An inverse problem solution for post-processing of PIV data

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Abstract In the presented paper an application of the inverse method for post-processing of PIV data have been discussed. The aim of the study is to develop a new methodology for filling of missing values in the experimental data. The problem concerns filling of large gaps in the vector velocity field caused by the limited optical access to the test section of high speed wind tunnel. The inverse procedure involves fitting of the PIV data with a CFD simulation results. In order to estimate unknown parameters of the flow the procedure utilises a multi-parametrical identification algorithm. The paper presents results of the numerical test performed in order to validate the proposed methodology. The simulated flow over an airfoil in a test section of a high speed wind tunnel has been locally masked in order to reproduce the limitations of the actual measurements. The recovered vector velocity filed is in very good agreement with the masked model data. The results of the numerical studies proved the feasibility of the proposed methodology for post-processing of vector velocity fields corrupted with large areas of missing data. The developed method will be applied for PIV measurements of the flow over an airfoil in a high speed wind tunnel. The location of the lightsheet optics do not allow to perform measurements of the flow over the leading edge of an airfoil, therefore the inverse method has been proposed.
Keywords: Particle Image Velocimetry, Inverse Methods, CFD

1 Introduction

Rapid development of the Particle Image Velocimetry method in last decade allow to increase the spatial and temporal resolution of the measurements. Especially greater accessibility of high frequency impulse lasers and advancements in camera technology allowed to investigate transient aerodynamic processes in more details. This holds true also for investigation of the transonic and supersonic flows. Nevertheless, the measurements in high speed wind tunnels can be subjected to some limitations. For example, the optical access to the test chamber of supersonic wind tunnel is often limited. This cause the limitations in the measurements area. Moreover, in many cases the light sheet optics cannot be positioned in desired position due to compact build of the test chamber. Therefore not all regions of the investigated flow can be properly illuminated. For example, in case when the light sheet optics is positioned in distant location downstream the flow, the leading edge of the investigated airfoil is not illuminated (See Figure 1).

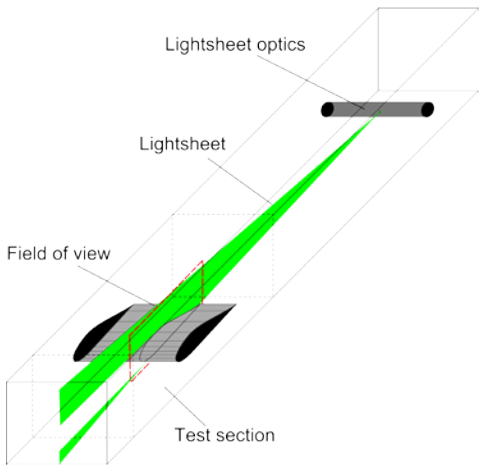

Fig. 1 A scheme of a lightsheet optics positioning in a high speed wind tunnel. The limited access to the test section do not allow to properly illuminate the whole field of camera’s view.

The limitations in light sheet introduction the test section and the limited optical access may cause large gaps in the vector velocity field measured with PIV. The effect of a lack of illumination in front of a leading edge of an airfoil is shown in Figure 2.

