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A four colours line grid schlieren method for quantitative flow measurement

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Abstract. This article describes the schlieren apparatus developed at the Institut für Luftfahrttechnik und Leichtbau (ILT, Institute of Aeronautics and Structures) for the Transonic Wind Tunnel of the Munich University of the Federal Armed Forces (TWM). Special features are the application of four separate, variously coloured beams of rays to identify the direction of density gradients and the line grids which are attached to the knife edges, in order to permit a quantitative evaluation of the amount of ray deflection and of the thermodynamical quantities.

List of symbols

c	sensitivity
h	light deflection
M	Mach number
s	distance
O	order of schlieren lines
T	spacing of the line grids
x	horizontal direction
z	vertical direction
α	angle of attack
φ	angle of light deflection
ϱ	density

1 Introduction

Schlieren optical systems are used to visualize light deflecting effects. Besides the original application, the quality testing procedure of optical lenses (Töpler 1864), they are presently employed especially in experimental fluid dynamics. Simple versions are frequently used for qualitative, two-dimensional analysis and flow visualization. Besides, for a long time, methods are known to gain quantitative results with the support of schlieren optics. The application of coloured filters is summarized by Schardin (1941), Holder and North (1956), Wüst (1957), Maddox and Binder (1971), Settles (1982) and Oertel and Oertel (1989). There, instead of a knife edge, filters with a coloured pattern are frequently used through which the light, depending on the spot at which it reaches the filter, is filtered into various colours. By identifying the colour on the schlieren picture the amount and the direction of the ray deflection may be determined. If the sensitivity of the apparatus is known, then the ray deflecting physical dimension, mostly the density gradient, may be computed.

The described schlieren system follows the one supposed by Settles (1970), in which the light is coloured on the side of the light source. Contrary to Settles (1970), four separate light beams are generated at the TWM as shown by Wagner and Hampel (1984). Together with line grids, which are attached to four knife edges, schlieren images with great information are obtained. The results are similar to those obtained by schlieren interferometry (Merzkirch 1974). The advantage of the method presented is that, in steady two-dimensional isentropic flow, not only the absolute value of the velocity, but also the direction can be determined since both components of the density gradients are simultaneously recorded.

2 The four colour schlieren method

The schlieren system at the TWM was outlined and realized by Hampel (1984). The light source system consists of four separate beams. Each of the four colours is generated by its own lens system. The four lens systems are radially arranged around a horizontally lying 1.6 kW Xenon lamp as shown in the perspective view of Fig. 1. The lens systems are displaced with respect to each other by 90°. Light source and lenses are located on planes 45° inclined towards the horizontal plane. In each of the four beam paths the light is filtered in one colour. Via a prism the four light beams are directed towards a slit aperture with four holes. The lenses and mirrors of the light source system focus the light source at the slit aperture. The selected arrangement allows maximum illumination at a simultaneously low thermal stress of the filters. Due to the high light density the apertures can be very small. Thus, the prerequisites for the later described line grid procedure are given.

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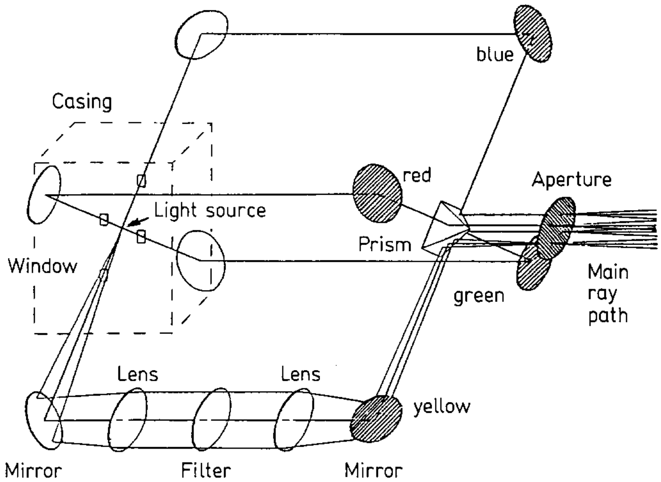

