PIV measurement of shock wave / laminar boundary layer interaction

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Abstract. The paper deals with study the area of interaction incident shock wave with a laminar boundary layer by PIV technique. The several data processing techniques to determine PIV measurements usability in transonic flow with small typical scales are compared in the paper. The results show that the major limitation of the PIV technique are associated with the seeding particles inertia.

Introduction
Resource limits and the necessity to reduce harmful emissions in areas of human living require permanent improvements in the efficiency of aircraft [1]. The problem can be solved by several methods: improvement of engines, aerodynamics and decreasing the weight of aircraft by the implementation of new material. One of the ways to aerodynamic improvement is providing laminar boundary layer at wings and engine manacles to reduce the drag. At the same time aircrafts have to be able to flight maximally fast at transonic and supersonic speeds which is accompanied by shock wave existence on the surfaces of aircrafts. An adverse pressure gradient generated by a shock wave can lead to separation of the boundary layer[2]. Laminar boundary layer separation can lead to significant instability, which provokes upstream shifting of laminar-turbulent transition [3]. The accurate prediction of the position of laminar-turbulent transition in the zone of Shock Wave / Boundary layer Interaction (SWBLI) is important for correct calculation of aerodynamic characteristics.

For engineering RANS calculations the transition position is mainly determined using $e^N$ method approach [4] or the four-parametric Menter's model [5]. These models use empirical data which depend on flow parameters. Therefore, the experimental data are necessary for calibration and testing the approaches for using in transonic flow calculations. The feature of transonic researches is the considerable difficulty of using probes, such as a hot-wire anemometer or Pitot tube, because of probable flow blockage. Therefore, non-invasive methods, such as PIV, are more preferable for use in transonic flows [6]. In addition, the velocity fields obtained by PIV measurements can be used to calculate the pressure field in the measurement area [7].

Zone of laminar flow separation has a large dimension in the streamwise direction, but small size in the normal direction. The spatial resolution of the PIV method in the vertical and horizontal directions is usually approximately the same. Therefore, the measurements in such flows can be accompanied by the problems of measuring the flow parameters in the boundary layer. In addition, in high-speed flows, the inertia of seeding particles leads to additional inaccuracies in the measurements, which has to be taken into account in the data processing. For example, in paper [8], the PIV method was used to study the interaction of an oblique shock wave with a laminar and turbulent boundary layer with a Mach
number \( M_\infty = 1.7 \). During the data processing, it was found that the concentration of particles in the laminar boundary layer is significantly lower than in the turbulent one. It occurs because the inertia of the particles prevents them from penetrating into the laminar boundary layer. The data processing algorithm with averaging of cross-correlation field allows decreasing the influence of incorrect (artificial) vectors in the area with low seeding particle density. The data processing algorithm with averaging of cross-correlation field allows decreasing the influence of incorrect crosscorrelation peaks in the area with low particle density.

The paper is devoted to testing various PIV data processing techniques by the example of the problem of the interaction of a shock wave with a laminar boundary layer at the condition of flow with small supersonic Mach number.

1. Experimental setup

The experiments similar to described in the paper [3] were chosen as the test task. The experiments were carried out in T-325 wind tunnel at \( M_\infty = 1.46; T_0 = 291 \text{ K}; \text{ and } P_0 = 0.7 \times 10^5 \text{ Pa}, \) unit Reynolds number \( (Re) = 11.5 \times 10^6 \text{ m}^{-1} \). The cross section of the wind tunnel working part \((160 \times 200 \text{ mm})\) was rectangular. The scheme of the experimental equipment consisting of a flat plate with a sharp leading edge and wedge (at the top) that generates the oblique shock wave is presented in Fig. 1. The incidence angle of the wedge was set to \( 4^\circ \) to correspond to the regular mode of the shock reflection from the model for a nonviscous flow. The position of the shock wave generator was chosen so as to provide the location of the incident point of the shock wave on the plate at the center of the optical window \((134 \text{ mm from the leading edge}).\) For these free-stream parameters, the boundary layer remained laminar. In addition, the measurements for the turbulent boundary layer were also performed. For turbulization of the oncoming boundary layer, the roughness was placed in spanwise direction at the distance of 40 mm from the leading edge. The roughness has a saw-like shape in plan and thickness (height) of 0.2 mm.

![Fig.1 Experiment scheme (at left) and flow velocity field (at right) obtained by PIV](image)

The study of the velocity field was carried out with a DantecDynamics measuring complex, with a LitronNano 135-15 laser. The measurements were carried out on two scales to study the possibility of increasing the spatial resolution of the method. In the one case, the Camera Phantom 310m \((1280x800 \text{ pix})\) was used with a Nikkor Lens f105 / 2.8 lenses; the measurement area was \(54.51x34.14 \text{ mm}\) covering the entire SWBLI area. The laser frequency was \(15 \text{ Hz}\), and the delay between frames was \(0.9 \mu\text{s}\). In the second case, a Hamamatsu camera with a resolution \((1344x1024 \text{ pix})\) was used, with a Nikkor Lens f105 / 2.8 lenses, which gave a measurement area of \(16.75x12.78 \text{ mm}\). During a series of experiments with a large scale, the camera moved in streamwise direction (along X coordinate), to obtain velocity fields in the entire SWBLI zone. Measurements with a Hamamatsu camera were carried out with two-time delays of \(0.9 \mu\text{s}\) - the minimum delay at which it was possible to obtain data for cross-correlation analysis and with a delay between laser pulses of \(0.3 \mu\text{s}\). In the last case, both
laser pulses occurred during the exposure of one frame. Therefore, to analyze these data, autocorrelation algorithms were used.