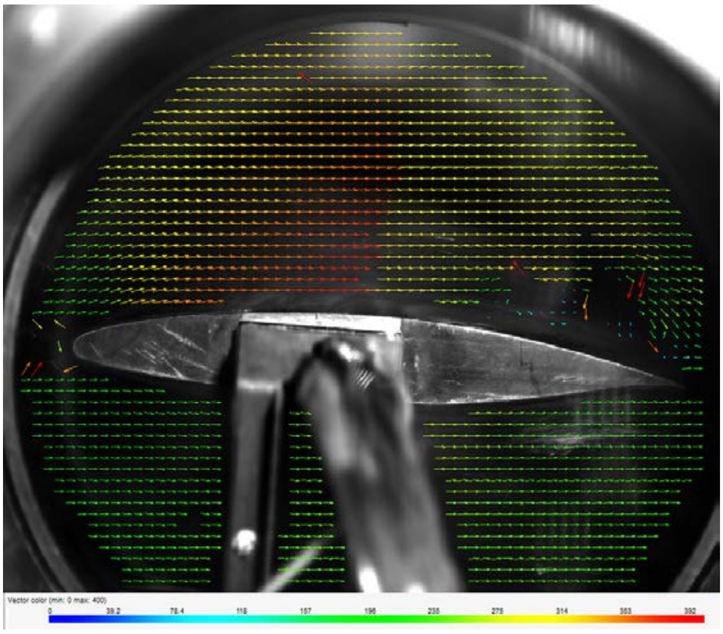

Fig. 2 Exemplary velocity field measured in the test section of a high speed wind tunnel with limited optical access. The freestream Mach number M=0.7.

Although, the procedures for filling missing values had been developed they are not fully applicable for post-processing results of investigation of compressible flow. In the case of investigation of a flow field with large velocity gradients associated with a shock wave (see Figure 2.) application of a method based on median filtering can reduce the rapid spatial changes in the flow field.
In the present paper a method for filling missing PIV data has been proposed. The inverse procedure involves fitting of the PIV data with a CFD simulation results. The present paper covers the issue of the inverse problem formulation, solution of the exemplary direct problem and multi-parametrical identification. Typical results of the performed numerical studies are shown. The simulated flow over an airfoil in a test section of a wind tunnel has been locally masked in order to reproduce the limitations of the actual measurements.

2 Method

In the proposed methodology missing velocity data where estimated by fitting a solution of a numerical simulation *V* to experimental PIV data *Y*. The solution of this inverse problem is based on the minimization of the ordinary least squares norm in a form:

$$S(P)=\sum_{i=1}^{I}\left[Y_i - V_i(P)\right]^2 \tag{1}$$

where: *S* - is the sum of squares error, *P* is the vector of unknown parameters, $V_i(P)$ – solution of a direct problem (CFD velocity field), Y_i – is a experimental velocity field (2D PIV data). In the presented work an identification of unknown parameter *P* is performed by Levenberg-Marquardt iterative procedure in a form:

$$P^{n+1}=P^n+[(J^n)^T J^n+\mu^n\Omega^n]^{-1}(J^n)^T[Y-T(P^n)] \tag{2}$$

where: *n* - is the iteration number, μ_n - is a positive scalar named damping parameter, Ω_n - is the diagonal matrix and *J* - is the matrix of the sensitivity coefficients in the form:

$$J(P)=\left[\frac{\partial T^T(P)}{\partial P}\right]^T \tag{3}$$

In the numerical test an identification of masked velocities was performed. The experimental PIV data *V* was simulated with use of MES software. In order to reproduce the limitations of the actual measurements the simulated flow over an airfoil in a test section of a high speed wind tunnel has been locally masked. The

Comsol Multiphysics Fluid Flow module was used in order to simulate 2D flow over an airfoil in the closed wind tunnel test section (See Figure 3).

