EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF LOCAL AERODYNAMICS OF CIVIL AIRCRAFT

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Abstract

Experimental and numerical investigations of local separations, surface streamlines and shear stress distribution on typical civil aircraft is carried out. Visualization in experiments is performed on the basis of method of viscous oil with small displacement. Experimental results are compared with results of calculations on the basis of RANS equations.

1 Introduction

Different experimental methods are used for surface visualization allowing understanding physical phenomena of complicated 3D flows. The method of oil film is one of widely used for surface visualization [1]. It consists in applying oil layer to the model's surface. Usually, kerosene, motor oil or their mixture is used as the base, while soot (alternatively, luminescent substances) serves as the pigment. Under the impact of air flow the oil moves over the model's surface, making tracks of the pigment over the flow lines and being accumulated in the areas of flow separation. Ideally, the oil should start moving when the wind tunnel flow speed is stabilized. However, actually it moves simultaneously with the tunnel's start-up. The method of oil film is very simple and efficient. The matter is that it requires certain preparation of the model and specific long-lasting launches of the tunnel for each analyzed flow regime.

In our work, new experimental visualization method for surface streamlines and shear stress distribution is used. It employs correlation analysis of the images produced by the particles in viscous oil (being applied to the studied surface and moving under the action of aerodynamic forces [2]). The method enables reconstructing surface streamlines without significant displacements of the oil film. This feature provides opportunity to study several flow regimes without extra preparation of the model. The algorithms of correlation analysis of the images were developed within the framework of Particle Image Velocimetry (PIV). Therefore, the proposed method was called Particle Image Surface Flow Visualization (PISFV). It is also referred to as the method of multi-usable oil or the method of "viscous oil".

Experimental results for typical civil aircraft are compared with numerical ones based on Reynolds Averaged Navier-Stokes (RANS) equations.

2 Experimental method

The idea of the method is to measure some small shift of viscous oil film applied on investigated object surface and to restore the complete pattern of surface flow numerically. Optically contrast (luminescent) hard 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 relative to model surface. The direction of oil shift coincides with the direction of surface streamlines that allows reconstruct these streamlines. Magnitude of particles shift is proportional to shear stress value.

Even the small oil shift for just the few pixels on the image is sufficient for surface flow visualization due to high accuracy of correlation method. As a result, several flow regimes can be studied using one oil film application. 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. This method was called the Particle Image Surface Flow Visualization (PISFV).

Shear stress field can be determined from oil shift magnitude if oil film thickness is known. Oil film of thickness *h* and oil viscosity μ is moving under an action of shear stress τ caused by external airflow with about linear velocity profile across the film having velocity *V* of free boundary of the film determined by equation:

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

If the oil contains some optically contrast particles (on the surface or inside the oil film) and they are moving with the oil the shift of the oil can be detected. 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* dependant on share stress, oil viscosity and depth of the particles in the oil film y ($0 \le y \le h$, measured from the model surface):

$$l = \frac{\tau y}{\mu} \Delta t \qquad (2)$$

Processing of this pair of images with cross-correlation analysis results in the vectors of particles shifts. Particles have some distribution inside oil film by the depth and correlation data processing gives some average shift of particles. This average shift is also proportional to shear stress τ.

Expression (2) shows that three parameters can be adjusted to obtain share stress value: oil film thickness, time interval and oil viscosity. Oil film thickness can’t be too large to exclude its influence on the flow. Reasonable thickness is about 20÷40 μm. Minimal time interval is determined by wind tunnel construction. For shock wind tunnels the reasonable time interval should be equal to flow duration. For long-duration wind tunnels, the too large time interval is disadvantageous because of increasing of test cost but it should not be essentially shorter than wind tunnel starting time to avoid too early blowing down of the oil from the model leading edges. Usually the reasonable time interval for long-duration wind tunnels is 10÷30 sec. Oil viscosity can be changed within wide range and can be fitted to expected shear 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 typical oil film method. As a result, different flow types ranging from low-speed to hypersonic ones can be studied using this method.

Shear stress values 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 flow. 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 time.

However the boundary layer transition can be detected easily because of large shear stress increase in laminar–turbulent boundary layer transition.

