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# Mach number determination of hypersonic flow with a new schlieren system

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**The possibilities of undisturbed flow Mach number determination, in the T-34 hypersonic wind tunnel, using a shape shock wave about a test model are analyzed. The used analytical method, concerns Billig's empirical equation. The visualization of shock waves is given using the schlieren method. A new schlieren system, Toepler type is designed and made in the VTI. The new schlieren system is used for flow field visualization and the Mach number is determined in the test section of the hypersonic wind tunnel. It is proved that the Mach number of an undisturbed flow is M=7.**

*Key words:* **hypersonic flow, hypersonic wind tunnel, shock waves, flow visualization, schlieren method.**

## Symbols in the text

M – Mach number in the wind tunnel test section
$P$ – static pressure in the wind tunnel test section, bar
$V$ – speed of the air in the wind tunnel test section, m/s
$T$ – static temperature in the wind tunnel test section
MRe – Reynolds number in the wind tunnel test section, 1/m
$q$ – dynamic pressure in the wind tunnel test section, bar
$\alpha$ – angle of attack, °
$\rho_o$ – density of the air in the test section of the wind tunnel, kg/m$^3$
$n$ – index of light refraction
$\varepsilon$ – beam deflection, °
$S$ – sensitivity of the schlieren system
$a$ – central part of the color filter or the width of the slit image in the knife edge plane, m
$f$ – focal length of the mirror, m
$\lambda$ – wave length of light, m
$d$ – effective section of molecule, m
Na – Avogadro's number
$R^*$ – universal gas constant
$L$ – length of the calibration model, m
$R$ – half radius on the model top, m
$Rc$ – half radius of the shock wave arc and the point of the hyperbola, m
$\delta$ – distance of the shock wave from the model top surface m
$x,y$ – coordinates in the axes system, m
$\beta$ – angle of the shock wave at infinite distance from the model top, the Mach wave angle, °

### Index

$o$ – total parameters
$s$ – static parameters values in the undisturbed flow
1 – values in front of the shock wave
2 – values behind the shock wave
$\infty$ – nonperturbate values

## Introduction

THE air flow with a Mach number M>5 is called hypersonic flow [1-6]. Such flow could be realized in hypersonic wind tunnels. Basic characteristics of this flow in wind tunnels are low density of air and low temperature due to used to adiabatic expansion in the throat of the nozzle. One group of methods which can be used to carry out flow field investigation is a group of optical methods. Those methods are especially useful for a complete visualization of aerodynamic effects about the test model. In the literature [7-18] the best method is the schlieren method.

By this method the changing of air density gradient can be registered, and the following can be seen: shock waves, expansion waves, compression waves, a boundary layer, etc. The schlieren effects, i.e. the shape of shock waves about the test model with known geometry could be used for the determination of the Mach number of undisturbed flow, i.e. for the calibration of the wind tunnel test section [1,2,11-17]. Using shock waves for Mach number determination in hypersonic wind tunnels is extremely difficult, because the Mach wave angle relatively slightly changes with Mach number changing. For example, changing in the Mach number from 5 to 10 results in changing the Mach angle from 11.54 degrees to 5.74 degrees.

The investigation of aerodynamic phenomen with hypersonic velocity requires the knowledge of flow fields in the wind tunnel test section. The T-34 hypersonic wind tunnel in the VTI is designed for a nominal Mach number M=7.0. Testing of the real flow field, i.e. calibration of the

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wind tunnel test section is an important phase of wind tunnel operating. In the experiment which was then organized the schlieren system was used for testing because the T-34 hypersonic wind tunnel does not have a primary measuring system for the determination of basic flow parameters such as Mach number, Reynolds number, dynamic pressure, etc. A new schlieren system was used to determine an appro-ximate value of the Mach number for the existing nozzle, on the basis of the shock wave shape about a test model which is a part of the wind tunnel equipment. There is also Detviler's schlieren system, which is a part of the wind tunnel equipment, with a convergent light beam and double passing through the test section, known as a coincident system. The preliminary results of investigation showed that this system is not satisfactory for set demands. Therefore, a new schlieren system with parallel light beams was designed. One part of this system is made in a prototype workshop of the VTI and the other part is procured from foreign producers. The system is integrated, tested and included in Mach number experimental checking.

The discussion of results, besides the visualization effects, also includes differences between advantages and disadvantages of the new and the old schlieren system. The experiment has shown flow in the hypersonic wind tunnel test section and enabled the determination of the undisturbed flow Mach number on the basis of Billig's equation and schlieren photos.

