

B. W. van Oudheusden · F. Scarano · E. W. F. Casimiri

Non-intrusive load characterization of an airfoil using PIV

Received: 3 February 2006 / Revised: 6 April 2006 / Accepted: 6 April 2006 / Published online: 29 April 2006
© Springer-Verlag 2006

Abstract An assessment is made of the feasibility of using PIV velocity data for the non-intrusive aerodynamic force characterization (lift, drag and pitching moment) of an airfoil. The method relies upon the application of control-volume approaches in combination with the deduction of the pressure from the PIV experimental data, by making use of the momentum equation. First, the consistency of the method is verified by means of synthetic data obtained from CFD. Subsequently, the procedure was applied in an experimental investigation, in which the PIV approach is validated against standard pressure-based methods (surface pressure distribution and wake rake).

1 Introduction

Many fluid-dynamic applications involve configurations where relatively slender objects are exposed to a cross-flow, like aircraft wings, wind turbine blades, bridge decks, towers, etc. For these configurations, the mean flow is predominantly two dimensional and is therefore conveniently studied by planar velocimetry techniques, particle image velocimetry (PIV) in particular (Adrian 2005). In technical fluid-dynamic design applications there is a further specific interest in the aerodynamic loads involved. In current experimental research practice, the flow field information and the mechanical loads are obtained by separate techniques. An appealing approach to establish a direct link between flow behaviour and force mechanisms is by deriving the loads from the

flow field information itself. Apart from the inherent synchronisation between the different flow aspects, it further removes the necessity of additional and/or intrusive instrumentation of the model itself. An example of this approach is the method to determine the drag of an airfoil from the momentum deficit in its wake (Jones 1936), which is a well-established technique in aeronautical wind-tunnel operations practice.

1.1 Operating principle

The wake-survey method is a particular implementation of the control-volume approach, which in its general form allows the integral load on an object (forces and moments) to be obtained from an integration of the flow variables over a control volume surrounding this object (Anderson 1991; Batchelor 1967), as illustrated in Fig. 1. Several procedures have been proposed recently, that would allow unsteady lift and drag loads to be determined from time-resolved PIV data (Lin and Rockwell 1996; Unal et al. 1997; Noca et al. 1999; Berton et al. 2004; Fujisawa et al. 2005), based on variants of the control-volume approach. Required flow field properties are velocity, pressure, density and viscous stresses. In most aeronautical applications, the direct contribution of the viscous stresses can generally be neglected when the control volume outer contour is taken sufficiently far from the body, but may be included for completeness.

Assuming incompressible flow, the density is constant and a direct application of the control-volume formulation requires the velocity and acceleration distribution inside the volume, as well as the pressure on the outer contour. The pressure field is generally not available in a PIV experiment, and basically two approaches can be followed to amend this. The first is to use a formulation of the control-volume approach from which the pressure has been eliminated (Noca et al 1999). The second is to explicitly evaluate the pressure (Unal et al 1997) using the momentum equation.

B. W. van Oudheusden (✉) · F. Scarano · E. W. F. Casimiri
Department of Aerospace Engineering,
Delft University of Technology, Kluyverweg 1,
2629 HS Delft, The Netherlands
E-mail: B.W.vanOudheusden@lr.tudelft.nl
Tel.: + 31-15-2785349

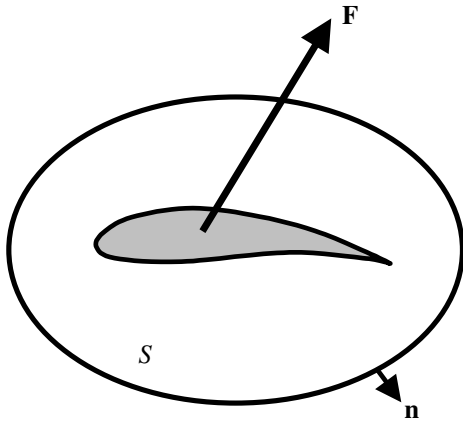


Fig. 1 Sketch of the basic working principle: control-volume approach for determining integral aerodynamic forces in a two-dimensional flow configuration

