APPLICATION OF LIGHT SCATTERING EFFECT IN AERODYNAMIC EXPERIMENT

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Abstract

The original optical method of transonic flow investigation around airfoils is offered based on the effect of essential influence of boundary layer state on light scattering effect of parallel beam passing through it. Some examples of the new method application are given.

1 Introduction

The refraction (deviation) phenomenon of a light beams in environments with variable refraction coefficient *n* is well-known in optics. In particular such an environment occurs to be air flowing around various objects. Also it is known that light beams refraction is influenced only by a component of refraction coefficient gradient which is perpendicular to the direction of light beams propagation [1]. The component along the direction of light beams propagation does not influence on light refraction, as in the case of orthogonal passage of beams through optical windows and boundary layer on wind tunnel walls.

The refraction coefficient *n* is connected with density ρ by the known formula

$$n-1=K\rho, \qquad (1)$$

where K is constant. For air it equals to value 0.2264 [sm³/g].

The deviation of a light beam in perpendicular direction Y from the direction of its propagation X is characterized by second derivative d^2Y/dX^2, which is proportional to a gradient of refraction coefficient: $d^2Y/dX^2 \propto \partial n/\partial Y$. According to (1) the value of refraction coefficient gradient is proportional to a density gradient; hence propagation of light beam is defined by the following equation:

$$\frac{d^2Y}{dX^2}=K\frac{\partial\rho}{\partial Y}, \qquad (2)$$

The phenomenon of light refraction gives opportunity to provide optical studies of gas flows by shadowgraph photography methods. The first attempts of optical methods application for visualization of light refraction picture in the boundary layer and determination of its state have been made by Pearcey [2].

2 Some features of light refraction in the boundary layer

In Fig. 1, characteristic dependence of $\rho=\rho(Y)$ in the boundary layer and the picture of light beams refraction at the surface of aerofoil model disposed between Schlieren quality optical windows of a wind tunnel are presented.

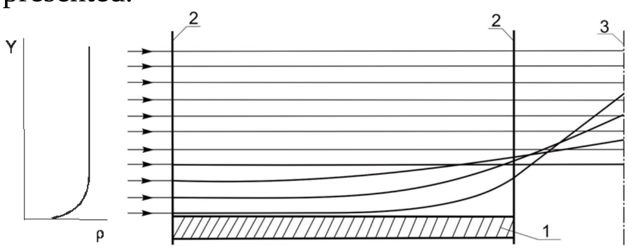

Fig. 1. Scheme of light beams refraction. 1 – aerofoil surface; 2 – optical windows; 3 – focusing plane of shadowgraph device.

Under the influence of cross-flow gradients of density, parallel light beams are scattered and ejected from the boundary layer region on a model surface and dissipate.

The main difficulty for monitoring and registration of a refraction pattern is due to brightness that is insignificant and difficultly distinguishable in the total light stream which is passing over a boundary layer from the source of light.

For more distinct revealing of light refraction picture in a boundary layer a simple method is proposed. Namely to limit the width of the light flux at the model surface to the size of a zone of light beams refraction is suffered. The width of this zone is comparable with the boundary layer thickness on a model surface.

The new scheme for observing of light refraction picture in the boundary layer is presented in Fig. 2. It differs from the traditional scheme by installation of additional blind which limits the width of light bunch spreading over an aerofoil surface. That allows to get rid of light flux propagation over the area of light refraction picture above a boundary layer.

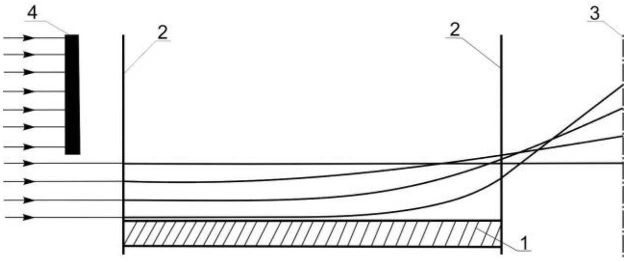

Fig. 2. Scheme of new method. 1 – aerofoil surface; 2 – optical windows; 3 – focusing plane of shadowgraph device; 4 – blind.

3 Experimental arrangement and test conditions

Experimental investigations of light scattering in a boundary layer were carried out in the transonic wind tunnel T-112 of the TsAGI. This facility has a test section size of 0.6m×0.6m×2.6m. The Mach number domain extends from 0.6 to 1.25. The top and bottom walls of the test section are perforated. The side not perforated walls are equipped with special Schlieren quality windows for optical researches. The experimental study was carried out on aerodynamic profiles models of different types with a relative thickness of 9 %, 12 % and 15 %, a chord length $c = 0.2m$. Angles of attack α differs from 0° to 6°. Investigations were carried out at Mach numbers M_∞=0.6 – 0.8. Reynolds number values are changed in the range $(2.4–3.0)\cdot 10^6$. Models were fixed between the optical windows in a test section of the wind tunnel on a special mechanism allowing continuous change of the angle of attack α.