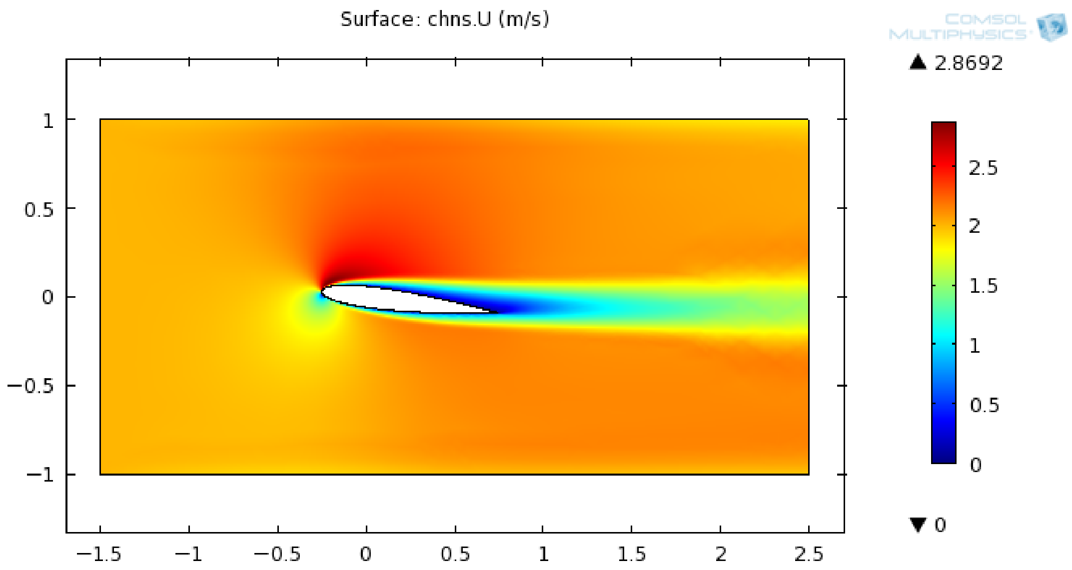

Fig. 3 Solution of a direct problem

The CFD velocity data was interpolated in order to simulate the rectangular gird of PIV data. The gaps in the data was created by masking of the PIV data (Figure 4.).

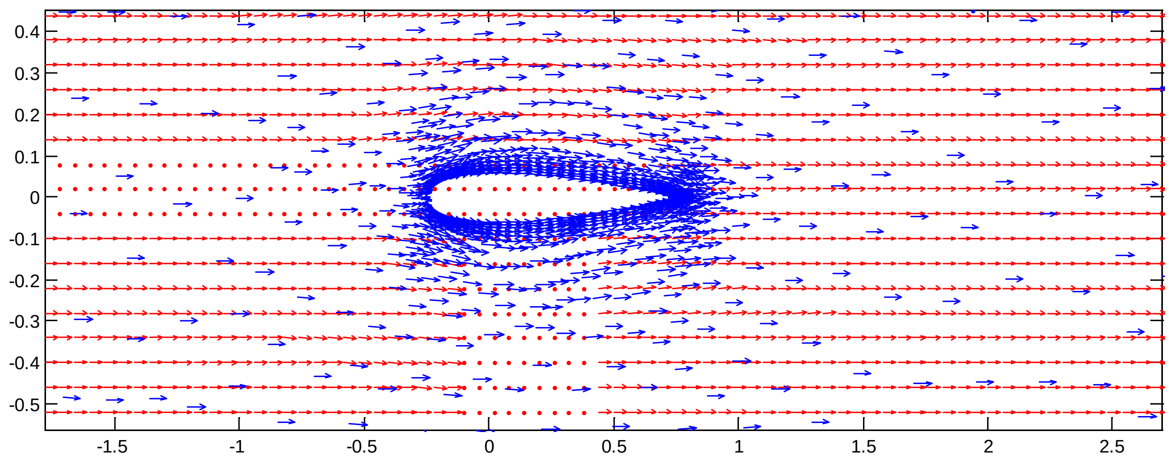

Fig. 4 The CFD simulation results (blue) was interpolated to rectangular grid - the simulated PIV data (red)

The simulated PIV data was used as an input data in the performed numerical test. The inlet velocity V_{inl} was estimated. The iterative estimation procedure was stopped when the following condition was fulfilled:

$$S(P) = \sum_{i=1}^{I} \left[Y_i - V_i(P) \right]^2 < \varepsilon \tag{1}$$

The CFD data from last iteration of the identification process *V(P)* was used for filling the gaps in the input experimental data *Y*.

3 Results

Typical result of the estimation procedure is presented in Figure 5. The missing data was filled with data resulted from estimation process.