Although these procedures in principle allow to obtain instantaneous pressure and force data, practice not always permits to perform time-resolved velocity measurements or to determine acceleration with a sufficient level of accuracy (Adrian 2005). Moreover, in many applications of technical interest it may be sufficient to study the flow in the mean sense, and to obtain knowledge on time-mean loads. Reynolds-averaging of the governing equations allows the aerodynamic force and moment on the object to be written in terms of integrals over the contour S of the control volume:

$$\begin{aligned} \mathbf{F} &= \iint_S (\boldsymbol{\sigma} - \rho \mathbf{u} \mathbf{u}) \cdot \mathbf{n} \, ds, \\ \mathbf{M} &= \iint_S ((\boldsymbol{\sigma} - \rho \mathbf{u} \mathbf{u}) \cdot \mathbf{n}) \times \mathbf{x} \, ds \end{aligned} \quad (3)$$

The total stress tensor ($\boldsymbol{\sigma}$) is composed of pressure, viscous and turbulent contributions:

$$\sigma_{ij} = -p \delta_{ij} + \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \rho \overline{u_i' u_j'} \quad (2)$$

These expressions show that for the purpose of obtaining time-averaged loads it is sufficient that the pressure and the velocity, as well as the velocity gradients and fluctuations (turbulent stresses), on the outer contour of the control volume are determined. The (mean) pressure is not measured but is obtained from integration of the momentum equation:

$$-\frac{\partial p}{\partial x_i} = \rho u_j \frac{\partial u_i}{\partial x_j} + \rho \frac{\partial \overline{u_i' u_j'}}{\partial x_j} - \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad (3)$$

For two-dimensional flows, all right-hand side terms can be derived from PIV data, in terms of mean values and statistics of the velocity, illustrating how time-averaged pressure fields, and with this the integral loads can be inferred from experimental velocity field data that can be obtained using PIV.

2 Test case: low-speed airfoil characterization

2.1 Objective

The motivation for the experimental test case is to assess the potential of the PIV-based approach for the aerodynamic load characterization of a low-speed airfoil section under realistic wind tunnel conditions. For this kind of tests standard procedures based on pressure measurements are available and regularly applied at the laboratory. The wing model needs to be equipped with pressure taps to determine the surface pressure distribution, from which the lift is inferred through integration. The drag is determined separately using a pitot-tube wake rake at some distance behind the airfoil (typically 2–3 chord lengths in view of its possible intrusive effect on the flow), as described in Jones (1936). The objective of the present study is to validate the PIV-based approach against the standard procedure. In perspective, the new approach can provide an alternative procedure, that may be suitable notably for low-Reynolds testing, where a correct simulation of the Reynolds number would require small dimensions and low flow speeds, which makes pressure-based methods increasingly inaccurate.

2.2 Numerical validation based on synthetic data

Synthetic flow data obtained with the CFD code Fluent has been used to check the PIV-based procedure for consistency. The simulation considers the airfoil used in the experimental investigation (NACA 642A015), assuming a fully turbulent boundary layer (in the experiment transition is free, so the actual drag will be lower than that in the numerical simulation). The flow solver has been used with an incompressible two-dimensional steady state model and $k = \epsilon$ turbulence model. The computational grid contains 1.4 million points and enhanced wall treatment is used for better modelling near the wall. From the CFD flow data, a comparison was performed between the loads provided by numerical integration of the surface forces and those obtained from a contour integral (the “PIV approach”). For the latter, the velocity data was interpolated on a rectangular contour surrounding the airfoil at a distance of about 0.5 chord lengths with a resolution of $90(H) \times 180(L)$ points, typical of expected PIV experimental conditions. The computational grid in this region is finer by a factor of about 5. The uncertainty in the load data from the contour integral was estimated by varying the distance of the contour to the airfoil, between 0.25 and 0.5 chord lengths (in 40 steps). Results are given in Table 1 for angles of attack $\alpha = 0$ and 5° and chord Reynolds number of 300,000. The typical order of the absolute error observed is 0.05×10^{-3} in C_d (0.2% in drag) and 0.001 in C_l and $C_{m0.25c}$. Note that the value of the

Table 1 Results of the synthetic experiment: comparison of force determination by two different methods

AoA	Surface force integration			Contour integral (“PIV approach”)		
	$1,000 \times C_d$	C_l	$1,000 \times C_{m0.25c}$	$1,000 \times C_d$	C_l	$1,000 \times C_{m0.25c}$
0°	16.38	0.0000	0.00	16.41 ± 0.03	0.000 ± 0.000	0.00 ± 0.00
5°	25.02	0.4886	- 5.20	24.96 ± 0.03	0.4870 ± 0.001	$- 5.97 \pm 0.07$