Fig. 1. Perspective view of the light source system

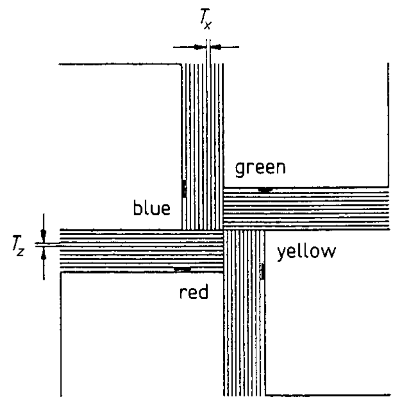

Fig. 2. The knife edges with line grids

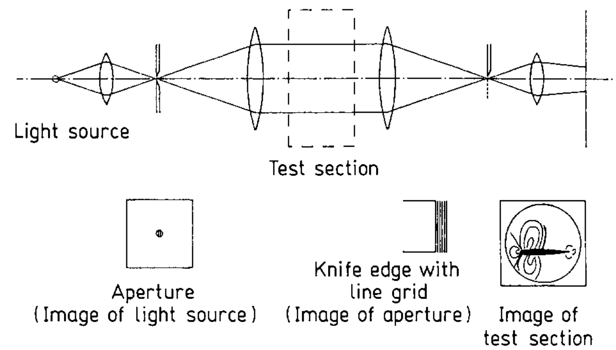

Fig. 3. Principle of operation of the line grid method (one beam)

Behind the slit aperture, the four light beams overlap and form the main beam. They pass in parallel and are displaced by the distance of the apertures. Concave and plane reflectors of the main ray path focus the apertures on four knife edges, one for each colour. They may be individually adjusted radially and in the direction of the beam to compensate astigmatism.

3 The line grid schlieren method

The principal deficiency of existing quantitative schlieren methods using colour pattern filters is mainly due to the fact that measurement of hue is necessary to estimate the amount of the ray deflection. This leads to a greater error, especially during automatic evaluation. The basic ideas to quantify the flow field by the schlieren system of the TWM are shown in the following chapter. More details are explained by Scheitle (1988).

The schlieren system described in Sect. 2 allows to identify the direction of the density gradient by the colour information. The resulting colour differences, however, show only coarse grades so that a quantitative statement with regard to the flow field cannot be made.

The separation of the four coloured light beams, also the high light density at the apertures, respectively at the knife edges, permit to follow a new way of approach. That is to attach a line grid at each knife edge as shown in Fig. 2. The line grids preserve the fundamental function of the knife edges, i.e. the generation of a light/dark- or hue-contrast. A line pattern is superposed upon the schlieren picture and allows quantitative analysis of the flow field.

In the following, only one beam is regarded (Fig. 3) in order to derive relevant relations. A line grid of alternate transparent and opaque stripes is attached to the knife edge parallel to the edge. If a deflection of a light ray occurs in a direction pointing away from the edge, then this ray either hits a gap or a stripe. The image appears either in the direction of the density gradient's matching colour or this specific colour is missing just at this spot. All light rays, whose deflections perpendicular to the knife edge are of the same size, appear on the same line or gap. Thus, in case of two-dimensional flow, loci of the same density gradient components will be visualized on the schlieren image. These loci, following the nomenclature used in photo elasticity, are classified in a way that the order of zero is associated with the light line without light deflection, the first order is the light line after the first dark line, etc.

The component of the density gradient perpendicular to the knife edge is

$$\frac{d\varrho}{ds} = \frac{\Delta h}{c}, \tag{1}$$

where Δh is the deflection of the light at the knife edge and c contains the constant parameters as focal distance and index of refraction.

When T is the spacing of the line grid in mm/line and O is the order of a line on the schlieren image,

$$O = \frac{\Delta h}{T}, \tag{2}$$

the component of the density gradient can be determined:

