Hot film/wire calibration for low to moderate flow velocities

Hot film/wire calibration for low to moderate flow velocities

X Grandchamp, A Van Hirtum and X Pelorson

GIPSA-lab, UMR 5216 CNRS, Grenoble Universities, Grenoble, France

E-mail: annemie.vanhirtum@gipsa-lab.grenoble-inp.fr

Abstract
Two simple iterative calibration methods accounting for the presence of the boundary layer are
proposed and evaluated for low to moderate velocities from 0.17 up to 15 m s^{-1} on a simple
axisymmetrical calibration setup. As a benchmark the calibration outcome is compared to the
iterative algorithm proposed by Johnstone and colleagues (2005 *Exp. Fluids* **39** 525–32),
requiring the measurement of the mean exit velocity. An overall good collapse of all
calibration methods for calibration velocities $U_{cal} \geqslant 3$ m s^{-1} is observed. For lower velocities,
an approach based on the displacement thickness from the measured mean exit velocity
profiles allows one to estimate velocities $U_{cal} \geqslant 0.17$ m s^{-1}. In addition, the measurement
procedure can be limited to the exit centreline position by assuming a linear growth of the
boundary layer, resulting in accurate velocity estimations for $U_{cal} \geqslant 0.5$ m s^{-1}.

Keywords: hot-film/wire anemometer, calibration, non-uniform velocity profiles

1. Introduction

Hot-wire/hot-film anemometers are widely used in fluid
mechanics research in order to investigate with a high
degree of accuracy fluid flow dynamic properties by deducing
instantaneous velocities from local heat transfer information
of the sensor. Therefore, the quality of the measurements is
dependent on the calibration procedure.

For velocities higher than 2 m s^{-1} (Yue and Malmstrom
1998), the procedure is simple and well established. The
outlet velocity produced by a calibration nozzle is measured
and supposed to be equal to the bulk velocity. Thus, the
procedure is based on the capacity of the calibration nozzle to
develop a 'top hat' velocity profile.

Nonetheless, calibration standards such as ISO 5167 are
designed for a range of applications limited to Reynolds
number $Re \geqslant 10\,000$, which for a nozzle with a diameter
$D > 5$ cm, as described in the ISO 5167 standard, correspond to
velocities above 2 m s^{-1}. Therefore, 'top hat' velocity profiles
are difficult to maintain. To overcome this difficulty, recent
devices such as the one developed by Al-Garni (2007) using
a swinging arm are developed together with dynamic velocity
calibration techniques. Other procedures use the regular nature
of vortex shedding in the wake of a circular cylinder (Lee and

Budwig 1991) or the characteristics of a laminar pipe flow
(Yue and Malmstrom 1998).

Despite the complexity of some techniques, the range
of velocity is limited due to their interest for low velocity
regimes. Therefore, in the case of a joint calibration for low
and moderate velocity, another calibration tool and method
is of interest suitable for uniform and non-uniform velocity
profiles.

By measuring the velocity profile from a unique nozzle
for 30 velocity levels, ranging from 0.125 to 13.78 m s^{-1},
Johnstone *et al* (2005) proposed an iterative calibration
procedure based on the ratio of the real volume flow rate Q_{meas}
to an estimated volume flow rate Q_e, corresponding to the
integration of the measured velocity profile across the nozzle
diameter. For each velocity level a correction of $Q_{meas}Q_e^{-1}$ is
applied and a new calibration curve is obtained. The global
optimization procedure is repeated until the velocity converges
to within 0.5%.

