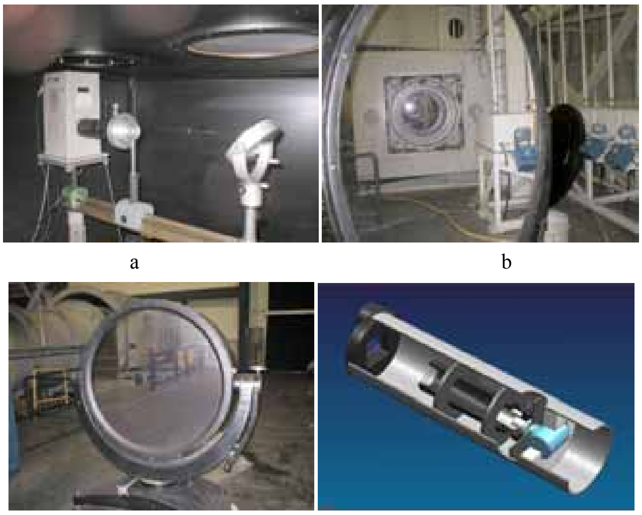


Figure 4. The Schlieren system of the T-38 wind tunnel

The diagonal mirror is a plane one placed at 45º to the centerline of the wind tunnel, and folds the light path within the available space, giving a clear aperture parallel beam of 900 mm diameter (Fig.5-b). This mirror, too, is housed in a fully adjustable rigid cell.



a b c d

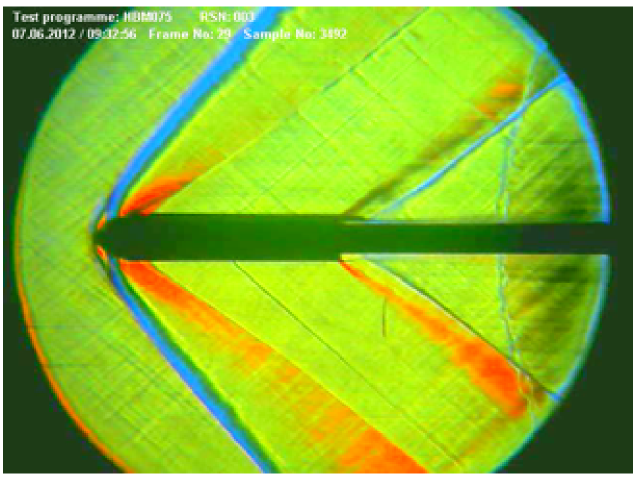
Figure 5. Parts of the T-38 Schlieren system: a – light source, b – diagonal mirror, c – second convave mirror (image forming mirror), d – optical receiver (shown as a CAD model in order to display it in a cross-section)

The image forming mirror (second concave mirror, Fig.5-c) is identical to the collimating mirror and it focuses the incident beam into the optical receiver assembly.

In the optical receiver assembly there are a three-colour filter serving as a knife edge, a telescope, and a Phillips SPC-600NC CMOS camera (Fig.5-d). The camera was selected for fair resolution, good low-light characteristics and acceptable image quality at low cost. The camera is connected to a Personal computer via a USB cable, with two USB repeaters inserted in the circuit in order to bridge the cca 15 m distance between the receiver and the controlling computer.

Test results

The bow shock waves from the hemisphere-cone nose of the tested model are shown in Fig.6 to Fig.11 for a model at zero angle of attack. In order to obtain better sharpness, the colour schlieren photos were transformed to contour plots that were thereafter digitized. The digitized positions of the shock waves were plotted in graphs together with corresponding data for the hemispherical and conical noses from [3]. The bow shock waves are shown for five Mach numbers in the range from Mach 1.5 to Mach 4. Zero of the coordinate axis is fixed at the nose of the model. The „X" axis goes through the centerline of the model. The "Y" axis is a normal on the „X" axis. The span between the top of the model and the ceiling or the floor of the T-38 test section is 750 mm.