$$\frac{d\varrho}{ds} = \frac{O \cdot T}{c}. \tag{3}$$

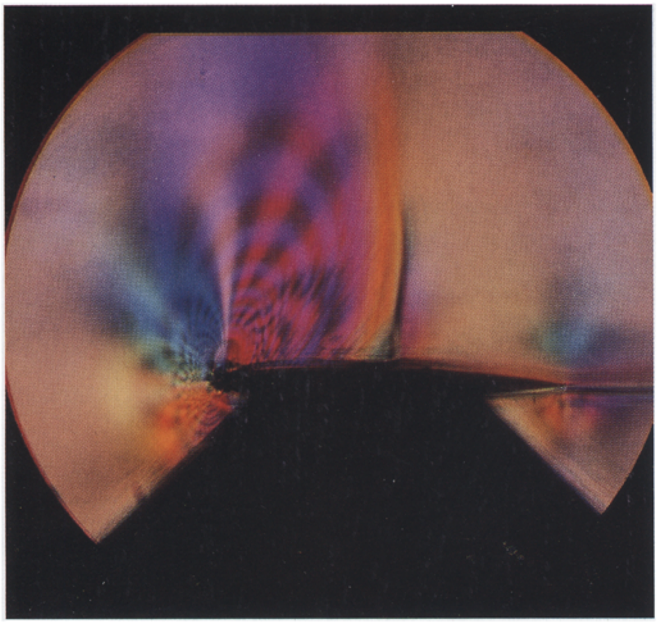

Fig. 4. Schlieren picture of a transonic flow field (NACA 0012, $M = 0.8$, $\alpha = 2°$)

To continue with a two-dimensional situation all four line edges are equipped with line grids, which are arranged parallel to these edges (Fig. 2), so that every change of density can be quantified.

The arrangement of colours, as selected at TWM, results in two superposed arrays of lines of various colours. Hereby the loci, at which integer orders appear in both directions of deflection (x, z), retain their mixed colours in accordance with the arrangement without the grids. The half-numbered orders omit that colour in which direction a density gradient of a half-order exists. If a density gradient of a half-order exists in both directions, then that spot on the image appears dark. By counting the orders and interpolating both components of the density gradient may be determined at each location. To determine the density distribution the density at one reference point must be known. This is, in general, easily achieved since pressure is measured along the model surface. In order to find the density at a point P, according to Eq. (4), the density gradients are integrated along the distance between the reference point and P:

$$\varrho_P = \varrho_{ref} + \int_{ref}^{P} \frac{d\varrho}{ds}\, ds\,. \tag{4}$$

The absolute values of the components of the density gradients are determined from the orders in accordance with Eq. (3). Positive signs result when the direction of integration is accompanied by an increase of the order, i.e. the gradient; negative signs appear during a decrease of the gradient order. Due to the symmetrical arrangement of the knife edges density gradients of the same direction but different sign appear in complementary colours. The signs of the gradients