4 Experimental investigations of light scattering in a boundary layer

In Fig. 3 the photo of the light bunch limited on width at the model upper surface is shown. This photo was made in absence of incoming flow and the boundary layer on a model. Restriction of a light bunch width was carried out with the help of a blind, executed in accordance with the profile upper surface shape.

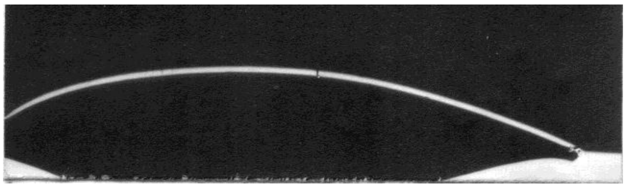
Fig. 3. Photograph of light bunch at upper surface of a model without flow.

The photograph in Fig. 4 shows an example of a picture of light scattering in the boundary layer on the upper surface of the model. The photo was received by means of new method at free stream Mach number M_∞=0,609 and flow incidence α =0 °.

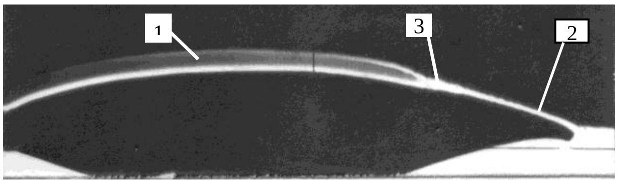

Fig. 4. Photograph of light scattering in a boundary layer. 1 – laminar boundary layer; 2 – turbulent boundary layer; 3 – intermediate layer.

In this photo the refraction light scattering is observed in a forward part of the upper surface of the aerofoil model where a laminar boundary layer is. The laminar state of a boundary layer has been confirmed by making use of standard china-clay method.

In the rear part of the upper surface of the aerofoil model where turbulent character of a boundary layer without separation takes place, light scattering practically was not observed.

Between these two parts one can see certain area of gradual weakening of light dispersion which corresponds to transition from laminar boundary layer to turbulent one (intermediate layer).

To test results obtained by new optical method, corresponding investigations were carried out of the boundary layer state on the aerofoil model by china-clay coating method. The thickness of coating layer was about 0.1mm. The boundary layer state was defined simultaneously with the help of china-clay and new proposed optical method at different angles of attack and free stream velocity.

The results of investigations have shown that the position of the boundary layer transition defined by china-clay coating method is in limits from the beginning to the middle of transition area observed on the light dispersion pattern (see Fig. 5). Concrete position depends on Mach number and an angle of incidence.

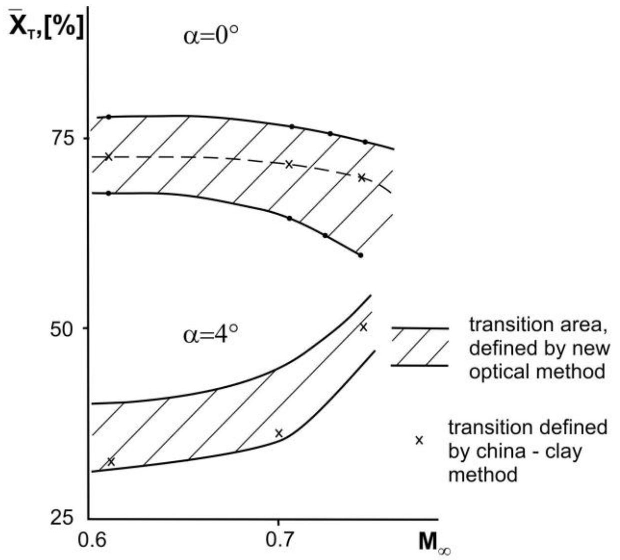

Fig. 5. Position of boundary layer transition.

The numerous investigations of light refraction in a boundary layer provided by new optical method on different aerofoil models of various types have shown that a light bunch scattering effect is clearly observed at a laminar state of the boundary layer and practically not observed in the turbulent state.

Because the value of light refraction is proportional to the value of density cross-section gradient, it is possible to make a conclusion that in laminar boundary layer cross-section gradients of density have essentially higher values, than in the turbulent boundary layer. This distinction of density gradients in laminar and turbulent boundary layers is associate with the fact that static pressure across a boundary layer is almost constantly; hence, the gradient of density is defined only by the temperature gradient, as $p = \rho RT$. When laminar flow there is an appreciable change in the temperature between the layers. In turbulent boundary layer, owing to the intensive mixing layers, the temperature across the boundary layer is aligned; density gradients become negligible and do not create an appreciable light dispersion.

Investigations of light scattering in the boundary layer can be provided also by advanced way. The described above restriction of light bunch width to a narrow strip allows one clearly observe the pattern of light dispersion in the boundary layer. However observed optical pattern does not show the direction of light dispersion which corresponds to the direction of density gradient. In order to define this direction one can divide light beam into separate light bunches. Fig. 6 shows an example of the light bunch with such division at the model upper surface. This photo was made in absence of a free stream flow.