The algorithm of correlation analysis consists in studying small windows of the image (interrogation windows). Note that every specific particle is not considered, since the interrogation window is analyzed as the "integrated one". Successful application of cross-correlation analysis requires that the images under consideration are well-modulated. Optical modulation of the studied surface is achieved via filling the oil film with the particles having optical contrast with respect to the model surface. It should be noted that the number of added particles should be relatively small (15–30 particles for each interrogation window). The size of the particles should be smaller than the thickness of the oil film. As the result, particle image is smaller than the size of the pixel of CCD or CMOS array (pixel projection size). Therefore, array pixel is exposed by a single particle. It seems natural to use luminescent particles for improving contrast of the images. Luminescence of such particles is excited by the light of proper spectral range. Excitation light source and detection camera should be equipped with crossed optical filters. The latter ensure detection of the luminescent light only and eliminate scattered light.

Choice of optimal oil viscosity depending on flow velocity, dynamic pressure and stagnation temperature is the main problem of experimentalist. "Optimal" means that the oil displacement between image acquisitions should be well detectable but should not be too large to bare model surface during the test. Transonic wind tunnels are characterized by large dynamic pressures, hence the high-viscosity oil must be chosen for such experiments. In presented experiments the optimal oil viscosity of about 60000 cSt was found experimentally.

Oil type choice seems quite evident – that is silicone fluids (PMS). Silicone fluids have very low value of surface energy, i.e. they are easily applied on any model material and move on their surface without fluid drops. An important feature of silicone fluids is that their viscosity has relatively weak temperature dependence. This feature simplifies the experiment in wind tunnels having significant change of stagnation temperature during the tests. The silicone fluids with viscosity in the range from 1 to 250 000 cSt are commercially available. Silicon fluids of different viscosity can be mixed easily to obtain oil of any required viscosity.

3 Experimental studies

Investigations were carried out for typical model of civil aircraft in T-128 large transonic wind tunnel (2.75x2.75m test section) of Central Aerohydrodynamic Institute (TsAGI), Zhukovsky, Russia. Cruise configuration of commercial jet model of 2 m span was investigated. Measurements were performed on the upper surface of the left part of the wing with engine nacelle. Two tests were made at Mach numbers 0.8 and 0.82 varying an angle of attack α in the range of 1.5 to 5º (8 points in each run).

Model vibrates in the flow. Therefore it is necessary to subtract model displacement on acquired images from particles shift vectors to obtain oil displacement with respect to model surface. For this purpose a set of luminescent markers (luminescent points having rigid connection with the model surface) were placed on the model surface to find displacement of the model on the images.

Mixture of viscous oil with luminescent particles diluted with a solvent was prepared in advance and was applied on the model surface by the sprayer. Silicone fluids (PMS) were used as viscous oil and crystal phosphor grains of 3–5 μm diameter were used as luminescent particles. Model image after oil application before wind tunnel test is shown in Fig. 1.

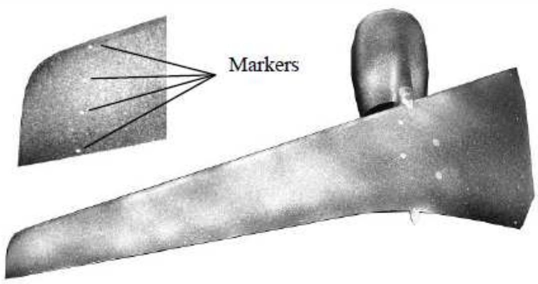

Fig. 1. Model before wind tunnel tests.

Luminescence of the particles dipped in the oil was excited by the light of appropriate spectral range. Excitation light source and CCD camera were equipped with appropriate optical filters to transmit luminescent light to the camera but to eliminate scattered excitation light.

Flash lamp was used as excitation light source to exclude image blur caused by model vibration during transonic tests. In present tests the electric energy of the flash was 500 J with flash duration less than 2 msec. Images were acquired with Alta U16M CCD camera of 4098×4098 pixels resolution. CCD camera was synchronized with flash lamp.

Transonic wind tunnels have restricted optical access usually. In T-128 wind tunnel the optical windows are placed downstream the model. As a result it is very difficult to obtain sharp image of the whole model. To solve this problem the “Tilt & Shift” lens was used. “Tilt & Shift” lens is working according to Scheimpflug principle, which means that a planar subject that is not parallel to the image plane can be focused completely if image plane, lens plane and subject plan intersect in one line, as illustrated in Fig. 2. Tilt angle of the lens was adjusted for average model angle of attack (about 3º). This adjustment allowed get sharp images at all test angles of attack.