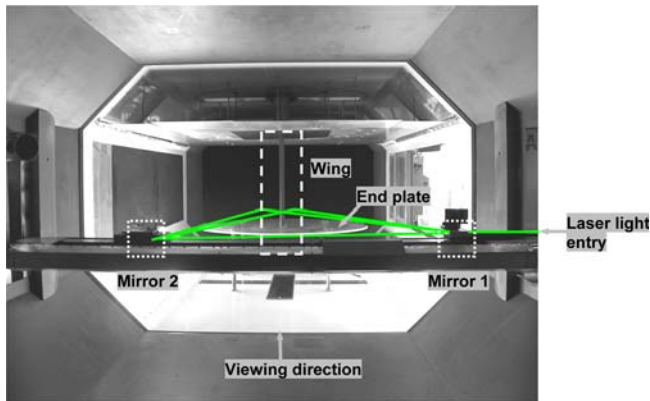


Fig. 2 Experimental setup, illustrating model assembly in the wind tunnel test section and illumination geometry (view from *downstream*); the laser light enters from the *right* and the camera viewing direction is from *below*

moment coefficient is very small, due to the absence of airfoil camber.

2.3 Experimental procedure

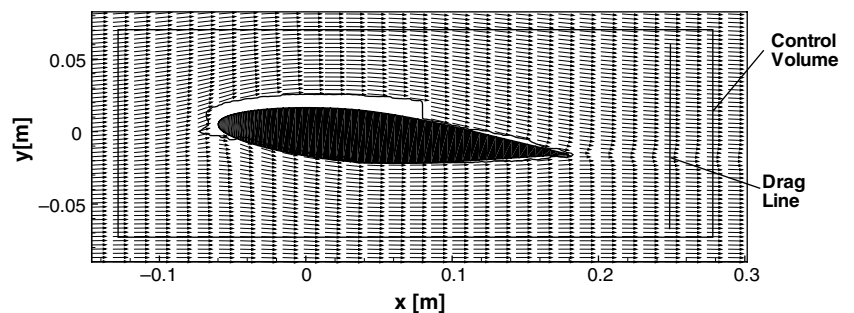
The experiments have been performed in the low-speed low-turbulence wind tunnel, which is a closed-circuit facility with a test section of $1.80 \text{ m} \times 1.25 \text{ m}$ (width \times height). The tests were carried out on a wing model with airfoil section NACA 642A015, with span of 0.64 m and chord of 0.24 m . The wing was suspended vertically from the upper tunnel wall and equipped at its lower free end with a transparent end plate, which allowed optical access to the flow around the wing from a window in the bottom wall of the test section (Fig. 2). Tests were carried out for a range of incidence angles (-5 to 17°) and free stream velocity between 6

and 44 m/s (Reynolds number based on chord varies from $100,000$ to $700,000$).

For each configuration, force data were determined with the PIV-based technique and with the standard pressure-based procedures (see earlier) as means of validation. The pressure distribution was measured with 48 pressure taps along the model contour, from which lift and moment were determined by integration. The wake measurement for obtaining the drag was performed with a rake of total and static pressure tubes. The static pressures were measured at 16 points and the total pressure at 21 points. The interval spacing applied in the central part of the wake is 24 mm for the static pressure and 12 mm for the total pressure. With the total wake rake width being ca. 500 mm , this assured that under all conditions considered the entire wake was captured, with sufficient resolution (at least 10 points describe the total pressure defect in the wake).