In this work, a simple inexpensive calibration setup is
presented. Next, two calibration methods are proposed for low
to moderate velocities that take into account the development
of the boundary layer. The first calibration procedure, labeled
Algo I, uses an estimation of the displacement thickness δ^*
from the measured mean velocity profile across the nozzle
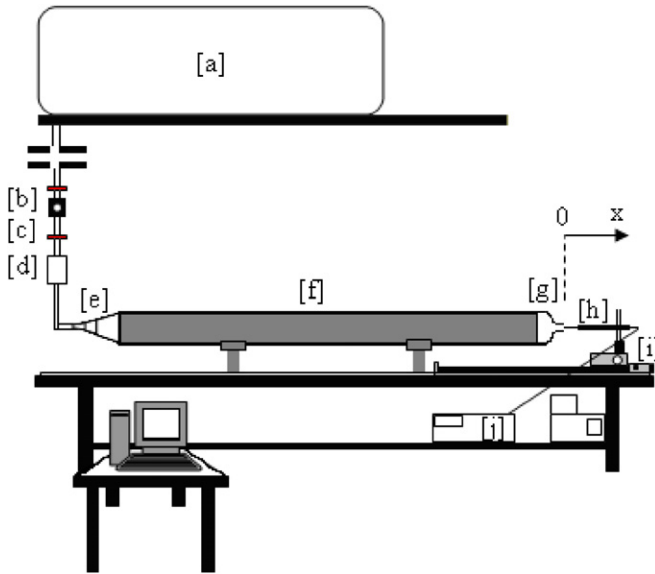exit. The second procedure, labeled Algo II, estimates the

1

Figure 1. A sketch of the apparatus: (a) air supply, (b) pressure regulator, (c) valve, (d) mass flow meter, (e) divergent, (f) uniform pipe, (g) convergent nozzle, (h) hot film, (i) positioning system, (j) IFA 300.

Figure 2. Nozzle mean exit velocity profiles for seven volume flow rates.

displacement thickness by making additional assumptions on the velocity profile in the boundary layer and its thickness δ. As a benchmark, comparison is made with the optimization method developed by Johnstone *et al* (2005).

2. Calibration setup and procedure

2.1. Description of the setup

A diagram of the apparatus used for the calibration is shown in figure 1. It consists in an oil-injected rotary screw compressor Copco GA7 with an integrated oil/water separator. To avoid any resulting vibrations, the compressor is isolated in a separated room. Downstream, a pressure regulator (b) (Norgren type 11-818-987) and a manual valve (c) are placed in order to reduce air pressure and prevent pressure fluctuations during experiments. The pressure regulator is connected with a thermal mass flow meter (TSI 4040) (d) via a uniform duct of diameter 0.01 m. Then, the air circulates through a concatenation of diffusers (e). In order to limit flow separation, diffusers are filled with steel wool and a first grid with 1 mm diameter holes is positioned at 2/3 of the total length of the divergent inlet section. A uniform pipe (f), separating the concatenation of diffusers from a ninth order convergent nozzle (g), is used as a settling chamber to ensure total flow mixing. It presents a diameter $D_{\text{pipe}} = 0.1$ m and length $L = 2$ m, and contains a second perforated plate at its entrance. The nozzle exit presents an area $S = 0.000\,36$ m^2, imposing on the air an area contraction ratio of 4.5 : 1, and a length equal to 1.16 times the diameter D.