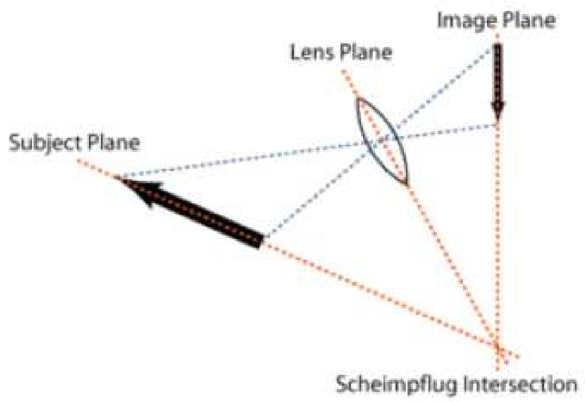

Fig. 2. Schematics Scheimpflug principle.

After wind tunnel start the each pair of images were acquired at investigated angle of attack with time interval of 20 sec between images. Pairs of acquired images were processed with cross-correlation analysis. In this analysis the maxima of cross-correlation function for small interrogation windows of images (32x32 pixels) were calculated:

$$M_{xy}(l,m) = \sum_{i=x-n}^{x+n} \sum_{j=y-n}^{y+n} \left[I_1(i,j) - I_1^a \right] \times$$
$$\times \left[I_2(i+l, j+m) - I_2^a \right]$$

where I_1 and I_2 are signal intensities on the first and second images, n is the size of interrogation window, x and y are coordinates of the window center, l and m are window displacement on the second image with respect to the first one, I_a is average intensity for the corresponding window. Maximum of this cross-correlation function is placed in the point of most probable displacement of analyzed window. Coordinates of this maximum are refined with two-dimensional second-order approximation of cross-correlation function (Fig. 3). Accuracy of this approximation is above 0.1 pixel. Varying initial coordinates of the interrogation window, one may find displacement matrix for image segments of the studied surface.

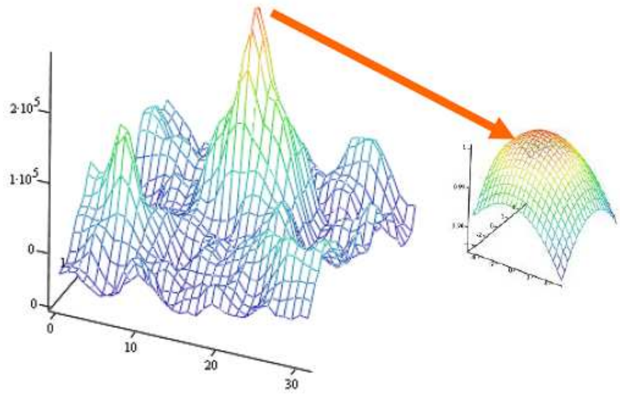

Fig. 3. Example of cross-correlation function and its maximum approximation.

Separately the displacements of the markers fixed on the model surface were found for these pairs of images and displacement of the model “as a whole” was calculated for each point of the model surface. Model displacement was subtracted from the displacement vectors of interrogation windows and, thus, the oil shift vectors relative to the model surface were obtained.

Direction of particles displacement vectors allows reconstructing surface streamlines. Magnitudes of displacement vectors are not important for this reconstruction. Streamlines can be reconstructed by commercial program TecPlot.

The model was covered by oil with viscosity 60000 cSt. Viscosity choice in this case was successful. Oil redistribution in this test was insignificant but well detectable. Image of model surface after this test is shown in Fig. 4. Oil film on the model surface is uniform except some oil accumulation along the shock position. Model inspection after this test showed that model could be used for new test without oil reapplication.

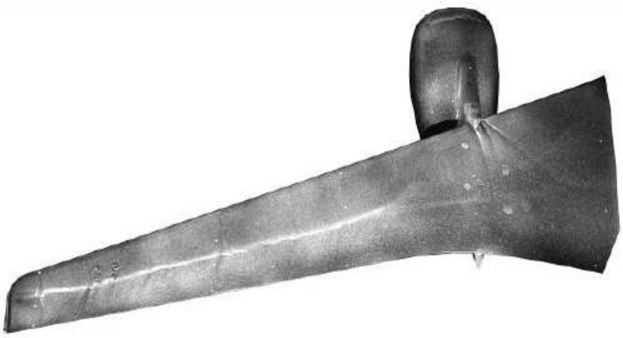

Fig. 4. Model after wind tunnel test with the oil viscosity of 60000 cSt.