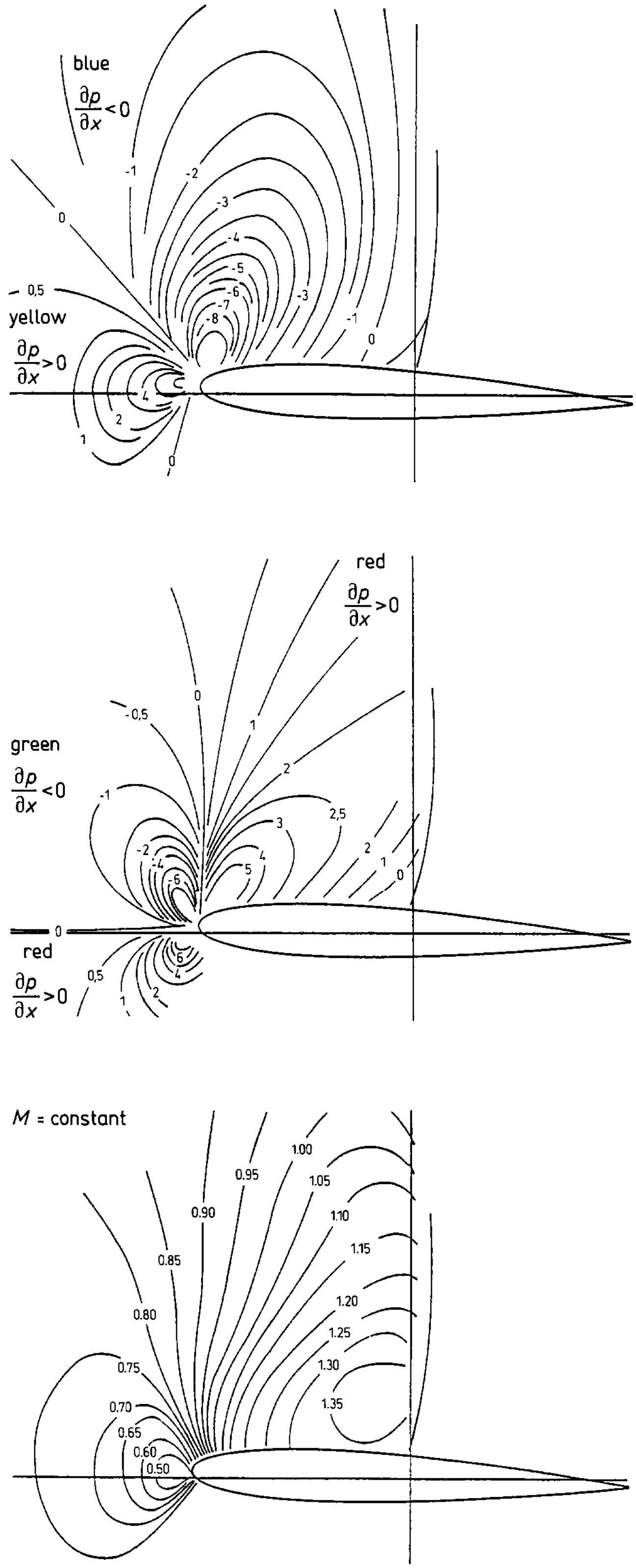

Fig. 5. Loci for constant orders and iso-Mach lines

can be recognized by the colours as follows:

$$\begin{aligned} &\text{blue:} && \frac{\partial \varrho}{\partial x}<0 && O_x<0 \\ &\text{yellow:} && \frac{\partial \varrho}{\partial x}>0 && O_x>0 \\ &\text{green:} && \frac{\partial \varrho}{\partial z}<0 && O_z<0 \\ &\text{red:} && \frac{\partial \varrho}{\partial z}>0 && O_z>0\,. \end{aligned} \tag{5}$$

If the field of density is known, then in case of isentropic flow the pressure and velocity distribution may be determined from the thermodynamic laws. Since both components of the density gradient are known the amount as well as the direction of the velocity vector may be computed.

The necessary width of the focal point is primarily determined by the illumination. For this reason, the maximum resolution of the line grid method depends on the available illumination and the exactness of the optical arrangement. The arrangement of the light source system still permits, at an opening of the aperture of approximately 0.1 mm, accurate photo and video pictures. However, diffraction phenomena may already be observed, which lead to a tolerable decrease of the bright/dark contrast. Because of the knife edges, which are individually adjustable in the direction of the beam, the astigmatism does not affect the accuracy. For this reason, the four beams can be concentrated almost to the opening of the aperture. For the picture, as shown in Fig. 4 (exposure time: 1/60 s), a line grid with a width of opaque stripes of 0.2 mm and a width of transparent stripes of 0.25 mm was used. The width of the focal apertures was 0.12 mm. At a distance of the focal apertures of 10 mm eleven grid lines may be attached at each knife edge, i.e. a maximum of eleven orders may be obtained. The resolution corresponds to a density gradient of 1.70 kg/m^4 per order.

The evaluation of the schlieren images is, at present, still performed manually. The results shown in Fig. 5 refer to a test run with a NACA 0012 airfoil at $M = 0.8$ and an angle of attack of 2°. The extracted loci of constant orders, i.e. components of density gradients in the x- and z-direction, and the resulting Mach number distribution are plotted. The schlieren image of Fig. 4 was used thereby. In practice, it is no problem to define the orders by taking into account the structure of the flow field.

4 Summary

The described schlieren system differs from other common systems by various improvements. The filtering of light into four colours via separate light beams permits a maximum illumination efficiency at a simultaneous minimum thermal stress of the filters. Due to the small sizes of the slit apertures a method for a quantitative analysis of the flow field is possible. For this purpose line grids are attached to the four knife edges. The resulting optical effect permits to quantify the light deflection without the necessity of measuring the value of hue. The thermodynamic quantities, especially amount and direction of the flow velocity, may be computed if isentropic two-dimensional flow can be assumed.

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