PIV on the surface

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ABSTRACT

New approach to surface flow visualization based on combination of oil film method with PIV approach is presented. Oil film is seeded with optically contrast particles and two or more images of these contrast particles are acquired at some time interval at desirable flow parameters. Cross-correlation analysis of these images allows to determine parameters of oil film movement and, as a result, to restore surface flow parameters. Surface streamlines can be restored correctly since the directions of oil shift vectors are coincident with the direction of surface streamlines. Shear stress distribution can be visualized since the magnitudes of oil shift vectors are proportional to shear stress value. Since oil film is moved along the model surface the restoration of surface streamlines is completely correct. Specific feature of presented method is that the model can move between acquisition of images, so this model movement should be determined and subtracted from particles movement to get the correct surface flow parameters. Since only small shift of oil film is analyzed, multiple tests with different airflow parameters can be made using single model preparation. Since oil viscosity can be varied within a wide range and can be fitted to expected shear stress value, different flow types ranging from low-speed to high-speed can be studied using this method.

Keywords: surface flow visualization, oil film method, cross-correlation analysis, particle image velocimetry, PIV, particle image surface flow visualization, PISFV

1. Background

The method of oil film is widely used in experimental aerodynamics for surface flow visualization. In this method the surface of investigated model is covered with thin film or with the set of points of the oil, usually containing some color pigment particles. Being exposed to the external airflow the oil begins to flow under an action of shear stress on the investigated surface forming the traces along the surface streamlines. Oil film method is very simple and effective, but is quite time and energy consuming since it needs separate model preparation and separate wind tunnel test for each investigated regime. Also the time of stable regime of wind tunnel operation should be much longer than the time of wind tunnel start and stop to decrease an influence of airflow with undesirable parameters on obtained visualization results.

Combination of oil film method with PIV approach allows to solve the above problems. This method was proposed in TsAGI recently [1-2] and similarly to Particle Image Velocimetry method was called the Particle Image Surface Flow Visualization (PISFV) method. In PISFV method some optically contrast hard particles are added to the oil film and two (or more) images of particles distribution on investigated surface are acquired at some time interval at the stable parameters of airflow.

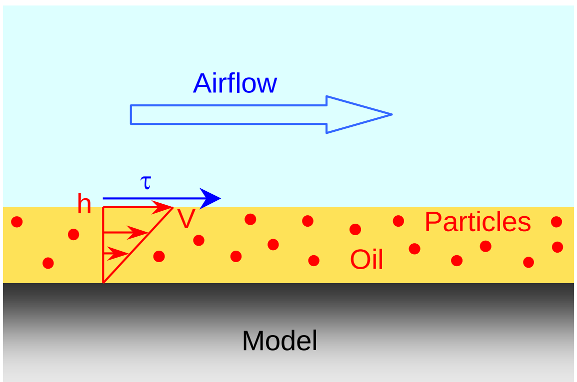


Figure 1 Oil film movement.

The movement of thin oil film of thickness *h* and viscosity μ under an action of shear stress τ and pressure gradient *dp/dx* caused by external airflow (2-dimential case) can be found by solving the Navier-Stocks equation with appropriate boundary conditions. Velocity profile in oil film in this case will be described as:

$$V = \frac{\tau}{\mu} y - \left(\frac{dp}{dx} \Big/ \mu \right) \left(hy - \frac{y^2}{2} \right). \quad (1)$$

In real cases of thin oil film (thickness of about 20 μm) a contribution of pressure gradient into the movement of oil film is significant only in the regions of high gradients of pressure, such as shock waves. In the other regions the movement of oil film is determined mainly by share stress of external flow causing about linear velocity profile (Fig.1).