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 regime, and in presented tests was 20 seconds.

Surface streamlines pattern is important information for CFD validation.

4 Numerical problem formulation

Three-dimensional Reynolds Averaged Navier-Stokes equations are solved numerically. The fluid is a perfect gas having the specific heat ratio 1.4 and Prandtl number 0.72. k-ω SST turbulence model is used. The viscosity-temperature dependence is approximated by the Sutherland law with the constant 110.4K.

The free-stream parameters correspond to Mach number M=0.82 and Reynolds number $\mathrm{Re}_\infty = 3\times10^6$ (based on free-stream values and mean aerodynamic chord).

Adiabatic wall temperature and no-slip condition are applied on the model surface. Far-field boundaries are placed at distance of approximately 50 wing spans from the surface. Computational geometry of the body corresponds to experiments without wind tunnel walls and support.

RANS equations are integrated using an implicit second-order finite-volume method. The governing equations are approximated by a conservative scheme. The flux vector is evaluated by an upwind flux-difference splitting. The time marching is proceeded until a steady-state solution sets in. Linear reconstruction of the functions in the cell is used. System of nonlinear algebraic equations is linearized. System of linear algebraic equations is solved with the help of algebraic multigrid method and ILU factorization. Numerical results were obtained with the help of ANSYS CFX solver.

The computational grid was designed as structured multi-block in ANSYS ICEM CFD and had approximately 20 millions nodes. The size of the first cell from the surface corresponds to $y_+ \approx 1$. Coefficient of cell growth in normal direction is approximately 1.2. Geometry and grid topology are presented in Fig. 5. Example of surface mesh is shown in Fig. 6 and example of pressure coefficient distribution is shown in Fig. 7 for α=2°.

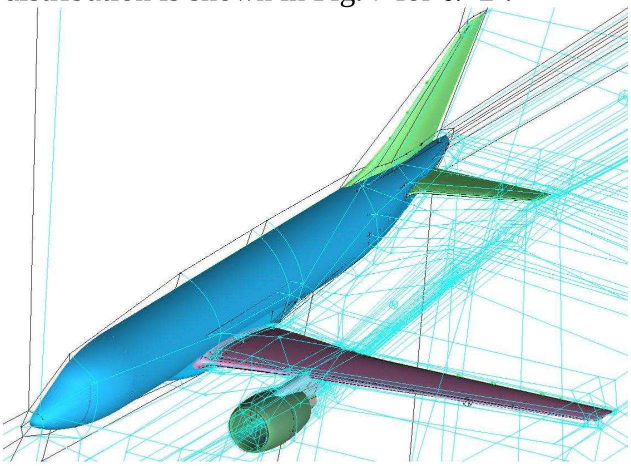

Fig. 5. Grid topology.

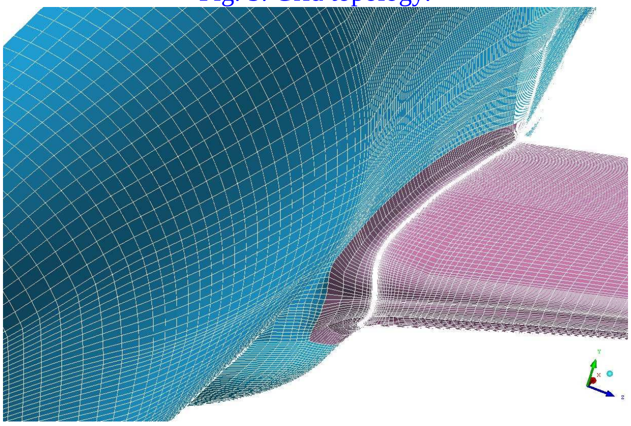

Fig. 6. Surface mesh.

