PARTICLE IMAGE SURFACE FLOW VISUALIZATION AND SKIN-FRICTION MEASUREMENT

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Abstract

Particle Image Surface Flow Visualization (PISFV) consists in measurement the velocity field of thin oil-film movement on the model surface in external gas flow. Surface streamlines and wall shear stress (skin-friction) field can be calculated from this velocity field. Surface streamlines are restored from velocity direction distribution. To calculate shear stress field it is necessary also to know the velocity value, oil-film thickness and oil dynamic viscosity in each point of the model surface. Particle distribution inside oil layer and the oil rheology can effect on accuracy of skin-friction measurements. The aim of the present work is to investigate the opportunity of wall shear stress field measurement by PISFV method. Flat plate in the subsonic flow with a known surface wall shear stress is used to test the method. Linear relationship between measured oil (particle) shift and shear stress values in a wide range of oil thicknesses and oil shifts suggests the possibility of skin-friction measurements.

1 Introduction

Wall shear stress is one of the fundamental quantities in fluid mechanics, which is important to determine the skin-friction drag. Up to half of the drag of commercial aircraft in cruise flight is a viscos skin-friction drag.

Shear stress remains a difficult quantity to measure experimentally. Most skin-friction measurement techniques are indirect and local methods that provide a value of the skin-friction magnitude at the location of a gage. Known global skin-friction measurement methods such as oil-film interferometry [1, 2], liquid crystals [3], global luminescent oil-film (GLOF) [4, 5], Surface Stress Sensitive Films (S3F) [6] have essential restrictions and are used rarely. Particle Image Surface Flow Visualization (PISFV) method [7, 8] is rather simple, universal and potentially can give shear stress fields. The aim of the present work is to investigate the opportunity of wall shear stress field measurement by PISFV method.

2 Overview of particle image surface flow visualization

PISFV method was proposed more than 10 years ago. The idea of the method is to measure some small shift of an oil film applied on the investigated object surface and to restore the complete pattern of surface flow numerically. Optically contrast (luminescent) particles are added to the oil film and at least two images of particle distribution on the model surface are acquired at some time interval in the flow by CCD camera. Processing of such images using cross-correlation analysis (similarly to PIV method) provides the determination of particle displacement vectors. (Possible model shift on the images should be subtracted from particle displacement to obtain oil shift vectors.) The direction of oil shift coincides with the direction of the surface streamlines that allows to calculate these streamlines. Even the small oil shift for a few pixels of image is sufficient for surface flow visualization. Oil redistribution on investigated surface is insignificant and several flow regimes can be studied using one oil film application. Method can be adapted for any flow types by using the oil of appropriate viscosity.

Examples of flow visualization are shown in Fig.1-3. Fig.1 presents flow on Δ-wing model at subsonic speed 50m/sec. Oil viscosity was 6400 cSt and time between image acquisitions was 20 sec.

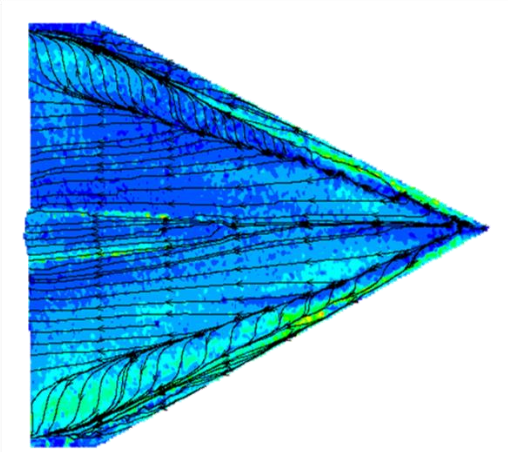


Fig.1. Surface flow visualization on Δ-wing model (V_∞=50 m/s α=12)

Result on Fig. 2 was received at transonic speed with oil viscosity 80000 cSt and with the same time interval 20 sec.