If some optically contrast hard particles are added to oil film (on the surface or inside the film) they are moving with the oil. At some time interval Δt the particle is moved on some distance l dependent on the depth of the particle in the oil film y ($0 \le y \le h$):

$$l = \frac{\tau y}{\mu} \Delta t \, . \tag{2}$$

Thus, two images of particles distribution on the surface acquired at the investigated test parameters in some time interval Δt provides an information allowing to determine some small shift of oil film on the model surface. Processing of this pair of images with cross-correlation analysis results in the vectors of particles shifts. Magnitude of particles shift is proportional to shear stress value and direction is coincident with direction of surface streamline. Correlation data processing deals with small interrogation window of images containing some number of particles; individual particles are not analyzed. Particles are distributed on oil film depth and correlation data processing gives some average shift of these particles. This average shift is also proportional to the shear stress τ.

Measurement volume in this method is determined by oil film applied on the model surface but not by the laser sheet. Images are acquired under the uniform illumination of the model surface. To increase the contrast of particles on the images it is preferable to use not the scattering but luminescent particles, e.g. crystal phosphors. Appropriate light source should be used in this case to excite luminescence of such particles. Acquisition of luminescent particles also allows to exclude any undesirable scattered light on the images using appropriate crossing optical filters on excitation light source and CCD camera.

Time interval between images should be comparable with the wind tunnel starting time and the time of investigated regime changing to avoid too fast oil flowing down from the model surface. Thus the optimal time interval for continuous wave wind tunnels is from few seconds to some dozens of seconds. It means that nothing specific double-exposure or fast camera is needed for this method, as well as the light source for this method is much simpler than double-pulse laser. On the other hand, it means that oil flow speed is very low – of the order of 1 mm/sec. In combination with quite high viscosity of the oil (1000-200000 cSt) and its quite high specific gravity (about 1g/cm^3) the problem of seeding particles slip becomes negligible even in the regions of high gradients of shear stress.

Since only small shift of oil film is analyzed, multiple tests with different airflow parameters can be made using single model preparation. Also, since both analyzed images are acquired at the same flow parameters, the obtained pattern represents oil film displacement precisely at these parameters and is free of flow prehistory influence, including wind tunnel launching regime.

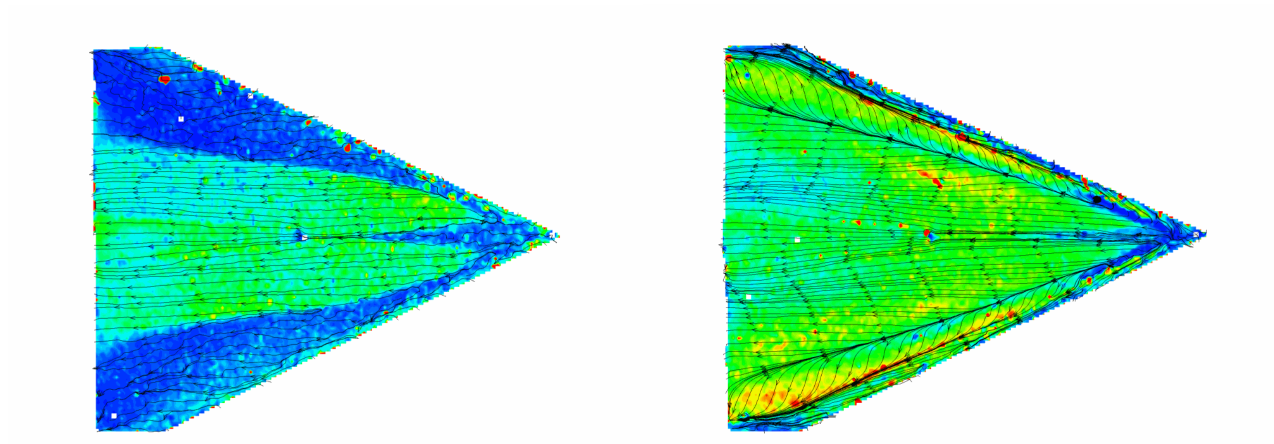
But the model image can move during experiment because of model deformation and vibration. Possible model shift on the images should be subtracted from particle displacement to obtain oil shift vectors in respect with the model surface. For this purpose a set of markers are firmly fixed on the model surface prior oil film application. Displacements of these markers are determined from the same images separately to displacements of particles and the shift of each model surface point is approximated from markers displacements. The procedure of model shift subtraction is specific for presented method in respect with PIV method. This procedure needs some specific modification of image processing algorithm.