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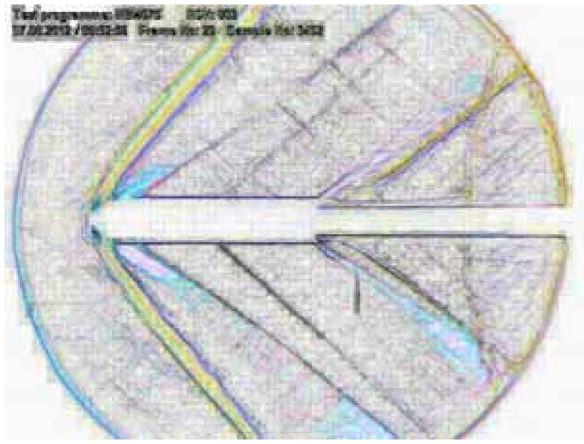

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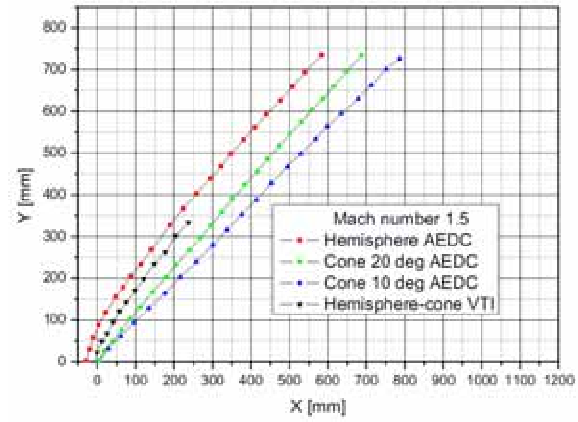
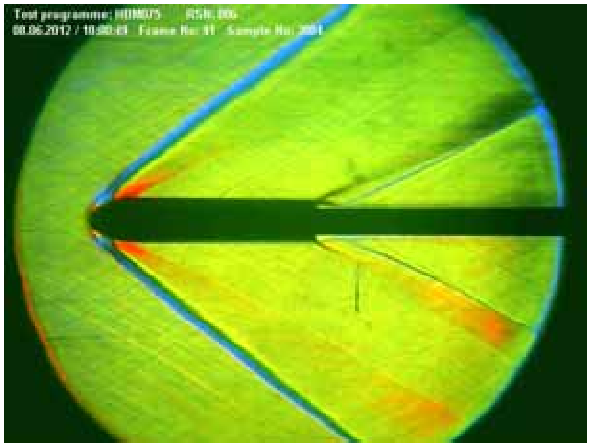


c

Figure 6. a – schlieren photo, b – contour plots and c – positions of bow shock waves at Mach number M=1.5 for hemisphere (source [3]), cone (source [3]) and hemisphere-cone nose (VTI source)



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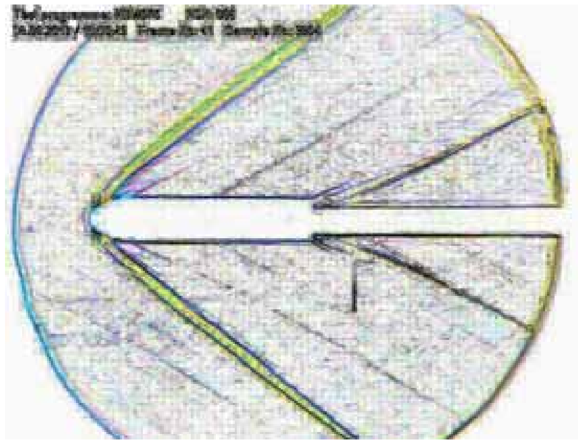

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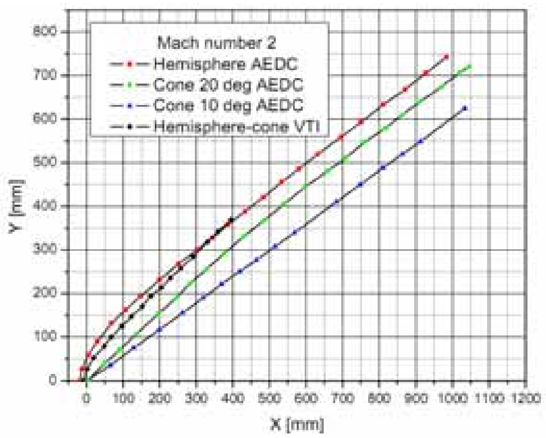