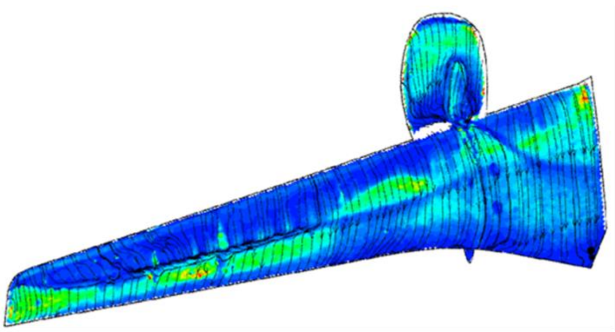
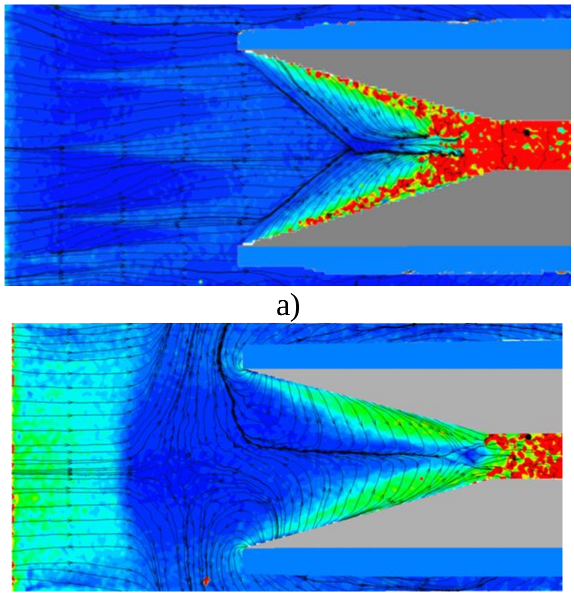


Fig. 2. Surface flow visualization on the wing of passenger airplane (M=0.8 α=3)

Hypersonic visualization (Fig.3) was done in Ludwiege type wind tunnel. First image was acquired before wind tunnel start and a second - at 40msec after flow initialization. Oil viscosity was only 1000cSt.

Color corresponds to magnitude of oil shift. Shift increases from blue to red (rainbow palette).

Theoretically the shear stress field can be calculated from oil shift magnitude if oil film thickness is known.



a)

b)

Fig.3. Surface flow visualization on the flat plate with two wedges at M=5: a - sharp plate; b - bluntness radius of the plate leading edge is r=2 mm

If oil film has thickness h and oil viscosity μ and is moving under an action of shear stress τ caused by external airflow (Fig. 4) then the oil flow has linear velocity profile across the film with velocity V of free boundary of the film and:

$$\tau = \mu \frac{dV}{dy} = \mu \frac{V}{h} \qquad (1)$$

Equation (1) is correct only for Newtonian liquids. The question is whether the oil is the Newtonian fluid requires validation. Usually the high molecular weight silicone oil is used in the PISFV method and it is not obvious that it is a Newtonian liquid.

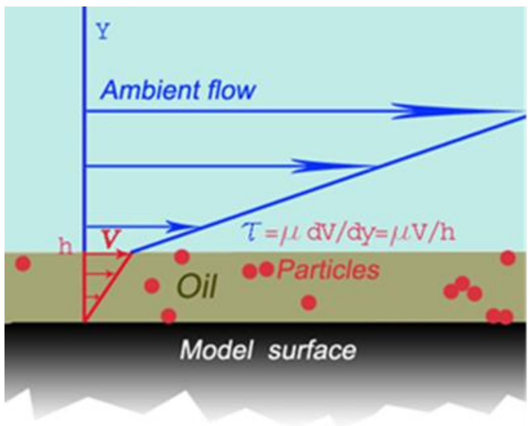


Fig. 4. Oil film movement under the shear stress

If oil contains some optically contrast particles and they are moving with the oil, the oil velocity can be determined using cross-correlation analysis. Two images of particles distribution on a model surface are acquired at some time interval Δt. Particles are displaced in this time interval on a distance l, that is

$$V = l/\Delta t \qquad (2)$$

Particles have some distribution inside oil film by the depth and particle displacement depends on depth of the particles in the oil film y ($0 \le y \le h$, measured from the model surface):

$$l = \frac{\tau y}{\mu}\Delta t \qquad (3)$$

Thus, correlation data processing gives some average shift of particles. This average shift is probably proportional to shear stress τ. This statement must be checked.

The problem of how to measure oil thickness is not discussed in this paper.

3 Test flow

3.1 Wind tunnel and test model

Experiments were made in open-circuit subsonic wind tunnel (Fig. 5) with speed range of 1-60 m/s.