For the PIV experiments, the flow was seeded with $1.5 \mu\text{m}$ droplets generated by a fog machine. The illumination source is a Spectra-Physics Quanta-Ray PIV 400 pulse Nd:YAG laser. The laser wavelength is 532 nm and the energy is 400 mJ/pulse . In order to be able to apply the control-volume approach, the illumination of the wing surrounding is necessary, for which the expanded laser sheet was introduced downstream of the test section and projected onto the model from two mirrors placed on opposite sides of the tunnel (see Fig. 2). Laser sheet thickness was about 3 mm . Two CCD cameras ($1,280 \times 1,024$ pixel and $1,376 \times 1,040$ pixel) with 35 mm objectives were used in a side-by-side configuration to produce an elongated view around the wing cross-section, measuring $45 \times 18 \text{ cm}^2$ (approximately 1.9×0.75 chord lengths). The pulse separation was chosen such that the free stream velocity produced a particle displacement of 7 pixels. Image analysis was carried out with a window-deformation and iterative multi-grid cross-correlation

Fig. 3 Mean velocity field and the integration contours ($U_\infty = 19 \text{ m/s}$, $Re = 300,000$)



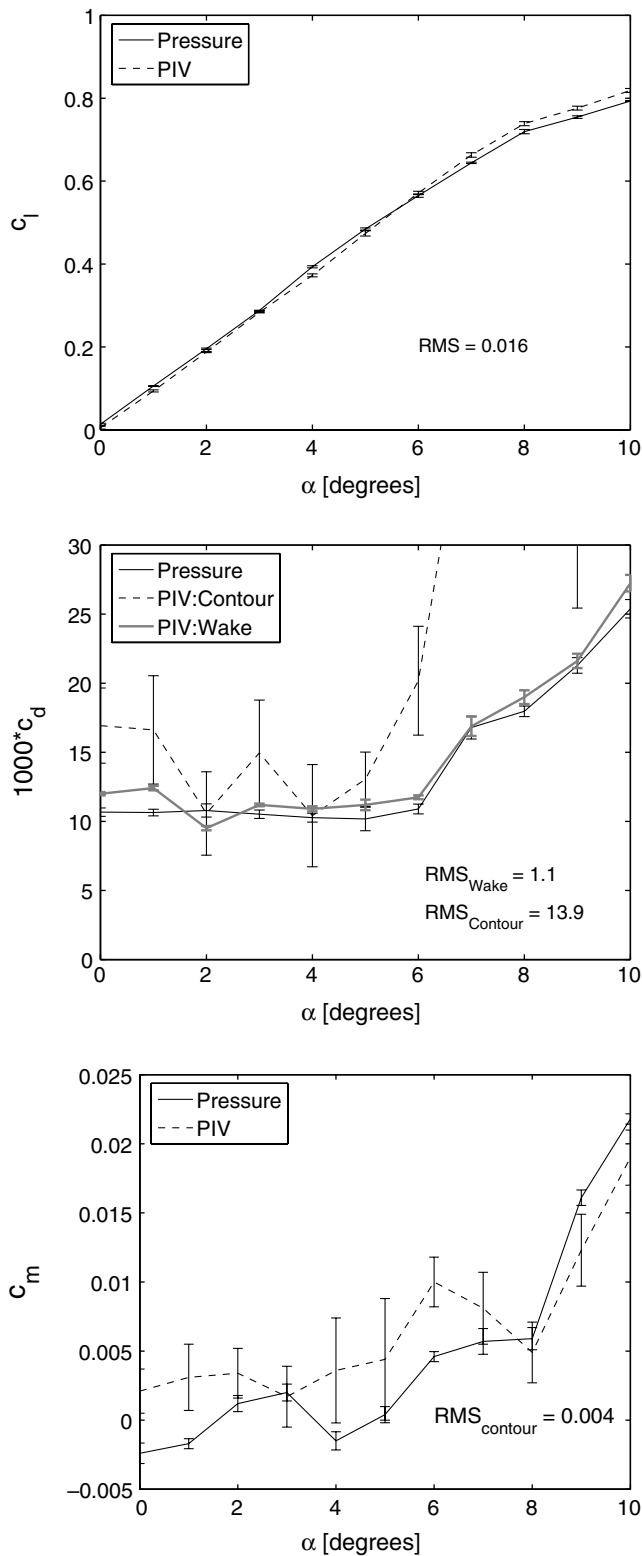


Fig. 4 Variation of lift, drag and moment with respect to incidence angle; comparison of results due to PIV and pressure measurements

algorithm (LaVision Davis 7.0), using an interrogation window size of 32×32 pixels and an overlap factor of 75%, yielding a measurement grid with spacing of ca.