## Billig's method of the determination of a shock wave shape in the hypersonic flow field

Hypersonic flow about blunt bodies in the aerodynamic sense is very important because all flying vehicles with speeds higher than M=5.0 have a blunt top which significantly decreases aerodynamic heating [1,2].

It is reason why a large number of methods is developed for solving flow fields about blunt bodies at hypersonic speeds [3,12]. However, there is not an absolutely exact method for solving hypersonic speeds because of dissociation and ionization of the air due to high temperatures (over 5000 C). It could be said that there are not exact solutions of hypersonic flow fields, but only approximate theoretical solutions based on simplified forms of basic flow equations.

The shapes of shock waves about blunt bodies in hypersonic flow fields could be obtained by experiments in wind tunnels. On the basis of data collected from wind tunnels measurements, Billig has given an empirical equation which describes quite well the shock wave shape about a body with the half-spherical top. Fig.1 defines the used coordinate system and Fig.2 shows a shock wave shape about a cone with the spherical top in the hypersonic flow fields at M=4.0 and M=8.0, obtained by the calculation with Billig's equation. For a quick engineering analysis of an unknown flow field about a model with well known geometry, Billig's equation can be used. In the cartesian coordinate system it has the form

$$x = R + \delta - R_c \cot^2 \beta \left[ \left( 1 + \frac{y^2 \tan^2 \beta}{R_c^2} \right)^{0.5} - 1 \right] \tag{1}$$

The values used in this equation are shown in Fig.1. Billig has considered two geometry shapes. The first one is a cone with the half-sphere and the other one is a cylinder with the half-sphere on the top. Using the experimental data from wind tunnels for these two models, Billig gave the following connections between the basic hyperbole parameters, geometrical parameters of the nose model part and the Mach number of undisturbed flow (Fig.2).

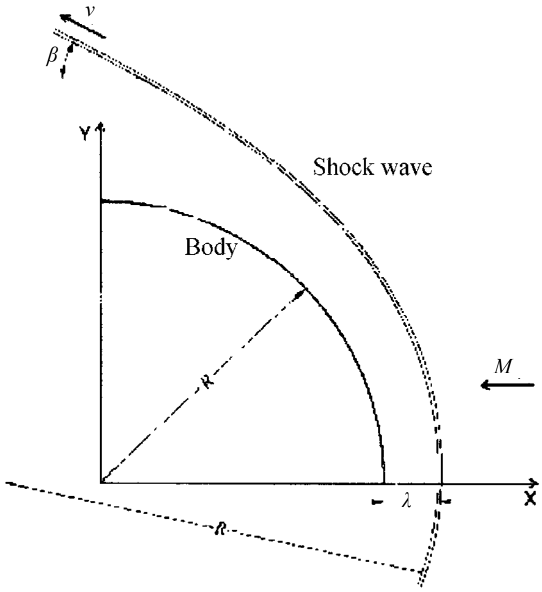



**Figure 1.** Coordinate system and variables in Billig's equation

For the model of the cone with the half-sphere on the top

$$\frac{\delta}{R} = 0.143 e^{\frac{3.24}{M_\infty^2}} \tag{2}$$

$$\frac{R_c}{R} = 1.143 \frac{0.54}{(M_\infty - 1)^{1.2}} \tag{3}$$

For the model of the cylinder with the half-sphere on the top

$$\frac{\delta}{R} = 0.386 e^{\frac{4.67}{M_\infty^2}} \tag{4}$$

$$\frac{R_c}{R} = 1.386 e^{\frac{1.8}{(M_\infty - 1)^{0.75}}} \tag{5}$$

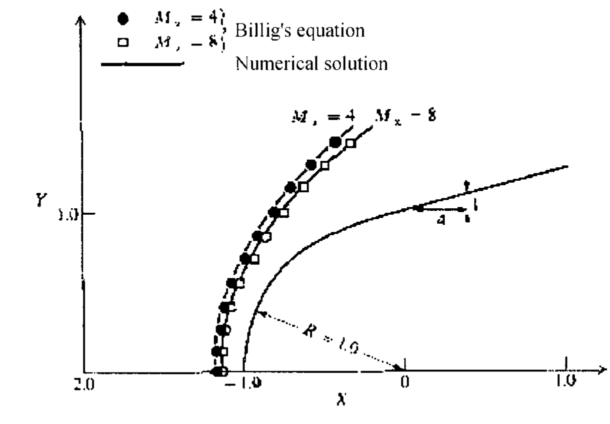



**Figure 2.** Shock wave shape for the cone with the sphere on the top $M_\infty$=4.0 and $M_\infty$=8.0 [3]

Fig.3 shows the shape of the shock wave for the 'SPACE SHUTTLE' hypersonic vehicle at Mach number M=7.4 [3]. The results are obtained experimentally and by calculations based on Billig's equation. As it can be seen in Fig.3, which shows a shape of shock waves in front of the vehicle nose, the accordance of experimental and theoretical results is very good.