Obtained array of oil shift vectors allows to restore surface streamlines. This operation is completely correct since surface streamlines goes along the model surface and nothing perpendicular oil film movement takes place. Shear stress values also can be calculated if oil film thickness, oil viscosity and particles distribution inside oil film are known quite precisely for each point of model surface. Oil viscosity can be determined quite easily if model temperature is known. Oil film thickness should be determined simultaneously with particle shift measurements since some oil redistribution takes place in the airflow. This procedure needs some modification of PISFV method and is now under development. The most problematic aspect is to determine the particles distribution inside oil film. The easiest approach is to assume uniform distribution of particles inside the oil film, but this assumption is not correct in all cases. This problem is under investigation now, but not yet solved. Thus the correct shear stress value can not yet be determined at the present moment. However, qualitative pattern of shear stress distribution can be obtained quite easily and allows to visualize specific features of investigated flow structure, i.e. positions of separation zones, shock waves and boundary layer transition.

Expression (2) shows that at investigated share stress value the oil shift magnitude is determined by three parameters: time interval between image acquisition, oil film thickness and oil viscosity. But minimal time interval is determined by wind tunnel construction while increasing of the time interval is disadvantageous. Oil film thickness can not be too large to exclude its influence on the airflow and can not be too small otherwise the particles will not be deepen in oil and may occur be firmly fixed on the model surface. Reasonable oil film thickness is about 20÷40 μm. Oil viscosity can be varied in large range and can be adjusted to expected share stress value. Oil viscosity should be selected to provide reasonable oil shift in selected time interval to get particles shift on acquired images just for few pixels, i.e. oil viscosity in PISFV method should be much larger than that in the regular oil film method. As a result, different flow types ranging from low-speed to high-speed can be studied using this method.

2. Low speed application

Fig.2 shows surface streamlines and shear stress field (false-color pattern of oil shift magnitude) on 65^o delta wing model of 420 mm length and 332 mm span with rounded leading edges at flow speed 50 m/s and α=0^o (a) and α=10^o (b). Joint experiment was made by DLR and TsAGI in 1 m subsonic wind tunnel in DLR, Goettingen [3]. Flow structure on the upper surface of delta wing was investigated using PISFV method. Silicon oil containing crystal phosphor particles was applied on the model surface. Luminescence of crystal phosphor was excited by UV flash lamps. A pair of luminescent particles images was acquired at each flow parameters with PCO4000 CCD camera (4008×2671 pixels) with time interval of 15 sec between them. All tests were made at constant flow speed 50 m/s varying the angle of attack.



a) b)

Figure 2 Surface streamlines and shear stress field on 65^o delta wing at flow speed 50 m/s and α=0^o (a) and α=10^o (b).

Data processing of acquired images was made both by standard PIV software of DLR (PivView program) and by specific software of TsAGI. Specific feature of TsAGI's software is that it provides the compensation of model displacement in two images (displacement caused by possible model deformation and vibration). For this purpose a set of bright luminescent markers was firmly fixed on the model surface before oil application. Model shift on the images was determined using these markers and then was subtracted from particles shift vectors. Fortunately, model shift in low-speed flow was negligible and, as a result, both software packages provided practically equivalent results.