Fig. 5. Subsonic wind tunnel

Flow speed is controlled by fan rotation speed and is measured by barometric method. Wind tunnel has square test section 200x200 mm and length of 600 mm. Two opposite side walls of the test section were made of organic glass to provide optical access to the model. The model was the flat plate of 400 mm length, 200 mm width and 10 mm thickness with sharp leading edge chamfered at 30 degrees angle (see Fig.6). Model was installed vertically between non-transparent walls of test section. Model was equipped with two Preston tube and static

pressure tap for share stress measurements. After the CFD simulation the plate angle of attack was chosen to be $\alpha = -2^o$.

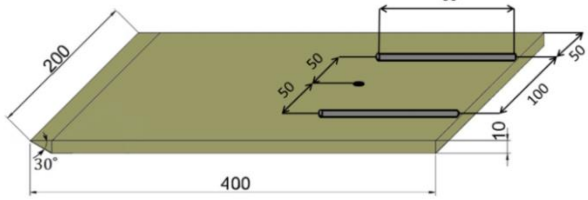


Fig. 6. Test model

3.2 CFD simulation

Numerical simulation of flow around the flat plate in the wind tunnel has been carried out by S. Drozdov and D. Fedorov (TsAGI) [9]. The calculations were performed using the software package FLUENT within the Reynolds averaged Navier-Stokes equations and using the Spalart-Allmaras turbulence models.

The calculation of two-dimensional flow in empty wind tunnel (subsonic nozzle, test section and the diffuser) was fulfilled first. After calculation setting which was carried out by the pressure measured at the wall of the test section, thethree-dimensional calculation of flow around the plate in wind tunnel was performed. Some CFD results are presented in Fig. 8. Based on calculation results the plate angle of attack was chosen to be -2 degrees. Substantially constant shear stress is realized on the most part of the plate at this angle of attack (Fig. 9).

3.3 Wall shear stress measurement by Preston tube

For CFD results validation the shear stress on the plate was measured by Preston tube. The Preston tube method is based on the difference of the static p_{st} and the total p_t pressures at the wall. Two Preston tubes were placed on plate surface