This empirical equation is thus verified and can be recommended for the analysis of the shock wave shapes in front of the body of similar geometry in hypersonic flow.

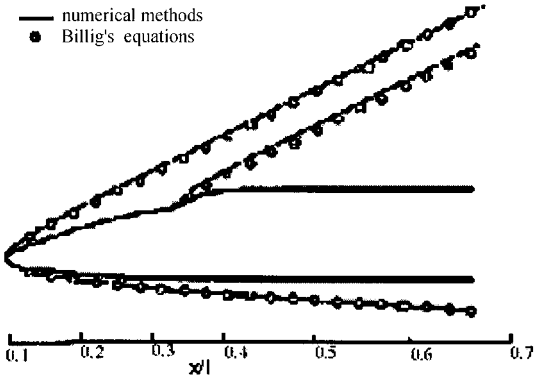



**Figure 3.** Shape of the shock wave for 'SPACE SHUTTLE' for $M_\infty$=7.4 $\alpha$=15.5 º [3]

## Optical methods for hypersonic flow fields visualization

The most significant group of flow visualization methods that cover a wide range of speeds (M=0.5 up to M=20.0) is that of optical methods [4-18]. These methods give qualitative and quantitative information about flow fields. Optical methods are based on the change of optical index of light refraction as a function of complex distribution of gas density (caused by aerodynamical phenomena), so that a compressible flow field represents an optical disturbance for each light ray passing through this field. A light beam passing through such an environment suffers changes in its direction, intensity, phase and polarization.

Optical methods are non contact and very sensitive to slight changes of flow characteristics. These methods have a lot of advantages when compared to classical ones. Optical methods can be expanded for low speed flow visualization (non compressible flow) if an additional density gradient is added to the flow. Optical methods enable the determination of aerodynamical parameters in the total volume of the test section (density, pressure, flow velosity, Mach number, etc.). Flow visualization shows the location of shock and expansion waves, investigation of nature and transformation of the boundary layer, interaction of different effects in complex flow fields [1,5-18], etc.

Optical methods can be divided in three groups:

- shadow method
- shlieren method
- interferometry

The shadow method visualizes only a field in which the second derivative of the optical refraction index is neither uniform nor zero. The shlieren method visualizes the field with the gradient of the refraction index (first derivative) in the direction normal to the light propagation. Interferometry (classical or holographic) enables the flow density evaluation.

All of these methods can be applied in two versions: conventional methods which use classical white light sources and laser optical methods based on the characteristics of the monochromatic laser light .

Beside these optical methods, for the past few years, there has been a wide range of combined methods which use laser as a light source and introduce some foreign materials for flow visualization (smoke, dye, oil emulsions, etc.).

Regarding the optical characteristics of the hypersonic flow and the goal of the experiment, the schlieren method is chosen as a method for Mach number determination.

*Optical characteristics of the hypersonic flow*

An air flow with a high Mach number is a compressible flow. In the same time, it is an optical environment, a transparent phase object with variable density depending on aerodynamical effects around the models. The flow parameters in the test section of the T-34 wind tunnel are: $M_\infty$=7, Re =12.5 $10^6$ $m^{-1}$, maximum total pressure $P_0$= 30 bar, maximum static pressure $Ps$ = $7.10^{-3}$ bar, total temperature $T_0$ = 720 K. The sound velocity under these conditions is $C_0$ =538 m/s.

The flow with $M_\infty$ = 7, in front of the shock wave has these parameters: $Ps_\infty$ = 7.0 $10^{-3}$ bar, $\rho_{s\infty}$ = 3.8 $10^{-2}$ kg $m^{-3}$, $Ts_\infty$ = 66.7 K, $C_\infty$ = 184.0 $ms^{-1}$, $V_\infty$ = 1254.8 $ms^{-1}$, $q_\infty$= 2.486 bar, $n_1$ = 1.00000855.