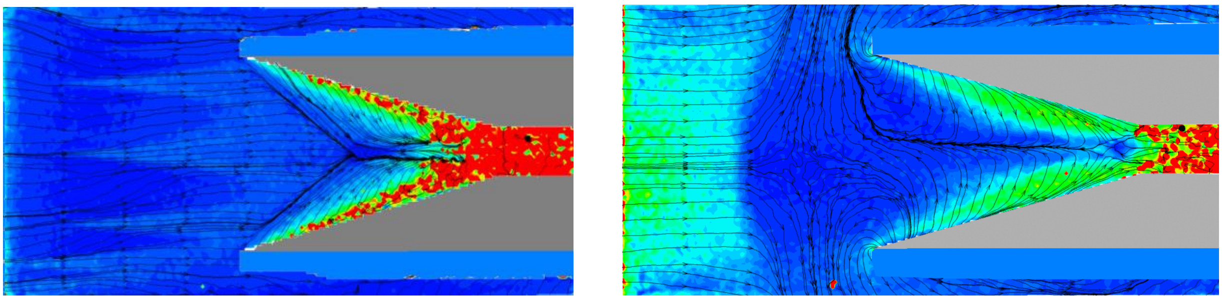
Flow structure development on the upper surface of delta wing with the angle of attack was investigated. 30 angles of attack were investigated in one test using single model preparation (oil film application). Figure 2 presents surface streamlines pattern combined with false-color distribution of oil shift magnitude. Red-yellow-green-blue colors correspond to larger-to-lower oil shift magnitude values. At α=0^o (Fig.2a) the shear stress value in the center on the wing is essentially higher than near the leading edges and can be attributed to turbulent boundary layer, while near the leading edges the boundary layer is laminar. At negative angles of attack the turbulent area is widening with an increase of angle of attack. But at the positive angles of attack the separation vortex appears along the leading edges and boundary layer transition takes place at the reattachment line of this vortex. Strength of this vortex is growing with an increase of angle of attack forming flow structure typical for delta wing (see Fig.2b).

3. High speed application

PISFV method was used to investigate flow on the blunted flat plate of 320 mm length and 150 mm width with two 15^o wedges installed on the plate surface at the distance of 128 mm from plate leading edge [4]. Wedges form the channel of contraction ratio h/H=0.25. Blunting radius of the plate leading edge was changed from r=0 mm to r=4 mm.

Test was performed at high speeds in Ludwieg wind tunnel UT-1 (TsAGI) having flow duration 40 msec. Short flow duration leads to necessity to use the oil of quite low viscosity, much lower than the one used in long-duration wind tunnels. On the other hand the variation of shear stress value from undisturbed flow (leading part of the plate) to the channel throat is very large, as a result the single oil can not provide visualization of flow structure on the whole plate surface and different oils (of different viscosities) should be used for investigation of different features of such flow. Luminescence of crystal phosphor particles was excited by UV flash lamp synchronized with flow initialization of wind tunnel. First image was acquired before wind tunnel run and the second - at the end of the run. Images were acquired with “VideoScan VS-CTT-11002” CCD camera of 11 Megapixel resolution. A set of luminescent markers was placed on the model surface to exclude model shift on the image in the flow. Taking into account of the model displacement is very critical for shock wind tunnel since the model vibration in shock flow is very high and the model displacement on the image is much higher than oil film shift on the model surface.

Surface streamlines and shear stress field at M=5 and $Re_{\infty L}$=27x10^6 are presented on Figure 3 for bluntness radii r=0.5mm (a) and r=2mm (b). Oil viscosity in these tests was chosen to investigate flow structure in the region of low shear stress value. Regular flow is clearly visualized at low bluntness radius of the plate (Fig.3a). Additionally the shear stress distribution pattern visualizes turbulent wedges on the leading part of the plate proving that boundary layer is in the turbulent state at the beginning of the wedges. Increase of plate bluntness leads to flow blocking in the channel between wedges (Fig.3b) and to the formation of global separation ahead the wedges.



a) b)

Figure 3 Surface streamlines and shear stress field on blunted flat plate (bluntness radii r=0.5mm (a) and r=2mm (b)) with two wedges (channel contraction ratio h/H=0.25) at M=5 and $Re_{\infty L}$=27x10^6.

PISFV method provided visualization of significantly different flow structures determined by flat plate bluntness influence. Chosen oil viscosity was too low for shear stress values in the channel throat between wedges, as a result the oil film shift in the channel throat occurs too high for correct correlation analysis. For investigation of flow structure in the channel throat the oil of much higher viscosity was used.