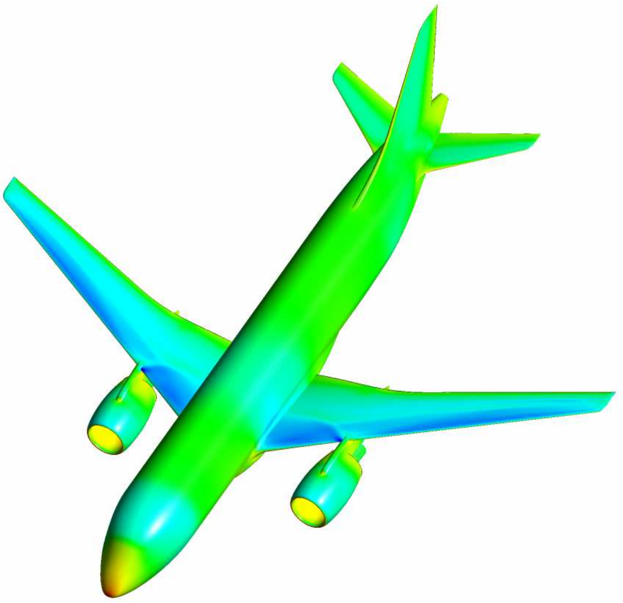

Fig. 7. Pressure coefficient distribution.

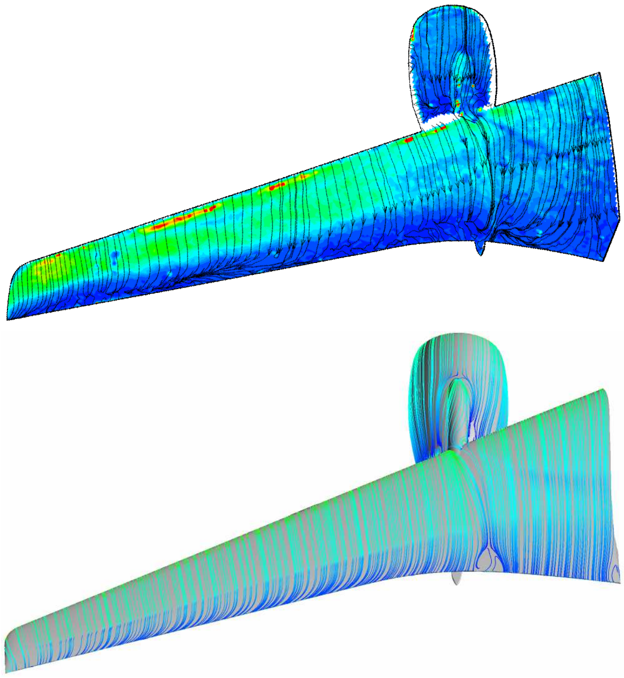

Fig. 8. Experimental visualization of surface streamlines (upper) and surface streamlines predicted by RANS calculations (lower), M=0.82, Re=3x10^6, α=1.3º.

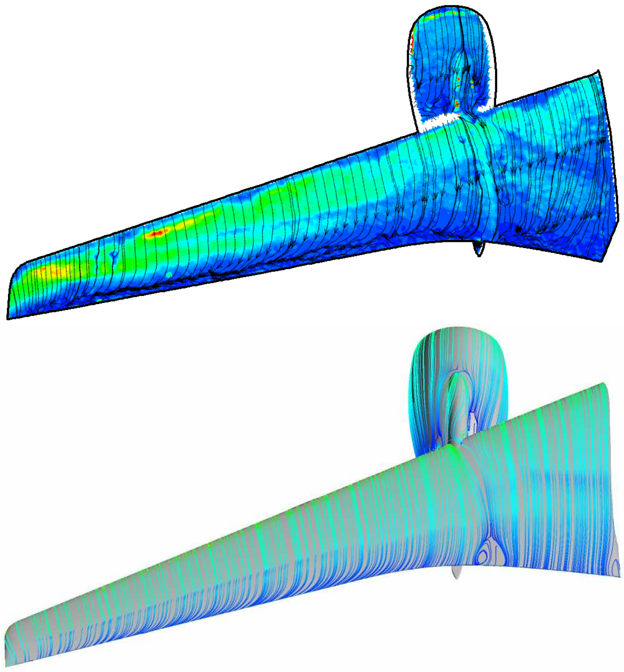

Fig. 9. Experimental visualization of surface streamlines (upper) and surface streamlines predicted by RANS calculations (lower), M=0.82, Re=3x10^6, α=1.7º.

5 Comparison of experimental results with numerical simulations

Experimental results are compared with numerical ones. Good agreement between experimental and numerical surface streamlines is achieved. Comparisons for α=1.3º, 1.7º, 2.3º, 2.9º are shown in Figs. 8-11 respectively. Color corresponds to shear stress distribution.