The bow shock is formed in front of the test model. The zone of the shock wave can be approximately divided in three parts. The first one is in the vicinity of the stagnation point, where it can be considered as a normal shock wave. In this region, the subsonic flow is obtained with $M_{2n}$=0.3974. Here the flow parameters are: $Ps_2$=399 $10^{-3}$ bar, $\rho s_2$ =20.67$10^{-2}$ $kgm^{-3}$, $Ts_2$ =698.4K, $C_2$ =595$ms^{-1}$, $M_{2n}$=0.3974, $V_2$ =236.6 $ms^{-1}$, $n_2$ =1.00004651.

The second part is the bow shock around the blunt body, and the third one has a shape similar to the shape of the shock wave formed ahead the cone with $\theta c$=20˚, for $M_\infty$=7. This occurs at half of the model length, with respect to the stagnation point. The angle of the shock wave of a great distance from the top of the model is the angle of the Mach wave. The flow is supersonic here with: $M_2$=4, $\rho_{s2}$=14.7 $10^{-2}$ kg $m^{-3}$, $C_2$ =285 $ms^{-1}$, $V_2$ = 1140 $ms^{-1}$, $n_2$ =1,00003374.

The width of the shock wave is approximately the mean free path of air molecules between two collisions $\lambda_s$.

$$\lambda_s \approx \frac{R^* T_{s\infty}}{\sqrt{2}\pi d^2 \mathrm{Na} P_{s\infty}} \tag{6}$$

Here $d$ is the effective cross-section of the air molecule $d$=0.3365 $10^{-9}$m, Na is Avogadro's number, $R*$ is the universal gas constant. For the flow in consideration, $\lambda_s \approx 2.08\ 10^{-6}$m.

The approximate calculation of the light beam deflection in the region of the shock wave makes possible the determination of the full measurement scale of the schlieren system. For the experiment conditions in the hypersonic wind tunnel, the deflection of the light in the stagnation point region, and for the width of perturbation around the model $h_m$=30 mm, is

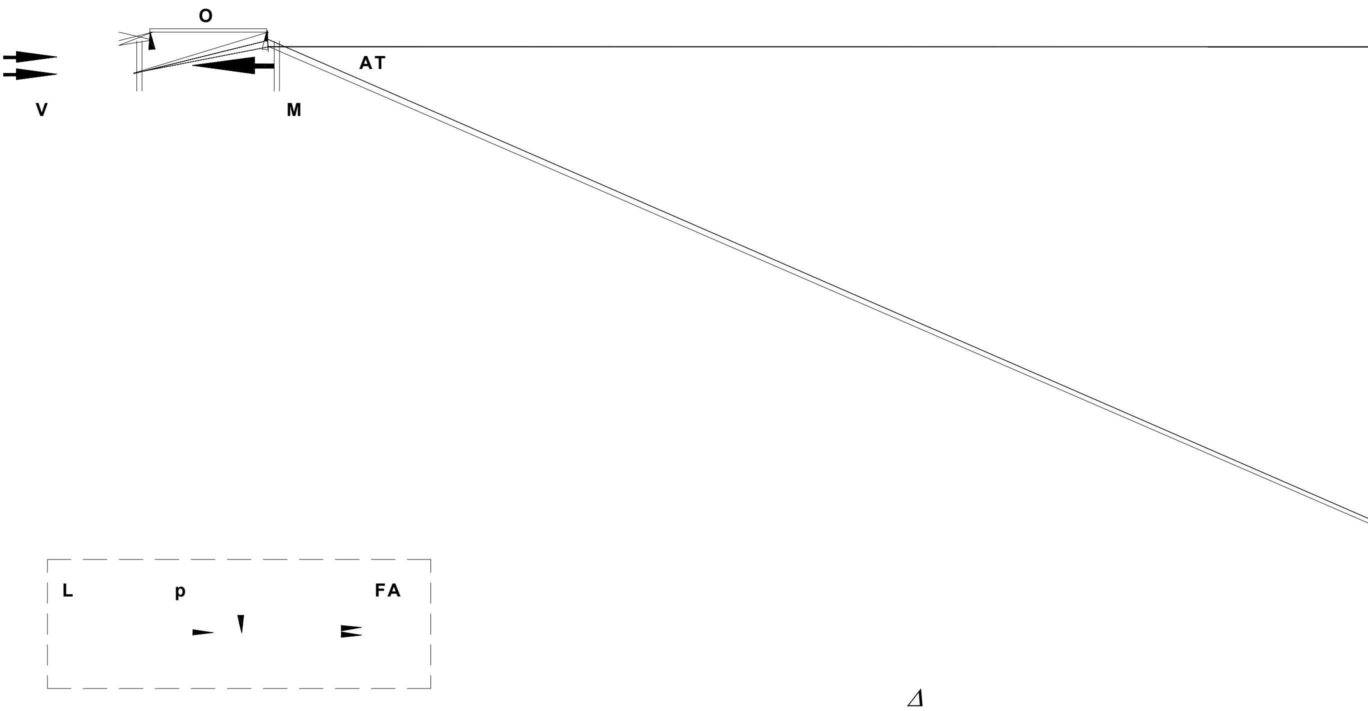
$$\varepsilon = h_m\, grad\, n = h_m \frac{\Delta n}{\lambda_s} \tag{7}$$