The hot film (h) (TSI 1201–20; diameter of 50.8 μm and a working length of 1.02 mm) under calibration is placed at a distance $x/D < 0.04$ downstream of the nozzle exit. In order to measure the exit velocity profile, the probe is mounted on a two-dimensional stage positioning system (i) (Chuo Precision
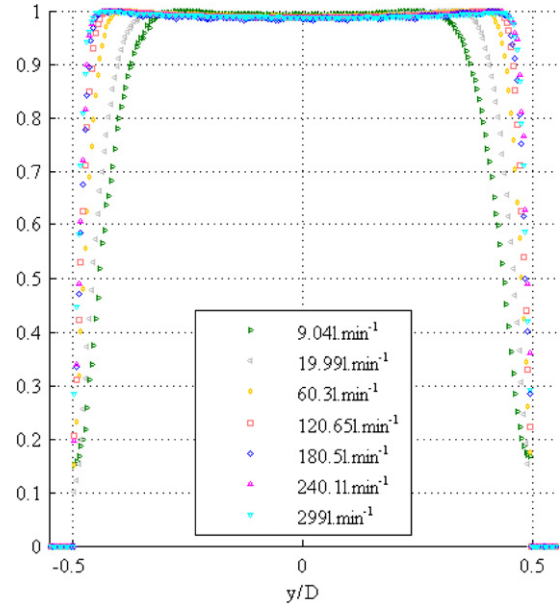
Industrial Co. CAT-C, ALS-250-C2P and ALS-115-E1P), providing a positioning accuracy in the radial *y*-direction perpendicular to the airflow of 2 μm. The displacement is controlled by a user-defined matrix implemented in LabVIEW (National Instruments). At each measurement station, the signal is collected for 4 s at 40 kHz by a constant temperature anemometer system (j) (TSI IFA 300) and stored on a computer. The choice of a high sampling frequency with an acquisition time of 4 s leads to an accuracy within 1% for the mean velocity. Except for the air compressor, the whole setup is placed in a confined room in order to avoid any flow disturbances. The room temperature at the beginning of each velocity profile measurement is controlled thanks to an air conditioning system in order to minimize temperature variations. To account for drift in room temperature T_{a} from the reference ambient temperature, $T_{\text{a,r}} = 21.5$ °C, the room temperature is measured for each calibration velocity and the measured hot-film output voltages E_{meas} are corrected to E_{corr} using the approach adopted by Kanevce and Oka (1973), with T_{f} denoting the airflow temperature:

$$E_{\text{corr}} = E_{\text{meas}} \left(\frac{T_{\text{f}} - T_{\text{a}}}{T_{\text{f}} - T_{\text{a,r}}} \right)^{-1/2} . \tag{1}$$

All instruments used in the calibration procedure and their corresponding uncertainties are listed in table 1.

The flow characteristics are checked by displacing the probe across the horizontal centreline of the jet at a distance $x/D < 0.04$ with a step size equal to $\Delta y = 10^{-5}$ m for all 27 calibration velocities. The normalized mean velocity profiles for seven volume flow rates Q_{meas} are shown in figure 2. For velocities, Q_{meas}/S, above 1 m s^{-1} the variation in the mean velocity profiles is lower than $\pm 0.5\%$ in the centre portion of the jet $|y|/D < 0.25$, and does not exceed $\pm 2\%$ for the lowest velocity 0.17 m s^{-1}. The centreline turbulence intensity T_{U} is

Table 1. Relevant measurement range and corresponding uncertainties of instruments.

	Instruments	Relevant measurement range	Uncertainties
Flow rate	TSI model 4040	9–300 l min^{-1}	±2%
Fluid temperature	TSI model 4040	20–25 °C	±1 °C
Room temperature	OTAX 421001	22–25 °C	±0.2 °C
Nozzle diameter	Manufacturing precision	2.16 cm	±0.02 mm
Fluid pressure	TSI model 4040	97–115 kPa	±1 kPa
Data acquisition system	PCI-MIO-16XE-10 (National Instruments) in combination with IFA 300 (TSI)	±10 V	±72.3 μV

defined as $T_U = \frac{\sigma}{U}$, where σ represents the root mean square obtained as

$$\sigma = \sqrt{\frac{1}{N_{\text{tot}}} \sum_{p=1}^{N_{\text{tot}}} (U_p - U)^2} \qquad (2)$$

with N_{tot} the total number of samples, U_p the pth instantaneous sample and U the mean velocity; it is less than 1% for all calibration velocities. As a consequence, turbulence corrections are ignored (Johnstone *et al* 2005). In addition, because the probe surface in the flow direction imposes a percentage of obstruction lower than 4.7% at the nozzle surface exit, the blockage effect can be ignored following the consideration of Khan *et al* (1987).