Local separation arises on the upper surface of the wing due to pylon wake. Another local separation arises near the junction of the upper wing surface with fuselage. Two small separation bubbles are shown near the junction of pylon with nacelle. The size of these separations increases as α increases. Streamlines downstream of the shock begin to be curved at α≥2.3º. In general, experimental surface streamlines are similar to numerical ones.

It should be noted that color scales of shear stresses in Figs. 8-11 for experimental and numerical results are different. This is due to the scale of experimental results is not defined.

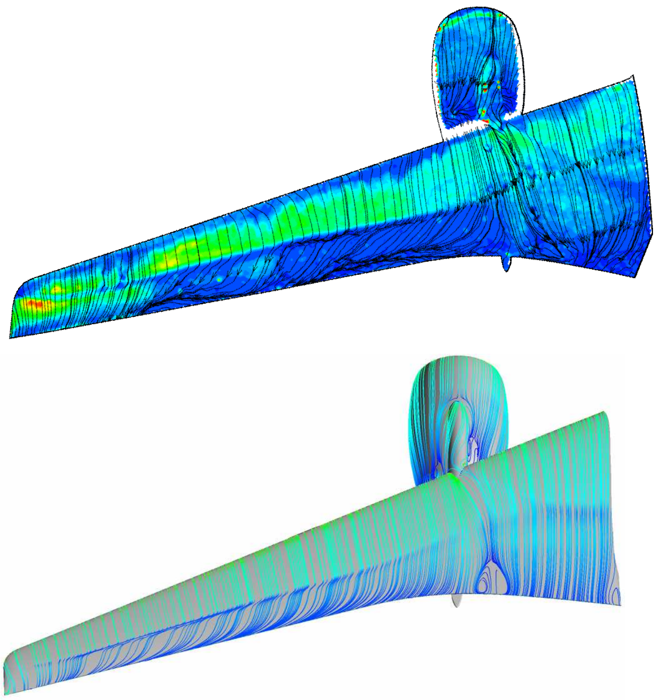

Fig. 10. Experimental visualization of surface streamlines (upper) and surface streamlines predicted by RANS calculations (lower), M=0.82, Re=3x10^6, α=2.3º.

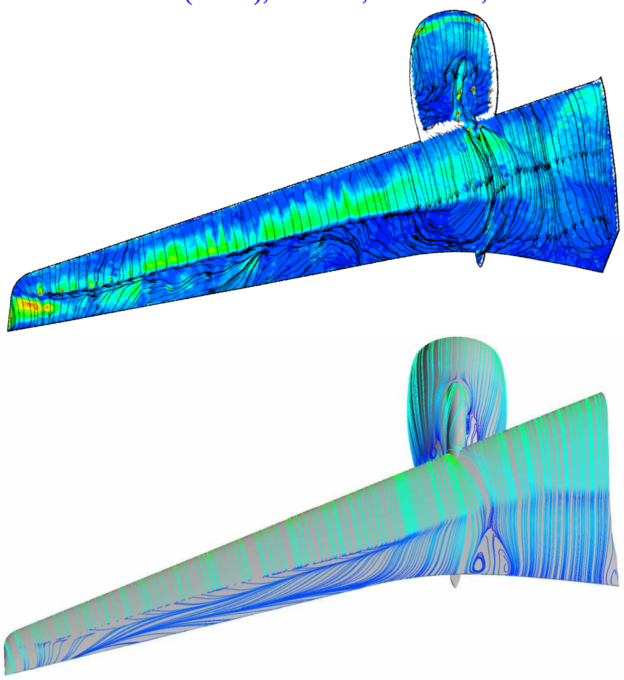

Fig. 11. Experimental visualization of surface streamlines (upper) and surface streamlines predicted by RANS calculations (lower), M=0.82, Re=3x10^6, α=2.9º.

5 Conclusions

Particle Image Surface Flow Visualization method (PISFV) can be successfully used at large transonic wind tunnel. PISFV method provides investigation of several regimes in one wind tunnel test with one model preparation. Method allows visualizing surface streamlines on the regular metal models without specific model preparation contrary to thermovision and TSP methods.

Experimental results for typical civil aircraft are compared with numerical ones based on Reynolds Averaged Navier-Stokes (RANS) equations. Good agreement between experimental and numerical surface streamlines is achieved. Local separations which arise at different places are similar both in experiments and in calculations.

References

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