$$\varepsilon \sim 48{,}46\ 10^{-4}\mathrm{rad}$$

The value ε (angle deflection of the light beam) is obtained under the supposition that the flow in front of the test model is not axially symmetric, but two-dimensional and 30 mm wide. The calculation is based on the premise that the density gradient is constant inside the zone of the shock wave and that it does not exist outside it.

*Schlieren method with convergent and parallel light beams*

The fundamental physics principles of the schlieren method are given in the cited literature [5-10,14-18]. The special equipment helps the realization of the method. The schlieren device in the T-34 wind tunnel exists in two versions. The first one is the most simple system (Fig.4) consisting of: spherical, concave mirror (O), light source (L), narrow slit placed in front of the source and in the curvature center of the mirror, optical prism (P) and still camera (FA). The prism and the camera are placed in the curvature of the mirror, too, but they are dislocated for about 1º. This system is called the Dotwyler schlieren system, or coincidence system. A divergent light beam passes through the wind tunnel test section (the flow field around the test model), reaches the mirror (O) and comes back through the test section as a convergent beam. The angle between the optical axes of these beams is 1º.




$\Delta$

x mn

The mirror is of high quality, the focal length is 2440 mm, and the diameter is 300 mm. The first collimating mirror gives a clear aperture parallel beam of 300 mm. This beam passes through the wind tunnel test section. The Xe lamp of 200 W is the light source.

The optical receiver assembly contains the Fouceaulot knife-edge, or the color filter. The filter has three strips. The central one is green, 1.5 mm wide, and the lateral ones are blue and red and 15 mm wide. The optical prism is placed behind the filter. The prism splits the beam to be recorded with a still (FA) and a TV camera and watched on the screen at the same time. Optical adjustment is more simple. The various optical components are mounted on carriers with accurate micrometers adjustable in three directions.

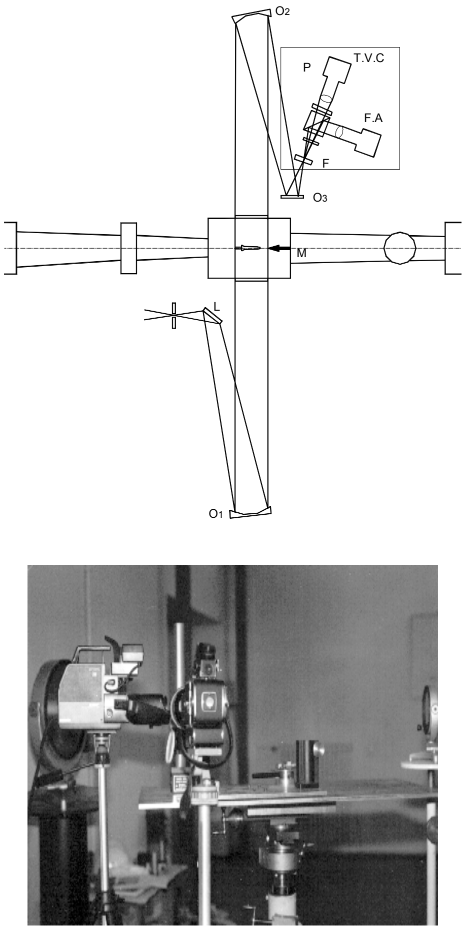



**Figure 5.** Scheme and photos of the receiving assembly in a new schlieren system with parallel beams.

The sensitivity of a new system (according to eqs.(8),(9) and (10)) is

$$S = 0.163 \cdot 10^{4} \text{ 1/rad}, \ \varepsilon_{min} = 6.44 \cdot 10^{-4} \text{ rad}$$

The measurement range $\Delta\varepsilon$ for $\varepsilon_{max} = 64.6 \cdot 10^{-4}$ rad is $\Delta\varepsilon = 58.11 \ 10^{-4}$ rad.