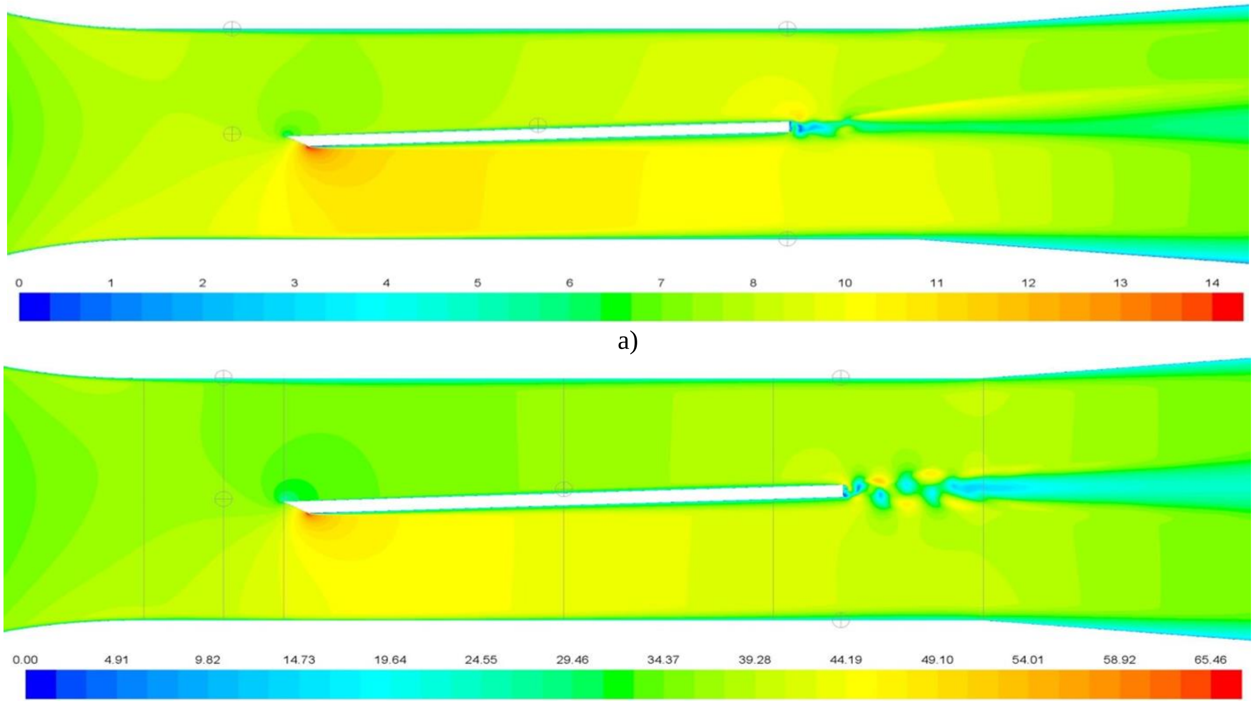


Fig. 8. CFD results: velocity fields around flat plate in wind tunnel test section at angle of attack -2 degree, free-stream velocity is 6.5 m/s (a) and is 30 m/s (b)

parallel to the free-stream velocity (Fig. 7). The tubes have an external diameter *d* of 1.1 and 0.8 mm. Static pressure was measured on the plate surface between Preston tubes.

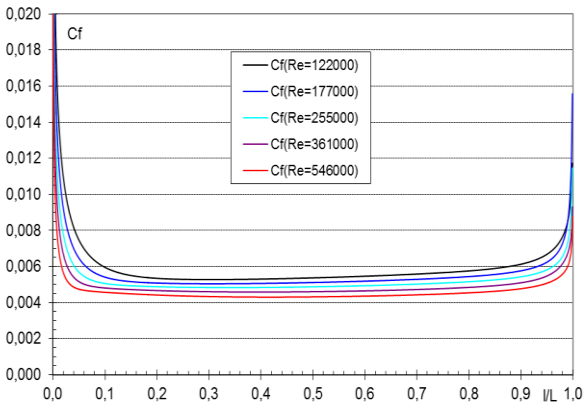


Fig. 9. CFD results. Shear stress coefficient distribution along the central line of the plate

Static pressure on the plate and total pressure in the boundary layer were measured at all possible wind tunnel speeds. The shear stress τ was calculated according to the Bechert formula [10].

$$\tau^+ = [28.44(p^+)^2 + 6.61\cdot 10^{-6}(p^+)^{3.5}]^{(1/4)}, \quad (4)$$

where $\tau^+ = \dfrac{\tau_w d^2}{\rho v^2}$, $p^+ = \dfrac{pd^2}{\rho v^2}$, $p = p_t - p_{st}$

ρ is the gas density, v is the kinematic viscosity of the gas.

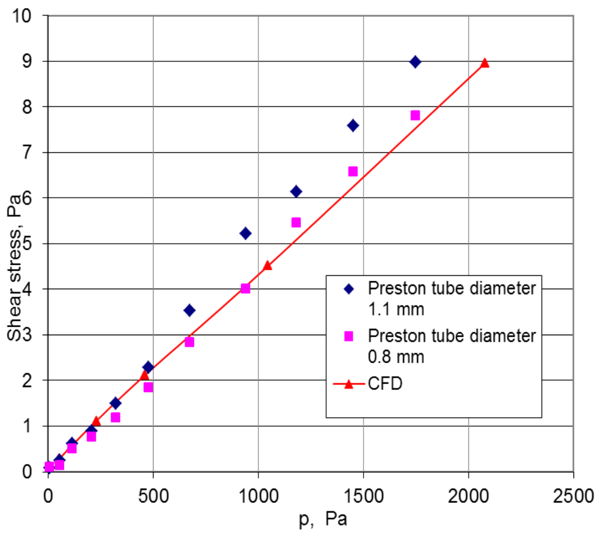


Fig. 10. Calculated and measured shear stress vs difference between static and the total pressures in the wind tunnel

Comparison of the computed shear stress at the Preston tube positions and experimental results is presented in Fig.6 In the figure the measured and computed shear stress characterizes depend on dynamic pressure (difference between total pressure and static pressure). Static pressure is measured on the test section wall outside of model influence.

Figure 10 illustrates the convergence of the numerical simulation with experiment. Especially good agreement was obtained for a thin Preston tube with a diameter of 0.8 mm. This good agreement allows to accept calculated skin-friction values of the whole plate surface as correct ones.

4 Experiment and results

4.1 Model preparation

Investigated side of the model surface was covered by white paint and carefully polished. Then a set of luminescent markers (small luminescent spots) was applied on the models surface. The markers are used to compensate possible model displacement during a test.