2.2. Calibration procedure

By considering a cross section of a real fluid in a duct with a sufficiently large section, two distinct parts can be schematically identified: the boundary layer, in which viscous effects are of the same order of magnitude as inertial effects, and the flow core, where viscous effects can be neglected. For high velocities and at the exit of a calibrator system using a convergent, the boundary layer is confined to the vicinity of the wall. A velocity reduction leads to an increase of the viscous effects and a boundary layer thickening. As a consequence, we observe a reduction of the core region where the velocity is uniform, and the difference between the centreline mean velocity and the bulk velocity is increased. In the following, two iterative calibration methods are proposed taking into account the development of the boundary layer when the volume flow rate, and so the centreline velocity, is reduced. In both cases, the calibration is initialized by the ratios of the measured volume flow rates to the nozzle exit area as was also done in Johnstone *et al* (2005). This common initial calibration is obtained by considering the exit centreline velocity U_0 to be equal to the bulk velocity:

$$U_0 = \frac{Q_{\text{meas}}}{\pi \left(\frac{D}{2}\right)^2} \qquad \text{or} \qquad U_0 = \frac{Q_{\text{meas}}}{S}. \qquad (3)$$

The first method is based on iteratively estimating the displacement thickness δ^* from the measured mean velocity exit profiles computed with the calibration of the previous step as

$$\delta^* = \int_0^{D/2} \left(1 - \frac{U(y)}{U_0}\right) \mathrm{d}y, \qquad (4)$$

where $U(y)$ represents the velocity at a transverse position. The displacement distance corresponds to the distance the wall has to be displaced to keep the same mass volume flow rate in the case of an ideal flow where the boundary layer is absent. Therefore, the exit centreline velocity U_0 in (3) is corrected as

$$U_0 = \frac{Q_{\text{meas}}}{\pi \left(\frac{D}{2} - \delta^*\right)^2}. \qquad (5)$$

A new calibration curve is obtained from the corrected centreline velocities from which the displacement thickness is re-estimated. The procedure is repeated until the calculated centreline exit velocities are found to converge to within 0.5%.

Obviously, the previous calibration method as well as the method proposed by Johnstone *et al* (2005) requires integration of the measured velocity profile over the nozzle exit either in order to estimate the displacement thickness or to estimate the volume airflow rate. The second calibration method further simplifies the measurement procedure by assuming a linear velocity profile in the boundary layer. In addition, the boundary layer thickness is estimated from the previous estimation of the centreline velocity as

$$\delta = \alpha \sqrt{\frac{\nu D}{U_0}} \qquad (6)$$

with α an 'ad-hoc' parameter depending on the nozzle (Schlichting and Gersten 2000).

The difference between the real area S and the area corresponding to an idealized inviscid fluid based on the displacement thickness is then easily seen to correspond to $S(1 - \delta)$. As before, the procedure is repeated until the calculated centreline exit velocities are found to converge within 0.5%. The equations for implementation of Johnstone's method, Algo I and Algo II, are summarized in table 2.

3. Results and discussion

Figure 3 shows the calibration curve $U_{\text{cal}}(E)$ obtained by the three different methods. The fourth curve corresponds to an ideal fluid. As expected from the presence of the boundary layer, Algo I, Algo II and Johnstone's method exhibit an increase in the predicted velocity compared to an ideal fluid. The differences between the methods are evaluated in more detail in figure 4, where the calibration curve obtained with Algo I is taken as the reference. For velocities $U_{\text{cal}} \geqslant$ 4.5 m s^{-1} ($E = 1.69$ V) the overall difference is less than 3% between the three techniques. As the velocity is further

Table 2. Summary of the main steps for the three calibration algorithms.

Johnstone *et al* (2005)	Algo I	Algo II
$U_{0,i} = U_{0,i-1} \times \left(\frac{Q_{\text{meas}}}{Q_e} \right)_i$	$\delta^*_{i+1} = \int_0^{D/2} \left(1 - \frac{U_i(y)}{U_{0,i}} \right) dy$	$U_{0,i} = \dfrac{Q_{\text{meas}}}{S \left(1 - \alpha \sqrt{\frac{\nu D}{U_{0,i-1}}} \right)}$
	$U_{0,i} = \dfrac{Q_{\text{meas}}}{\pi \left(\frac{D}{2} - \delta^*_i \right)^2}$	