4. Transonic speed application

PISFV method was used to investigate surface flow structure on the wing of civil aircraft model at transonic speed [5]. Experiments were performed in large transonic wind tunnel T-128 (TsAGI) having 2.75×2.75 m^2 test section. Cruise configuration of civil aircraft model of 2 m span was investigated. Two tests were made at Mach numbers 0.8 and 0.82 varying an angle of attach in the range of 1.5 to 5^o (8 points in each test). Two images were acquired at each test point with time interval 20 sec. Images were acquired with 'Alta U16M' CCD camera of 4098×4098 pixels resolution. Luminescence of crystal phosphor particles was excited by UV flash lamp with electrical power 500 J. Distance from the lamp and CCD camera to the model was about 1.5 m. A set of luminescent markers was placed on the model surface to exclude model shift on the images.

Figure 4 presents surface flow pattern on the civil aircraft model wing at Mach number M=0.82, Reynolds number Re=3*10^6 and angle of attack α=2.5^0. Surface streamlines are combined with false-color map of shift vector magnitudes. Surface streamlines pattern clearly visualize positions of shock wave and separation zones. Oil shift magnitude patterns clearly visualize boundary layer transition although oil film thickness was not uniform.

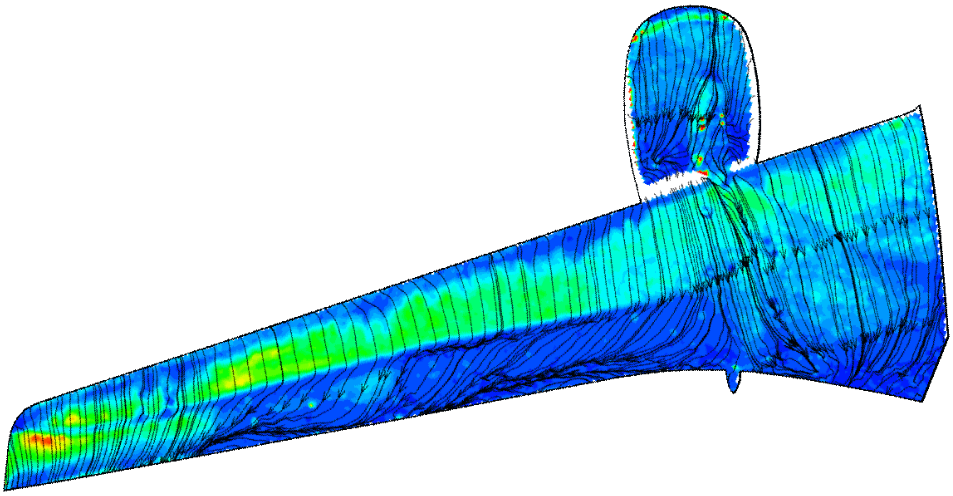


Figure 4 Surface streamlines and shear stress field on the civil aircraft model wing at M=0.82, α=2.5^0.

It should be noted that PISFV method provides average flow pattern but not instantaneous. Averaging time is equal to time interval between two images acquired at test regim, and in presented tests was 20 seconds.

Obtained patterns allow to analyse surface flow structure and to verify CFD results.

5. Conclusions

Particle Image Surface Flow Visualization (PISFV) method is a new approach to surface flow investigation using digital image acquisition and processing. The idea of new method is to register some small shift of oil film applied on investigated surface and to restore surface flow pattern numerically. That means that PISVF method is obtained as combination of oil film method with PIV. New method has the next advantages in respect with traditional surface oil-flow visualization methods:

- multiple tests with different airflow parameters can be made using single model preparation;
- method is insensitive to previous oil film movement, e.g. to oil film movement during wind tunnel starting;
- numerical presentation of surface flow obtained by this method can be used not only for generation of surface flow pattern but also for some further calculations or for numerical comparison with other results (e.g. with CFD results);
- method provides visualization of not only surface streamlines but also of shear stress distribution, particularly to visualize laminar-turbulent boundary layer transition;
- method can be used for investigation of different kinds of flows ranging from subsonic to high-speed flows.

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