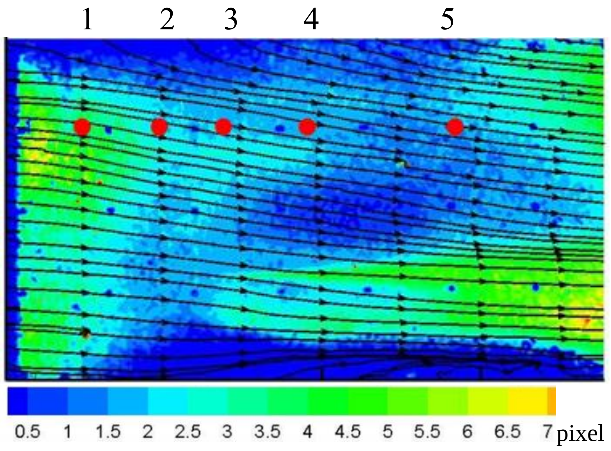


Fig. 11 Surface streamlines and false-color field of oil displacement on the plate at free-stream velocity 45 m/c; red spots are points marked on Fig.8

A mixture of silicon oil and crystal phosphor particles diluted in toluene was applied on the model surface by spray gun. The thickness of oil film was about 20-40 micrometers. Particles had diameters in the range of 3-5 microns. Silicon oil viscosity was 10000 sSt.

4.2 Measurement system

The model was illuminated by UV flash lamp operated with electric power W=100 J. The distance from the lamp to the model was about 0.5 m. Images were acquired by a digital CCD-camera of 4008*2672 pixels resolution (VS-CTT-11002). A combination of blue and yellow glass filters crossing with UV filter of flash lamp was installed in front of the camera lens (Nikkor F50mm). The distance from the camera to the model was also about 0.5 m.

4.3 Measurement results

Plate model covered by oil with crystal phosphor particles was installed in wind tunnel test section and exposed to the flow with the speeds from 5 to 50 m/c. Flow speed increased sequentially with some step. Several images of the model were acquired with time interval 10 second at each flow speed. Pairs of images at each flow speed were processed by the correlation method and oil displacement was determined. Oil film on plate surface had a variable thickness so the oil was shifted irregularly. Figure 7 presents surface streamlines and false-color field of oil displacement on the plate at free-stream velocity 45 m/c. Streamlines have vertical component because of gravity force.

Five points were selected on the plate surface (red spots in Fig.11) and for these points the oil displacement magnitude was presented as a function of CFD predicted shear stress. The result is shown in Fig. 12. It can be seen that the displacement of the particles depends lineary on share stress value, and approximation lines of experimental data are passing through the zero. It means that the used oil is a Newtonian fluid (Equation (1) is true) and oil shift is measured correctly.

Only one data point fell out significantly from a linear trend. This point was obtained with large oil displacement. The measured displacement is 3.6 pixels, while the expected is 4.3. The reason may be the fact that particles are distributed inside oil film by the depth and are moving at different speeds depending on their depth. At a large displacements the particle ensemble is changing and correlation method works with an error.

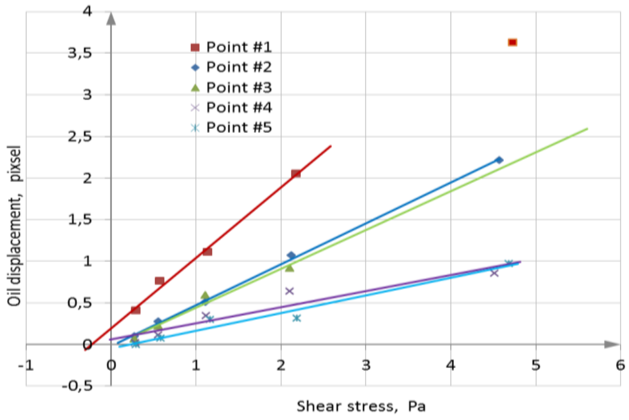


Fig. 12: Measured oil (particle) displacement vs shear stress

It is possible to estimate potential accuracy of skin-friction measurement based on an accuracy of the trend line passing through a zero. Potential skin-friction measurement accuracy can be estimated as better than 0.25Pa. Naturally, provided that the thickness of the oil is known without error.

5 Conclusions

Linear relationship between the measured oil (particle) shift and shear stress value in a wide range of oil thicknesses and oil shift magnitudes suggests the possibility of skin-friction measurements.

Apparently, these studies should be carried out for all types of oils which will be chosen to measure the friction stress.

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