2. Results and discussion

At the image processing routine, the necessary operation to obtain high-quality velocity fields was the elimination of the vertical plate movements caused by wind tunnel vibration, which led to image oscillations up to 10 pixels. These oscillations were eliminated by searching the Y position of the plate on each frame and equating it to zero. The position of the plate was determined based on the positions of the flare from particles sticking to the plate during the start of the wind tunnel run.

As noted above, the lack of convective flows in the laminar flow prevents the penetration of particles into the laminar boundary layer. The turbulization of the boundary layer leads to the formation of strong vortices, which quickly increase the concentration of particles in the shear layer.

Fig. 3 shows the distribution of the smoothed intensity of the averaged images of particles (averaged over 2000 frames) at Y=0.3 mm and normalized to the maximum value that was in the area of inviscid flow behind the shock wave.

The data presented in the figure can be interpreted as the concentration of particles distribution in the measurement area. Different curves correspond to measurements performed during different wind tunnel runs. It is clearly seen that for a turbulent boundary layer the concentration of particles is much higher than in that the laminar case. Moreover, with passing through the region of the laminar separation bubble, the concentration of seeding particles drops to almost zero. Turbulization of the shear flow after the separation zone leads to a rapid increase in the concentration of particles. This means that in order to obtain correct data using standard PIV processing methods in the laminar separation region, it is very important to use strict conditions for filtering false (incorrectly determined) velocity vectors. An alternative way is to use the averaged correlation or autocorrelation algorithm. In this algorithm, when analyzing the data, the averaging of correlation distributions, rather than velocity values, occurs. This allows for minimizing errors due to the absence of particles or the disappearance of particles in the measurement area. The disadvantage of the algorithm is the lack of data on the non-stationary characteristics of the velocity fields.

For the averaged autocorrelation algorithm, the calculation was performed on 2000 images using a 32x8 pixel interrogation area. Data normalization was not performed in the course of autocorrelation searching; this made it possible to minimize the influence of regions without particles on the resulting averaged autocorrelation distribution. An example of such distribution with and without low-frequency filtering (near zero speeds) is shown in Fig. 3. It should be noted that when using auto-
correlation processing methods it is impossible to determine the direction of velocity. Therefore, it must be determined on the basis of physical considerations.

For a large measuring area, the recovery of the velocity field was made only by using the cross-correlation algorithm implemented in DantecDynamics software using interrogation area 16x8 pixels and with implemented overlapping of 50x50%. The resulting velocity field was obtained by averaging 2700 instantaneous velocity fields.

![Fig.3 Example of autocorrelation peak with zero peak filtering (right) and without filtering (left)](image)

For a small measurement area, the analysis was performed using three algorithms. For images obtained with a larger time delay of 0.9 μs, the processing was performed using DantecDynamics software. An iterative cross-correlation algorithm was used with a 64x8 pixel interrogation window with overlapping of 75x25%. The resulting velocity field was obtained by averaging 2000 instantaneous velocity fields.

Testing of autocorrelation algorithms was performed on the example of experiments carried out with a small time delay between laser pulses - 0.3 μs. Two techniques were investigated. The first technique was based on using a standard cross-correlation algorithm to search for the movement of particles implemented in ActualFlow software, with an interrogation area size of 32x8 pixels without overlapping. This software allows setting a limit of the minimum and maximum particles displacement (in pixels), which allows discarding the correlation peaks associated with multiplying the intensity of the particles on itself and giving a zero speed. However, as can be seen in Fig. 4, the results of this processing give a serious discrepancy with cross-correlation and averaged auto-correlation algorithms. This is caused by the effect of losing the particles pair. As a result, the algorithm gives a large number of false vectors that ultimately reduces the average value of the velocity outside the boundary layer. At the same time, in the boundary layer, the situation is aggravated by a small number of particles, as a result, there are significant numbers of vectors with a higher velocity value.

Comparing the velocity profiles shown in Fig.4 for large and small scales and obtained both at a time delay of 0.9 μs and at 0.3 μs shows that an increase in the spatial resolution of the image does not allow better resolving the velocity in the boundary layer due to particle inertia. This conclusion was obtained based on the calculations the time constant of the used seeding particles for the case of a laminar boundary layer (Fig. 5). The time constant was calculated based on the Stokes formula for a particle with a diameter of 0.8 μm and a density of 1200 kg / m³ (boundary layer thickness δ = 0.55 mm). The obtained values of the time constant were multiplied by the local values of the velocities, which made it possible to obtain the typical length of free path of the particle. One can see that the length of the free path of a particle near the scope of the boundary layer is approximately 3.8 of the thickness of the boundary layer (about 2 mm). This means that although in this study, the PIV method has provided a large frequency range (up to 200 kHz), large values of speed will lead to significant smoothing of the velocity fields. Thus, decreasing the displacement of particles between frames up to
the characteristic typical lengths of the particles runs not lead to a significant improvement in the results of data processing.

Fig. 4 Profiles of the longitudinal component of velocity obtained by PIV
Conclusions
Comparison of the fields obtained for the small size of the measurement area, with the normal movement of particles (about 8 pixels, autocorrelation analysis) and significant movement of particles (about 30 pixels, cross-correlation analysis) did not reveal a significant difference. The absence of a significant difference was also shown when comparing the velocity fields obtained at different measurement scales, but with the same delay between frames. The reason for this is the significant typical length of trackers (particles) runs for the problem under study, which leads to the smoothing of the velocity fields. The results of the study show that increasing the spatial resolution more than the characteristic length of the free path of a particle does not improve the quality of the velocity field measurements.

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