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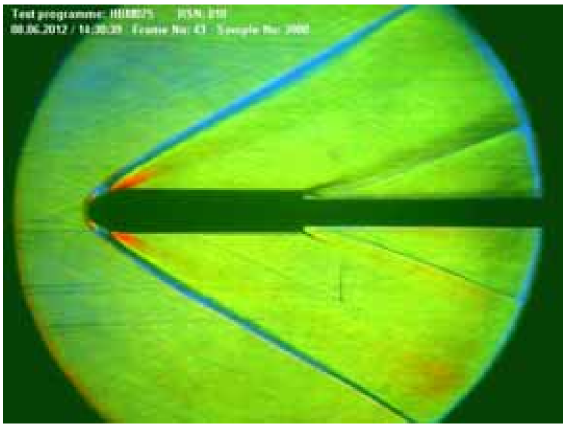
Figure 7. a – schlieren photo, b – contour plots and c – positions of bow shock waves at Mach number M=2.0 for hemisphere (source [3]), cone (source [3]) and hemisphere-cone nose (VTI source)



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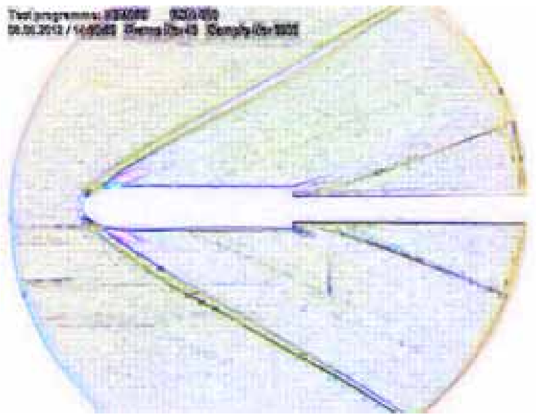

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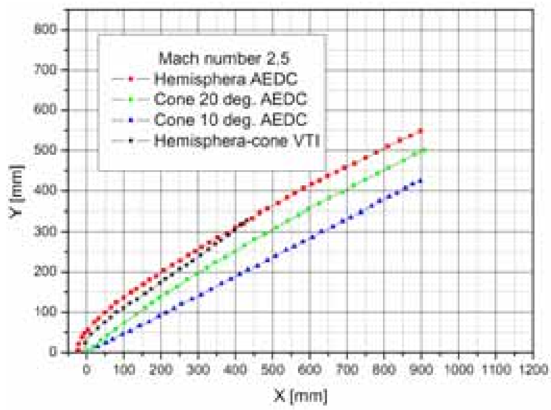

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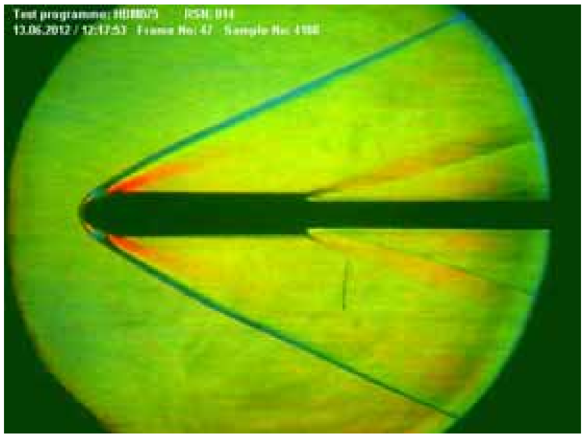
Figure 8. a – schlieren photo, b – contour plots and c – positions of bow shock waves at Mach number M=2.5 for hemisphere (source [3]), cone (source [3]) and hemisphere-cone nose (VTI source)