The results of the experiment show that, when the central filter part (green) is placed in the optical axis of the schlieren system, then a part of the deflected beam passes through the red strip and another part through the blue filter strip (depending on the density gradient orientation). In a recorded image, the shock wave is colored blue or red. If the filter is not in the optical axis, the image of the shock wave is dark. In that case the deflected light beam from the shock wave is completely blocked.

The sensitivity of the Töepler system is lower when compared to that of the Dötwyler schlieren system. The measurement range is four times increased. The additional increase of the Töepler schlieren system sensitivity can be done with the methods described in [14].

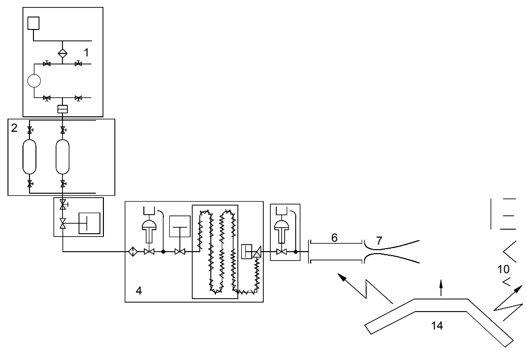
## Experiment description

The experiment has a program that enables the testing of optic-mechanical characteristic of a new schlieren system, the visualization of flow in the test hypersonic wind tunnel section and the determination of the free flow Mach number.

*T-34 hypersonic wind tunnel*

The hypersonic wind tunnel is designed for a nominal Mach number $M_{\infty}=7$. Fig.6 is a scheme of this construction. It has four installations mutually connected:

1. Installation for air compressing (1,2,3)
2. Installation for air preparation (4)
3. Wind tunnel (5-10, 14)
4. Vacuum storage tanks with suport installation



- pressure in the air heater must be 120 bar
- air temperature in the heater is 720$^{o}$ K.

The regulation valve makes it possible to obtain a total pressure of 30 bar and the vacuum installation provides a static pressure in the test section of $7 \cdot 10^{-3}$ bar.

Under these conditions the wind tunnel blow duration is about 25 s.

The model is always put into the jet after starting the flow, to avoid high stresses which exist in the moment of the wind tunnel starting. The same procedure is repeated before the wind tunel stops.

Recording of schlieren effects starts a few seconds after placing the model (about 10 s after the wind tunnel starts), i.e. in the moment when a steady flow is achieved in the test section. The flow visualization results are recorded by TV and still camera. The experiment program included a new schlieren sistem sensitivity test for vertical and horizontal air density gradient changes.

## Discussing of results and determining the Mach number in the T-34 wind tunnel test section

According to the calculation (eqs.(7),(8) and (9)), weaker flow visualization effects have been expected when the schlieren system with a parallel beam is adjusted so that the hight of the central part of the green filter zone is equal to the hight of the wind tunnel axis. The expectations proved to be corect. Fig.8 shows a photo where the central part of the green filter zone is in the wind tunnel axis, so that the refracted beam parts pass through the red and blue filter zones.

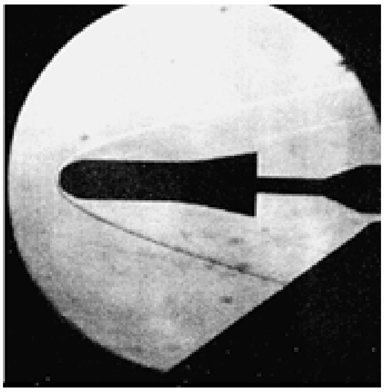


**Figure 8.** Photo of schlieren effects around the test model with the centered schlieren system

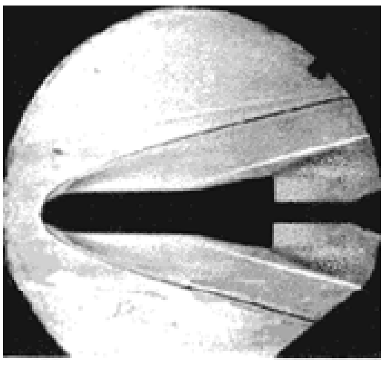


**Figure 9.** Schlieren photo with the vertical slot and the filter for horizontal gradients registration

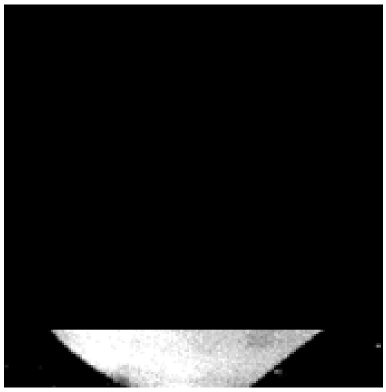
In the next blows the filter is, therefore, positioned so that the boundaries between the central, green and lateral filters zones have the role of the Fouceaulot knives. During the experiment, slots and filters orientations change, so that the gradients in the horizontal (Fig.9) and vertical (Fig.10a and 10b) direction are recorded.