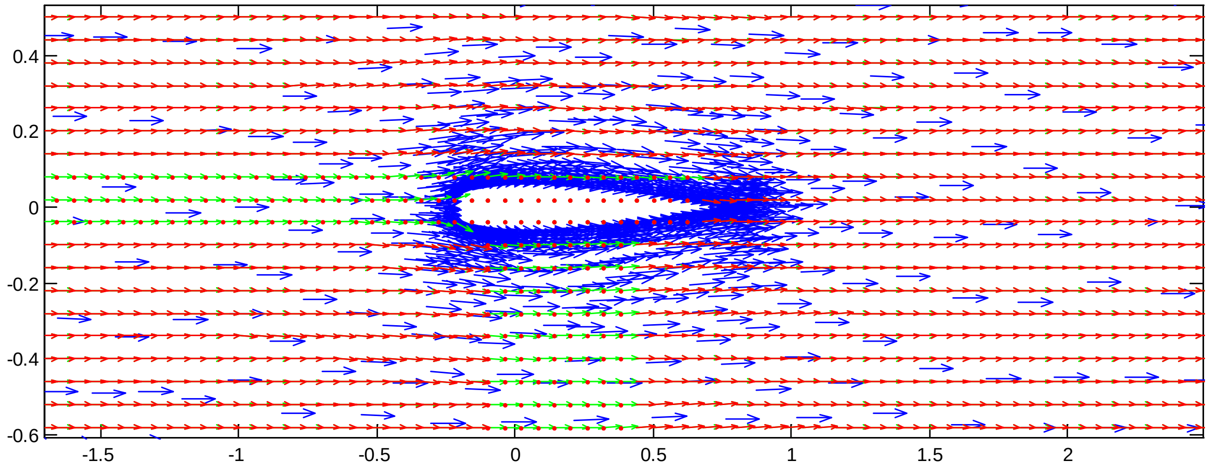

Fig. 5 Exemplary result of the fitting procedure. The estimated velocity filed (green) is superposed with the masked data (red).

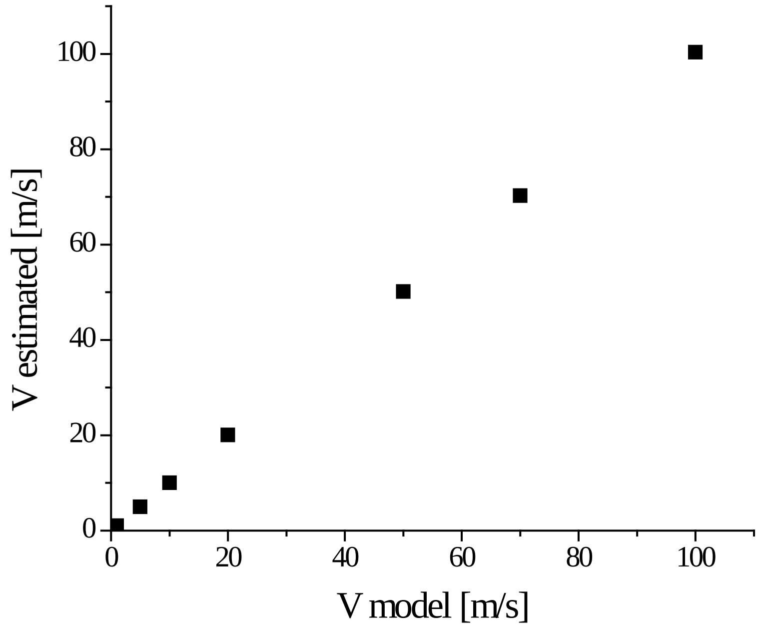

Fig. 6 Plot of the freestream velocity estimated: *V estimated* versus *V model* (the simulated results)

4 Summary

In the presented work a concept of a method of filling of large gaps in PIV data was described. The aim of the work was to develop a method for replacing of the missing data in vector velocity field, especially for post processing of data from high speed wind tunnel tests. The proposed inverse methodology involves fitting PIV data with solution of direct CFD simulation of the investigated flow. The present paper covered the inverse problem formulation, exemplary solution of the direct problem and parametrical identification using Levenberg-Marquardt algorithm. In the presented paper, the results of performed numerical test was shown. Results show good agreement between the estimated and the masked data (see Fig. 6). It is important to underline, that in presented preliminary test the PIV data was simulated with use of simplified numerical 2D model of a flow. In the next stage of the procedure development, experimental PIV data from wind tunnel tests (See Figure 2) and 3D numerical model of the test chamber of the wind tunnel will be used.

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