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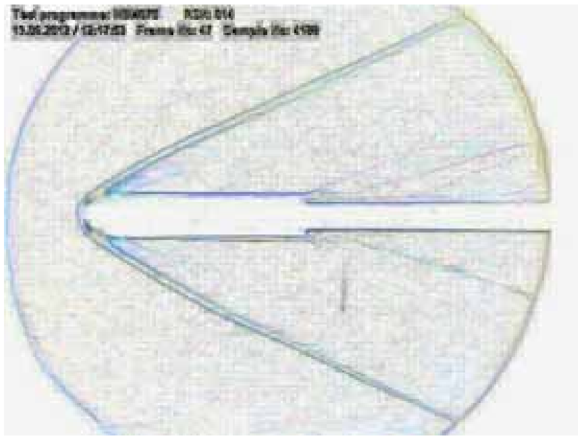

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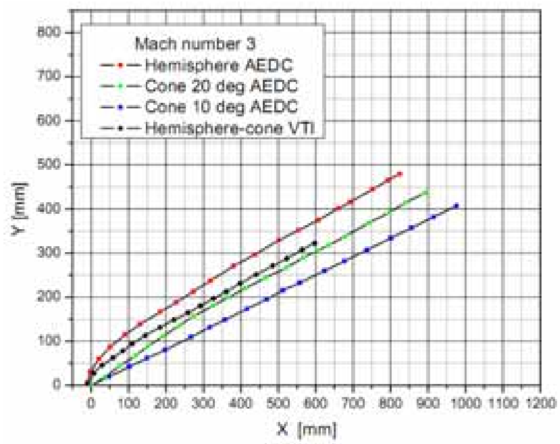

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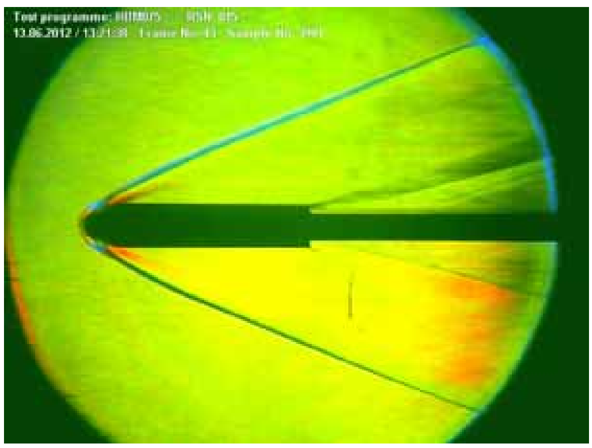
Figure 9. a – schlieren photo, b – contour plots and c – positions of bow shock waves at Mach number M=3.0 for hemisphere (source [3]), cone (source [3]) and hemisphere-cone nose (VTI source)



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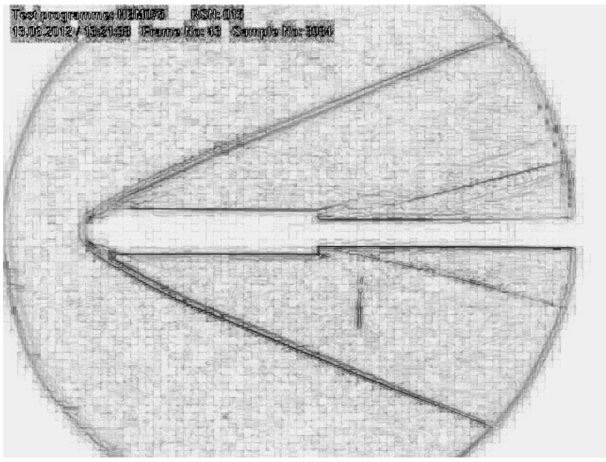

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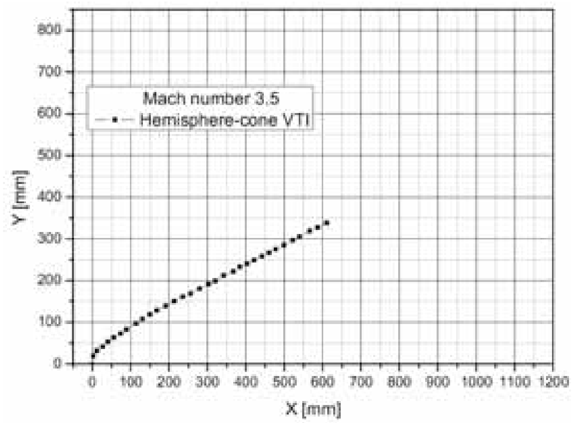