Table 3. The three different procedures and their corresponding required measurements, principles and assumption, and velocity range.

| Procedure	Required measurement	Principle and assumption	Velocity range	Major drawback	Major advantage
Johnstone *et al* (2005)	Velocity profile $U(y)$ + volume flow rate Q_{meas}	Correction on U_0 induced by the ratio between the measured volume flow rate Q_{meas} and the estimated one Q_e	$U_{\text{cal}} \geqslant 3 \text{ m s}^{-1}$	Accuracy loss with boundary layer development	Simple to implement
Algo I	Same as Johnstone's method	Correction on U_0 induced by the introduction of the displacement thickness δ^*	$U_{\text{cal}} \geqslant 0.17 \text{ m s}^{-1}$	Accurate measurement of the velocity profile in order to estimate the displacement thickness	Most accurate for low velocities
Algo II	Volume flow rate Q_{meas} + single point measurement of U_0 at the nozzle centre	Correction on U_0 induced by the estimation of the displacement thickness δ^* + assumption on the velocity profile in the boundary layer + estimation of boundary layer thickness	$U_{\text{cal}} \geqslant 0.5 \text{ m s}^{-1}$	Ad-hoc coefficient	Reduced number of velocity data
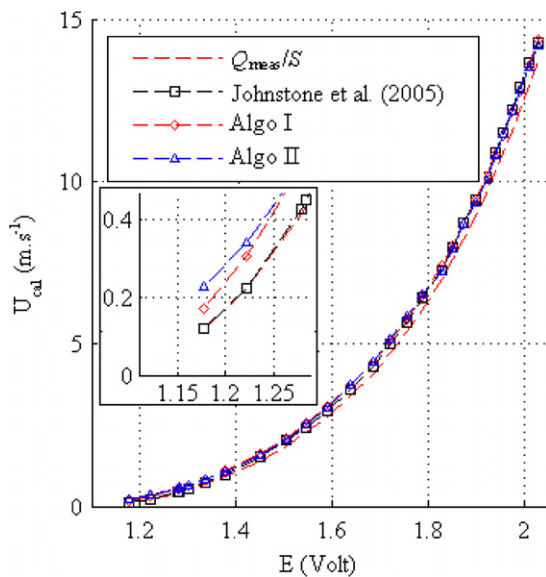
Figure 3. Calibration curves obtained from four methods: $U_{\text{cal}} = Q_{\text{meas}}/S$, Johnstone's method, Algo I and Algo II.

Figure 4. The resulting differences between four methods: $U_{\text{cal}} = Q_{\text{meas}}/S$, Johnstone's method, Algo I and Algo II.

reduced the discrepancy between Johnstone's method and the two proposed calibration procedures Algo I and Algo II increases up to 4% for $U_{\text{cal}} = 3 \text{ m s}^{-1}$ ($E = 1.59$ V). For lower velocities Johnstone's method converges towards the curve $U_{\text{cal}} = Q_{\text{meas}}/S$. This tendency reveals a loss of pertinence of the applied optimization approach and its incapacity to evaluate the real behaviour of the flow, when an increase of the boundary layer is observed from the measured profiles shown in figure 2. In contrast, velocities predicted by Algo I and Algo
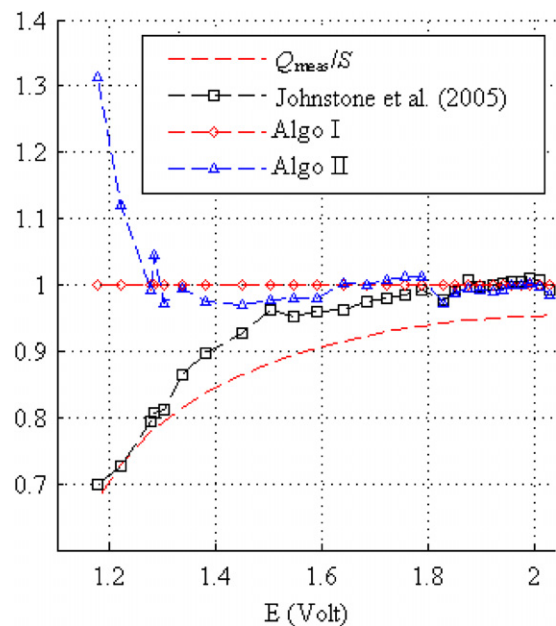
II exhibit a greater magnitude compared to the curve $U_{\text{cal}} = Q_{\text{meas}}/S$, with a good agreement for $U_{\text{cal}} \geqslant 0.5 \text{ m s}^{-1}$ ($E = 1.278$) since the overall difference between the two methods is lower than 3%. At the lowest calibration velocity $U_{\text{cal}} = 0.17 \text{ m s}^{-1}$ ($E = 1.178$ V), Algo II presents respectively an overestimation of about 30% of the velocity predicted by Algo I, indicating that the assumption of a linear boundary layer fails for velocities $U_{\text{cal}} < 0.5 \text{ m s}^{-1}$. The level of