The air density gradients in both directions evidently exist: in the vertical direction the gradients are higher except around the stagnation point, where horizontal air gradients are dominant. The light beam deviation occurs in the horizontal plane.

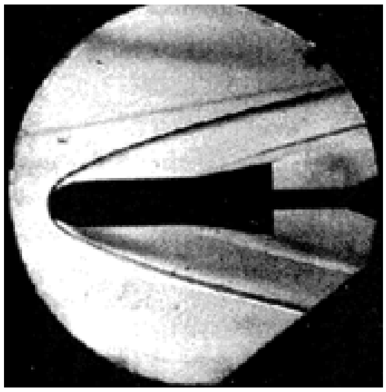
Because of that, the shock wave 'glues' to the frontal model area, and from this photo it is not possible to determine the distance between the shock wave and the stagnation point on the model.

The shock waves are dark and the expansion waves are light which confirms that the parts of the light beam in this area deviate in different directions.

Fig.10a and b show the photos of the flow field visualization obtained by using the horizontal filter for two different position levels for two diferent system sensitivities. When the filter is positioned at the maximum hight level with respect to the main focus, darker photos are obtained because a greater part of the control beam is blocked.



a)



b)

**Figure 10.** Schlieren effect with the increased sensitivity and the horizontal filter

The experiment is repeated with the Dötwyler system, with an old lamp and an old filter.

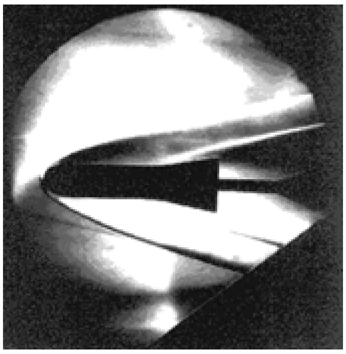
The old filter transparency is very low and the obtained photos are of very poor quality and not useful.

In the black and white version, the schlieren system works with a knife. The knife represents a black and white filter. It has two surfaces; the first one has transparency zero and the other has transparency 99%.

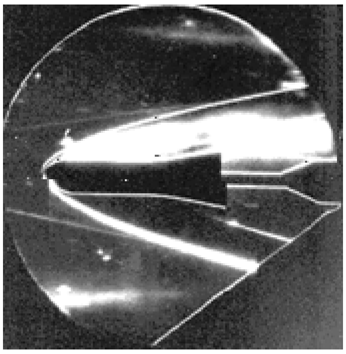
Fig.11a is a photo of the schlieren efect when the deviated light beams are blocked by the Fouceaulot knife, and some parts are transmitted. Fig.11b shows the opposite case.

Better schlieren system sensitivity can be obtained with a larger focus lenght concave mirror or with a narrow central strip filter. Because of the laboratory dimensions, it is not posible to use mirror optics with $f$>5 m.

The best flow visualization effects are with the horizontal filter, because the air gradients are higher in the second and third flow zone (except around the stagnation point) for the used test model.



a)



b)

**Figure 11.** Flow visualization in the black and white technique (Fouceaulot knife instead the filter)

Table 1 and Fig.12 show the results of the theoretical estimation of the coordinates $x$ and $y$ based on eqs. (1) (4) (5) and the recorded shock wave shape. The shock wave occurs at 1.7 mm before the stagnation point of the test model, and at 7.5 mm of the origin (aerodynamic center of the model, Fig.12). The theoretical and experimental results are very simillar. It is very difficult to obtain the Mach number for so high values [1].