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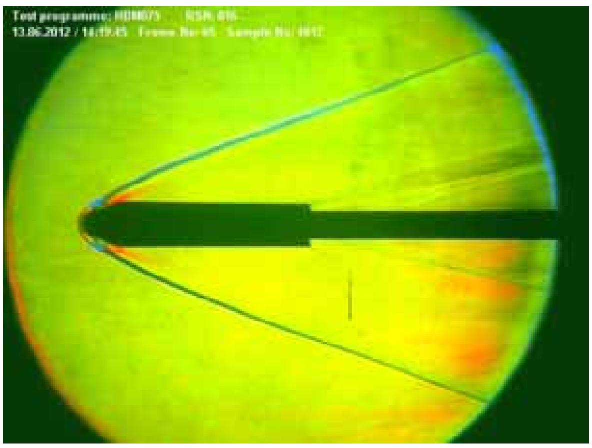
Figure 10. a – schlieren photo, b – contour plots and c – positions of bow shock waves at Mach number M=3.5 for hemisphere-cone nose (VTI source)



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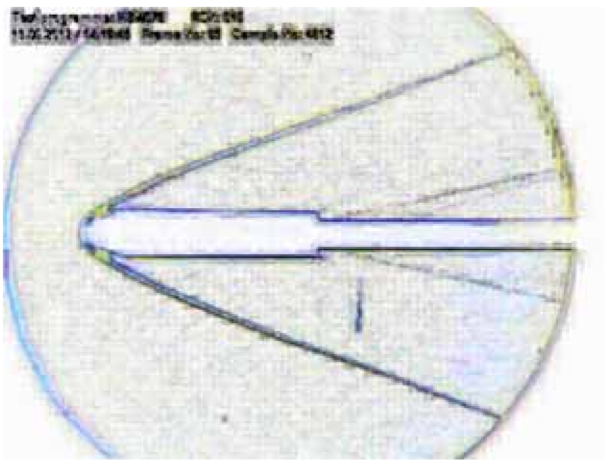

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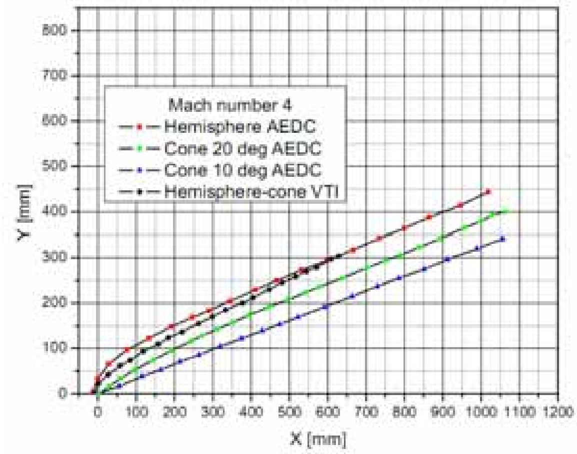

c

Figure 11. a – schlieren photo, b – contour plots and c – positions of bow shock waves at Mach number M=4.0 for hemisphere (source [3]), cone (source [3]) and hemisphere-cone nose (VTI source)

In order to use the obtained graphs for the estimation of the allowed model length, one has to ”reflect” the shock wave plots from a line at the Y-position equal to the half height of the wind tunnel (minus the estimated displacement thickness of the boundary layer), and check for an intersection of the reflection with the rear part of the model. Admittedly, this can only give approximate results (more so as the data were obtained from images not corrected for a slight receiver-lens-caused distortion), but the data are considered to be sufficient for a preliminary estimation when planning new wind tunnel tests.

