Assessment of instantaneous pressure determination
in a transonic base flow based on four-pulse tomographic PIV

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The evaluation of the instantaneous pressure field in high-speed, three-dimensional, separated flows using PIV is investigated. Recent developments in PIV measurement capabilities, such as tomographic PIV, have extended the PIV-based approach to experimental pressure determination significantly (Van Oudheusden 2013). The ability of PIV to determine the material acceleration in the flow, from which the pressure is subsequently obtained, has been established for low-speed flows, but the extension to high-speed flows introduces a number of technical challenges. First, high-speed flows are characterized by time scales on the order of microseconds, which is far outside the current capabilities of high-speed laser and camera systems that are applied in low-speed flows, making multiple-pulse approaches necessary (Lynch and Scarano 2013). Further challenges lie in the subsequent processing of the acceleration data to extract the pressure in view of the variable property nature of compressible flows.

The objective of the current work is to assess the ability to perform instantaneous pressure determination in a high-speed, three-dimensional, separated flow. A method is developed for simulating the measurement chain using an LES data set, whereby the accuracy and error accumulation in the procedure is determined. The instantaneous pressure is evaluated from velocity by the following relation, derived from the momentum and energy equations (Van Oudheusden et al., 2007):

\[
\ln\left(\frac{p}{p_\infty}\right) = -\frac{1}{RT} \frac{Du}{Dt} - \frac{\gamma M_s^2}{2} \frac{\rho u}{V_a} - \frac{1}{2} M_s^2 \left(V_a^2 - V_e^2\right) \frac{Du}{Dt}
\]

Here \(Du/dt\) is the material acceleration, \(R\) the gas constant, \(\gamma\) the ratio of specific heats, \(T\) the local temperature and \(p\) the pressure; \(p_\infty, M_\infty, V_\infty\) are the free stream pressure, Mach number and velocity, respectively. Note that two modeling assumptions were introduced in its derivation: the viscous term is neglected and the flow is assumed to be adiabatic. The pressure value itself is subsequently obtained by recasting the gradient problem in a Poisson formulation.

The study investigates the validity of the modeling assumptions, as well as the errors introduced in the determination of the material acceleration and the numerical solution of the Poisson problem.

The flow under consideration is an axisymmetric afterbody configuration, which has been studied in detail using numerical simulations (Weiss et al. 2009). The data from this simulation were kindly provided as input for the present study. The used dataset consists of a time-series of 96 images with a time separation of 10 μs. The free stream Mach number is 0.7 and the Reynolds number based on the forebody diameter is 1.2 million. To obtain velocity fields that better reflect the result of the experimental PIV campaign, the simulation data is used to generate synthetic PIV measurements with a time separation 2.5 μs and vector spacing of 0.67 mm. Simulation data was interpolated to the same grid to provide a reference dataset.

The study follows a structured approach in which sources of errors are gradually added to the analysis in an attempt to isolate their impact on the final result. As a first step in the assessment the isolated influence of the pressure-gradient integration by means of the Poisson procedure is evaluated. Subsequently, the two modeling assumptions (neglecting the viscous term and the assumption of adiabatic flow) are addressed and assessed to be indeed of negligible impact. Next, the influence of the procedure to compute the material acceleration (Eulerian or Lagrangian) is evaluated. The impact of errors in the velocity field is represented by comparing the results obtained with the numerical velocity input against the synthetic PIV data.

The deviation between the calculated pressure fields and the reference pressure fields is found to differ substantially from one snapshot to another. This could partly be attributed to the Poisson solver which seemed to be highly sensitive to the cropping of the data domain. Errors in the velocity field were however found to be the most important source of error as their impact on the resulting pressure field is several times higher than those introduced by other factors.

References

Lynch K, Scarano F (2013) Material derivative measurements in high-speed flows by four-pulse tomographic PIV, 10th Int. PIV Symp., 1-3 July 2013, Delft, The Netherlands