divergence of this method from Algo I is similar to that obtained with Johnstone's method, where an approximate underestimation of 30% is observed. The reasons for the divergence are inherent to the principles and assumptions formulated by the three procedures and summarized in table 3. While Johnstone *et al* (2005) assume a correction on the centreline velocity based on a difference in the volume flow rate, Algo I and Algo II introduce physical arguments with the estimation of the displacement thickness δ^*. Accounting for boundary layer development leads to more accurate calibration results. In particular Algo I is the most accurate since the displacement thickness δ^* is calculated from the mean velocity profile and no further assumptions are made. Therefore, the lower velocity limit of Algo I is mainly dictated by measurement errors. The lower limit of Algo II on the other hand is dictated by the failure of the assumption of the linear growth profile in the boundary layer. Finally, Johnstone's method is limited by the development of the boundary layer itself.

4. Conclusion

A simple calibrator system is presented ensuring uniform velocity profiles with low turbulence intensity for low to moderate velocities $U_{\text{cal}} < 15$ m s^{-1}. Two iterative calibration methods labelled as Algo I and Algo II are proposed to account for the presence of the boundary layer and compared to the iterative method proposed in Johnstone *et al* (2005) which is used as a reference. It is seen for Algo I that while applying the same measurement procedure as required for Johnstone *et al* (2005), i.e. precise measurement of the mean exit velocity profiles, accounting for the presence of the boundary layer extends the range of accurate velocity estimations from

$U_{\text{cal}} \geqslant 3$ m s^{-1} to $U_{\text{cal}} \geqslant 0.17$ m s^{-1} as long as the displacement thickness is estimated.

Algo I leads to a better estimation in a large range of velocities, due to the lack of assumptions compared with Algo II and the purely optimization approach compared to Johnstone's method. Nonetheless a significant number of data points is needed. In contrast, Algo II lightens the experimental procedure and in addition presents an accurate result in an intermediate range of velocities $U_{\text{cal}} \geqslant 0.5$ m s^{-1}.

Acknowledgments

References

Al-Garni A M 2007 Low speed calibration of hot-wire anemometers *Flow Meas. Instrum.* **18** 95–8

Johnstone A, Uddin M and Pollard A 2005 Calibration of hot-wire probes using non-uniform mean velocity profiles *Exp. Fluids* **39** 525–32

Kanevce G and Oka S 1973 Correcting hot-wire readings for influence of fluid temperature variations *DISA Inf.* **15** 21–4

Khan M K, MacKenzie K A and Bruun H H 1987 The effects of blockage correction in hot-wire probe calibration facilities *J. Phys. E: Sci. Instrum.* **20** 1031–5

Lee T and Budwig R 1991 Two improved methods for low-speed hot-wire calibration *Meas. Sci. Technol.* **2** 643–6

Schlichting H and Gersten K 2000 *Boundary Layer Theory* (Berlin: Springer)

Yue Z and Malmstrom T G 1998 A simple method for low-speed hot-wire anemometer calibration *Meas. Sci. Technol.* **9** 1506–10