Conclusion

A simple standard model with the hemisphere-cone nose was used for the calibration and verification of the supersonic test section of the T-38 wind tunnel. Using the schlieren photos taken for test-logging purposes at different Mach numbers and at zero angle of attack, bow shock waves have been analyzed and plotted against the existing similar graphs from the AEDC test center. As expected, the bow shock waves from the hemisphere-cone nose pass between the bow shock waves from the hemisphere and the bow shock waves from the blunt cone, and, as the distance from the model increases, all bow waves tend to become parallel with the angle equal to the Mach angle. The graphs with added data from the T-38 wind tunnel can be used for a quick estimation of the position of the bow shocks and, by reflecting the waves from the lines at the location of the test section floor and the ceiling, they can be used to estimate the allowed lengths of the model at various Mach numbers, which is useful information for planning future tests. Although similar results could have been obtained using CFD, the graphs were obtained from the existing data at no additional cost and without burdening the meager CFD computational resources of the VTI.

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Received: 23.06.2013.

Analiza lučnih udarnih talasa od vrha polulopta-konus za opseg Mahovih brojeva od 1.5 do 4 u aerotunelu T-38 VTI-a

Jednostavan standardni model je upotrebljen za kalibraciju supersoničnog radnog dela aerotunela T-38. Telo modela je cilindrično sa konusno – poluloptastim nosem. Model je ispitan u opsegu Mahovih brojeva od 1.5 do 4.0. Osim merenja aerodinamičkih sila i momenata, izvršena je i vizualizacija strujanja oko modela Šliren sistemom. Analizirani su lučni udarni talasi generisani na vrhu modela. Rezultati mogu biti upotrebljeni kao dodatak dijagramima iz AEDC (Arnold Engineering Development Center) sa udarnim talasima generisanim na poluloptastim i konusnim nosevima, koji su korisni za procenu dozvoljene dužine modela u radnom delu s obzirom na udarne talase odbijene od zidova radnog dela

Ključne reči: **aerodinamičko ispitivanje, aerodinamički model, udarni talas, vizualizacija strujanja, Šliren sistem, aerodinamički tunel.**

Анализ арочных ударных волн от верхней части полушарие-конуса для диапазона чисел Маха от 1,5 до 4 в аэродинамической трубе Т-38 ВТИ

Простая стандартная модель здесь использована для калибровки сверхзвуковой тестовой части аэродинамической трубы Т-38. Тело модели имеет цилиндрическую форму с коническо - полусферическим носом. Модель была протестирована в диапазоне чисел Маха от 1,5 до 4,0. В дополнение к измерению аэродинамических сил и моментов, также проведена и визуализация обтекания около модели системой Schlieren. Тоже анализированы арочные ударные волны, генерируемые в верхней части модели. Полученные результаты могут быть использованы в качестве дополнения к диаграммам AEDC (Arnold Engineering Development Center) с ударными волнами, генерируемыми в полусферических и конических носах, которые являются полезными для оценки допустимой длины модели в тестовом разделе по отношению к ударным волнам отвергнутым от стен рабочей части.

Ключевые слова: **аэродинамическое испытаний, аэродинамическая модель, ударная волна, визуализация потока, система Schlieren, аэродинамическая труба.**

Analyse des ondes de chocs latéraux du sommet hémisphère – cône pour les nombres de Mach de 1.5 à 4 dans la soufflerie T-38 de VTI

Un simple modèle standard a été utilisé pour le calibrage de la section de travail supersonique de la soufflerie T-38. Le corps du modèle est cylindrique avec le nez conique en forme de hémisphère. Ce modèle a été examiné pour les nombres de Mach de 1.5 à 4. Outre les mesurages des forces aérodynamiques et des moments on a effectué aussi la visualisation du courant autour du modèle à l'aide du système de Schlieren. On a analysé les chocs arqués produits au sommet du modèle. Les résultats obtenus peuvent s'utiliser en tant que le supplément aux diagrammes de AEDC (Arnold Engineering Developpement Center) avec les ondes de chocs produits sur les nez coniques et hémisphériques qui sont utiles pour l'estimation de la longueur permise du modèle dans la section de travail quant aux ondes de chocs reflétées sur les parois de cette section.

Mots clés: **essai aérodynamique, modèle aérodynamique, onde de choc, visualisation de courant, système Šliren, soufflerie.**