**Table 1**

| $X$ [mm] | -7.5 | 0 | 10 | 20 | 40 | 60 |
|---|---|---|---|---|---|---|
| $Y_{theor}$ [mm] | 0 | 12.75 | 19.00 | 23.79 | 31.76 | 38.619 |
| $Y_{exper}$ [mm] | 0 | 14.164 | 19.457 | 23.808 | 27.825 | 34.316 |
| $(\Delta y/y)$ % | 0 | 10.5 | 2.4 | 0.8 | 12.2 | 13.1 |

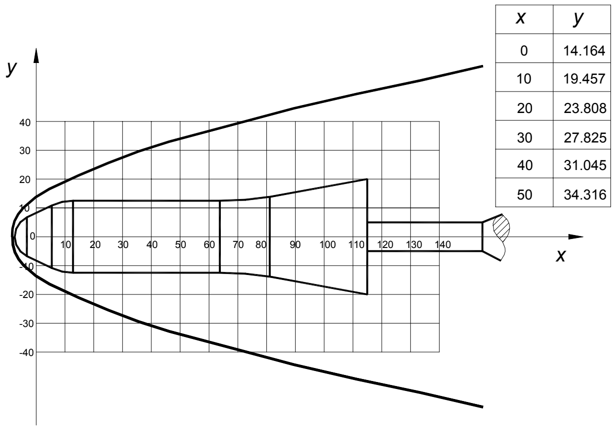



**Figure 12.** Theoretical and experimental values for the coordinates $x$ and $y$

The mean deviation between the theoretical and experimental results of the ***y*** coordinate is 6.5%. One reason for that result is that the test model geometry is different from Billig′s geometry. This method is acceptable for the aproximative determination of the Mach number. Therefore, it is confirmed that the Mach number in the free stream flow in the hypersonic wind tunnel is $M_\infty$=7±0.45. The Mach number has to be measured with the pitot tube for a complete analysis.

## Conclusion

With minimum financing, the new schlieren system with a paralel light beam has been designed, made and tested in the VTI. The optical test area and system sensitivity are optimally chosen with respect to the optical flow characteristics in the hypersonic wind tunnel test section. The system has possibilities for a very accurate adjustment, so it is very suitable for manipulation. The schlieren effects can be observed and recorded with TV and still camera at the same time.

This new schlieren system is capable of giving a very good flow visualization. The shock waves around the test model recorded with this metod are used for the Mach number in the free stream calculation. Billig's equation is applied for calculating the coordinates of the Mach waves around the test model. The theoretical and experimental results are compared. They proved to be very similar. It can be concluded that the Mach number is about 7 in the free stream flow in the test section of the T-34 hypersonic wind tunnel.

In the schlieren effects photos, there are shock waves coming from the throat which spoil the flow quality and must be avoided by modifying (polishing) the throat of the wind tunnel nozzle. The registration of these schock waves justifies the use of optical methods during tests of missile models in hypersonic wind tunnels.

The test continuation is being planned in a few different directions. The first activity is to connect the wind tunnel control system and the schlieren control system to enable the automatic synhronous running of the wind tunnel and the schlieren system. The next activity is to choose, design and make new test models for hypersonic wind tunnels. The third activity is to introduce other optical methods for flow visualization, for example holographic interferometry.

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# Određivanje Mahovog broja hipersoničnog strujanja pomoću novog šliren sistema

**U radu su analizirane mogućnosti određivanja Mahovog broja neporemećenog strujanja u hipersoničnom aerotunelu T-34, na osnovu oblika udarnog talasa oko test modela. Analitička metoda, koja se u tu svrhu koristi, zasniva se na empirijskoj jednačini Billiga. Vizualizacija udarnih talasa je dobijena pomoću šliren (schlieren) metode. Za potrebe operemanja aerotunela, u VTI-u je projektovan, izrađen i testiran novi šliren sistem Toplerovog (Töpler) tipa. Pomoću novog šliren sistema izvršena je vizualizacija strujanja i određen je Mahov broj u radnom delu hipersoničnog aerotunela. Dokazano je da je Mahov broj neporemećene struje $M_\infty$=7.**

*Ključne reči:* **hipersonično strujanje, hipersonični aerotunel, udarni talasi, vizualizacija strujanja, šliren metoda.**

# Détermination du nombre de Mach de l’écoulement hypersonique à l’aide d’un nouveau système schlieren

**Le papier analyse les possibilités de déterminer le nombre de Mach de l’écoulement continu dans la soufflerie hypersonuque T-34 en utilisant la forme de l’onde de choc autour de la maquetle. La méthode analytique ici appliquée est basée sur l’équation empirique de Bilig. La visualisation des ondes de choc est obtenue à l’aide d’un nouveau système schlieren du type Töpler qui est concu réalisé et essayé dans l’JMT. Le nombre de Mach de l’écoulement continu est déterminé dans la champre d’expérience $M_\infty$=7.**

*Mots-clés:* **écoulement hypersonique, soufflerie hypersonuque, ondes de choc, visualisation de l’écoulement méthode schlieren.**