Fig. 6. Photograph of divided light bunch at upper surface of a model without flow.

In Fig. 7 an example of separate light beams dispersion at an upper surface of aerofoil model at M_∞=0.6 and α =0° is shown. Dividing the light bunch into separate small beams allows to reveal distinctly both size and direction of light dispersion which correspond to size and direction of density gradients. Illumination by separate light beams can be made by means of the way described above, and by means of the laser beam.

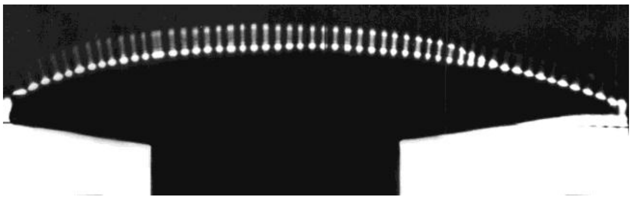

Fig. 7. Photograph of divided light bunch at upper surface of a model with flow.

5 Experimental investigations of transition trips efficiency

The offered new optical method for boundary layer investigation, based on the registration of light scattering, has shown its high sensitivity to the degree of boundary layers mixing. As noted above, in the full developed turbulent flow the dispersion is not observed. This effect can be a good criterion for transition trips choice for artificial flow turbulization.

Selection of the type, size and transition trips location depends on the Reynolds number, the boundary layer thickness, pressure distribution, free stream initial turbulence and other factors. For this reason the selection of transition trips in each specific case represents an independent problem.

Both natural and artificial boundary layer turbulization occur not immediately. The size of the transitive area is an important criterion in selecting of the concrete kind of transition trip and it can be defined by the new optical method. The efficiency of two known types of transition trips was investigated on the model with extended part of the laminar boundary layer at M_∞=0.6 and α =0°.

The picture of light dispersion in a boundary layer on the upper surface of aerofoil without transition trips shows that total natural turbulization occurs approximately at a distance of 80 % of the model chord that corresponds to the value of the Reynolds number $1.9 \cdot 10^6$, calculated on the length of the laminar part and free stream parameters (see Fig. 8.).

At first the most common type of transition trips as the carborundum strip width of 5mm with an average roughness nearby 0.1mm has been investigated.

Fig. 8. Photograph of light scattering in a boundary layer without any transition trips. 1 – the end of boundary layer transition area.

Strip was located at 10 % of the model chord. The picture of light dispersion in a boundary layer has shown that the total turbulization occurs at the distance corresponding to the Reynolds number $\mathrm{Re}_T = 1.92 \cdot 10^6$, calculated by free stream parameters and distance from strip till the end of intermediate area (see Fig. 9).

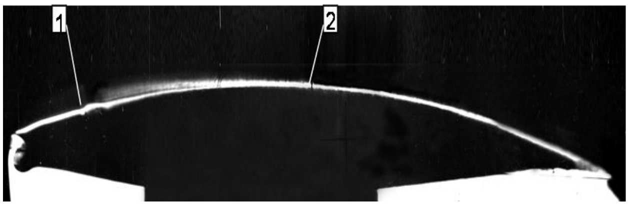

Fig. 9. Photograph of light scattering in a boundary layer with carborundum strip. 1 – location of strip; 2 – the end of transition area.

Then the efficiency of the simplest type of transition trips in the form of a wire by diameter 0.12мм has been also investigated. As in case of the carborundum strip the wire was located at the same position, 10 % of a model chord The picture of light dispersion has shown that in this case one can see somewhat shorter transitive distance corresponding to $\mathrm{Re}_T = 0.84 \cdot 10^6$, (Fig. 10).

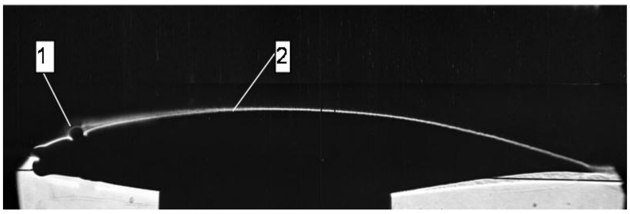

Fig. 10. Photograph of light scattering in a boundary layer with wire transition trip. 1 – location of wire; 2 – the end of transition area.

The resulted examples of efficiency of two various types of transition trips allow to make a very definite conclusion that the total turbulization occurs not immediately after transition trip, but of a distance corresponding to Reynolds number $\mathrm{Re}_{\mathrm{T}} = (0.84 - 0.92) \cdot 10^6$ and depends on its type and size.

4 Conclusions

The effect of light scattering (dispersion) in the boundary layer is more clearly shown when the light bunch is restricted till the width close to the thickness of the boundary layer.

Registration of light dispersion by new method allows defining the sizes of laminar, intermediate and turbulent areas of the boundary layer.

The offered new optical method permits to provide the comparison of different types of boundary layer transition trips.

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