1.45 mm (0.6% chord). For each configuration a data ensemble size of ca. 100 image pairs was obtained at an acquisition rate of 2.0 Hz. The uncertainty on the averaged velocities is about 0.1% of the freestream velocity. The velocity bias error due to the optical distortion as a result of the short focal length of the lenses is maximum ca. 0.4% of the freestream velocity. An example of the field of view and a typical mean velocity field is displayed in Fig. 3. (The bands above and below the airfoil are the flow regions masked by the viewing perspective and hence should not be considered.)

3 Results

The lift, drag and moment coefficients were computed by the control-volume method, taking a contour around the airfoil as illustrated in Fig. 3. An uncertainty estimate of the coefficients values was based on the different results obtained by changing the size of the contour, in which the distance to the cross-section was varied between 0.35 and 0.5 chord lengths (25 steps). Because of the low value of the drag, application of the contour procedure yielded unacceptably large relative errors for this parameter, and the drag-determination procedure is much improved by introducing a classical wake approach instead (see Fig. 4). The reason for the better performance of the wake approach is that it implicitly ensures mass preservation, while also it does not suffer from a possible incorrect projection of the total force on the coordinate axes, in case of a slight misalignment of the image orientation with respect to the flow axes. In the wake approach the static pressure is calculated along a vertical line across the wake (see Fig. 3), which allows computation of the local total pressure coefficient c_{pt} . The drag is subsequently determined according to Jones (1936), as:

$$D = \rho U_\infty \int_{\text{wake}} u (1 - \sqrt{c_{pt}}) dy \quad (4)$$

This expression is commonly accepted as being valid even close to the trailing edge. It may be further remarked that the location of the drag traverse in the PIV approach is much closer to the airfoil trailing edge ($0.5c$ at maximum) than usually applied for a wake rake. Changing again the location of this line, between 0.25 and $0.5c$ behind the trailing edge, provided an estimate of the drag uncertainty.

Variations of the lift, drag and moment as function of incidence are given in Fig. 4, for $Re = 300,000$. The error bars (corresponding to ± 2 rms deviations) indicate the uncertainty range of the data. Mean differences (in the rms sense) between PIV and pressure-based data, for the flow conditions considered, are 0.016 for the lift coefficient, 1×10^{-3} for the drag coefficient using the wake approach (14×10^{-3} with the contour approach) and 4×10^{-3} for the moment coefficient.

In conclusion, the comparison between the PIV-based force coefficients and the standard pressure-based procedures clearly demonstrates the capability of the PIV method to provide a non-intrusive characterization of the airfoil, based on velocity field information, with acceptable accuracy.

4 Conclusions

The approach to determine pressure fields and integral loads from planar velocimetry data was considered as a means for non-intrusive aerodynamic load characterization of a low-speed airfoil. Synthetic data obtained from CFD were used to assess the validity of the approach. In the experimental phase of the investigation, PIV results were validated with those obtained from the pressure measurements. With the flow being predominantly steady, an ensemble size of 100 turned out to be sufficient to produce force data with sufficient accuracy. The lift and moment were determined from the contour approach, while for the drag a wake-survey approach was found to improve accuracy significantly.

References

- Adrian RJ (2005) Twenty years of particle image velocimetry. *Exp Fluids* 39:159–169
- Anderson JD Jr (1991) *Fundamentals of aerodynamics*. 2nd edn. McGraw-Hill, New York
- Batchelor GK (1967) *An introduction to fluid dynamics*. Cambridge University Press, Cambridge
- Berton E, Maresca C, Favier D (2004) A new experimental method for determining local airloads on rotor blades in forward flight. *Exp Fluids* 37:455–457
- Fujisawa N, Tanahashi S, Srinavas K (2005) Evaluation of pressure field and fluid forces on a circular cylinder with and without rotational oscillation using velocity data from PIV measurement. *Meas Sci Technol* 16:989–996
- Jones BM (1936) Measurement of profile drag by the pitot-traverse method. *ARC R&M* 1688
- Lin JC, Rockwell D (1996) Force identification by vorticity fields, techniques based on flow imaging. *J Fluids Struct* 10:663–668
- Noca F, Shiels D, Jeon D (1999) A comparison of methods for evaluating time-dependent fluid dynamic forces on bodies, using only velocity fields and their derivatives. *J Fluids Struct* 13:551–578
- Unal MF, Lin JC, Rockwell D (1997) Force prediction by PIV imaging, a momentum based approach. *J Fluids Struct* 11:965–971