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Technical Notes

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Constant-Temperature and Constant-Voltage Anemometer Use in a Mach 2.5 Flow

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Introduction

TURBULENCE measurements in high-speed flows are very demanding because of the large bandwidth that is required to capture the high-frequency fluctuations. Despite recent advances in measurement technology, such as laser Doppler anemometry and particle image velocimetry, the primary measurement device for turbulence measurements in high-speed flows is hot-wire anemometry.[1] The primary reason is that variables other than velocity, such as mass flux and temperature fluctuations, can be obtained. However, as the hot wire behaves like a first-order, low-pass filter to the high-frequency fluctuations, it is necessary to compensate for the thermal inertia of the hot wire. Historically, the constant-current anemometer (CCA), with full thermal lag compensation, has been used for high-speed turbulence measurements. Later the constant-temperature anemometer (CTA) was introduced. In the CTA a feedback loop is used to maintain the wire at a constant temperature. A high bandwidth can however only be achieved after a very careful tuning of the CTA's circuit parameters; this process can be relatively time consuming. In addition, the bandwidth that is achieved with CTA systems is usually lower than for CCA, except when a 1:1 bridge system is used.[2,3] The constant-voltage anemometer (CVA) was recently introduced to address these limitations.[4] An early prototype CVA was used to make the first successful studies of hypersonic laminar boundary-layer stability in a quiet tunnel.[5] Subsequently there have been studies that have compared the response of the CVA and CTA in supersonic flows, including jets and boundary layers.[6,7] Although the comparison of CVA and CTA is quite satisfactory in some cases,[7] in other cases there are substantial differences at high frequency that are attributed to CTA.[8]

In the present work it is demonstrated that accurate large-bandwidth CTA measurements are possible without the need for either a 1:1 bridge or a time-consuming adjustment procedure. This is accomplished by measuring the in situ CTA frequency response and then applying this to the fluctuation measurements. The CTA's fluctuation measurements then show excellent agreement with the CVA measurements that are obtained with partial hardware compensation and then in posttest processing are corrected for the full thermal lag compensation.[6,8]

Constant-Temperature Anemometer

The CTA used in the present study is a prototype that was designed, in a cooperative effort between Universität Stuttgart, Russian Academy of Sciences–Siberian Branch, and the company Cosytec Elektronik GmbH. The CTA circuit has a 1:10 bridge that yields a typical cutoff frequency of approximately 100 kHz, which is a relatively low cutoff frequency for measurements in a fully developed supersonic turbulent boundary layer. To obtain high-frequency fluctuation measurements with this anemometer, its in situ frequency response is measured, and in a posttest software procedure the measured fluctuation data are corrected to account for the roll-off and/or the nonoptimum tuning of the anemometer's electrical parameters. This software correction procedure was developed to provide for large-bandwidth measurements with CTA in a short-duration supersonic wind tunnel.[9] The correction procedure can be written in the frequency domain:

$$e'_{\mathrm{CTA}}(s) = \frac{e'_{\mathrm{CTA,raw}}(s)}{H_{\mathrm{CTA}}(s)} \tag{1}$$

The transfer function of the anemometer $H_{\mathrm{CTA}}(s)$ is determined from the digital processing of the anemometer's response to an electrical square-wave signal. This method is equivalent to the traditional sine wave test, but is advantageous as the desired frequency response is obtained more quickly.[10] In the present work, a 2-kHz square-wave signal of 2 V peak to peak is injected through a 33-kΩ resistance that is placed parallel to the hot wire. Phase averaging of the square-wave response, over approximately 5 s in the turbulent boundary layer, is used to obtain a converged signal for the determination of $H_{\mathrm{CTA}}(s)$.

Constant-Voltage Anemometer

The CVA used in the experiment is the Tao Systems® prototype VC-01. The characteristics of the circuit and its mode of operation are given by Sarma.[4] The hardware thermal compensation in the CVA is accomplished by a resistor–capacitor (RC) network whose time response T_c is fixed for the present tests, as 0.1 ms. The bandwidth is measured as 470 kHz, using a sine wave signal injection test.[11] The use of a fixed T_c avoids the need to make a time-consuming adjustment to match the hardware and hot-wire time constants. During the posttest software procedure, the measured in situ time constant M_w^{CVA} of the hot wire is used to correct the measured fluctuations using the

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relation[6,8]

$$e'_{\text{CVA}}(s) = e'_{\text{CVA,raw}}(s)\left[\frac{1 + M_w^{\text{CVA}} s}{1 + T_c s}\right] \tag{2}$$

M_w^{CVA} is measured in situ from the dynamic CVA response to a 16-Hz square wave that is applied to the hot wire. As is typical of a first-order system, M_w^{CVA} is the time taken for the amplitude to reach 63% of its final value. Phase averaging over approximately 8 s yields a converged CVA response.

Hot-Wire Response

In a supersonic flow at Mach 2.5, the output voltage of the hot-wire anemometer is a function of the mass flux and total temperature.[1] This mixed mode response can be written as

$$\frac{1}{S_{T_0}^2}\frac{\overline{e'^2}}{E^2} = \frac{a_w^2}{4}T_m^2 - a_w \Re T_m T_{T_0} + T_{T_0}^2 \tag{3}$$

where the three unknowns—mass flux turbulence intensity T_m, correlation coefficient $\Re$, and total temperature turbulence intensity T_{T_0}—are fluid dynamic fluctuations, a_w is the wire overheat, and S_{T_0} is the relative sensitivity to total temperature. Here a_w is used as an approximation of the general overheat parameter A_w (Ref. 1). For a given overheat, the right-hand side of Eq. (3) is a function only of the fluid dynamic fluctuations and is independent of the anemometer type. Comte-Bellot[1] has derived approximate expressions for S_{T_0}; for the CTA the left-hand side of Eq. (3) is

$$\frac{\overline{e'^2}}{S_{T_0}^2 E^2} \cong 4a_w^2\frac{\overline{e'^2}}{E^2} \tag{4a}$$

and for the CVA it is

$$\frac{\overline{e'^2}}{S_{T_0}^2 E^2} \cong (1 + 2a_w)^2\frac{\overline{e'^2}}{E^2} \tag{4b}$$

Fourier transform analysis of Eq. (3) yields the power spectral densities (PSD) of the voltage, mass flux, and total temperature

$$\frac{\text{PSD}_{e'}}{E^2 S_{T_0}^2} = \frac{a_w^2}{4}\text{PSD}_{\text{Tm}} - a_w \Re\,\text{PSD}_{\text{Tm}}^{\frac{1}{2}}\text{PSD}_{To}^{\frac{1}{2}} + \text{PSD}_{To} \tag{5}$$

Therefore, as with Eq. (3), it is instructive when comparing CTA and CVA to examine the left-hand side of Eq. (5).

Experimental Method

The experiment was conducted in the Halb Modell Mess Strecke (HMMS) wind tunnel at Universität Stuttgart. The HMMS is a suck-down supersonic wind tunnel, whose test section is bounded by a Mach 2.54 nozzle block, the wind-tunnel floor, and parallel side walls. The stagnation conditions are close to ambient conditions (stagnation pressure 1×10^5 Pa, and total temperature 290 K), and the maximum run time of the tunnel is approximately 90 s. The measurements are performed in the turbulent boundary layer of the tunnel floor 480 mm downstream of the nozzle throat. The boundary-layer thickness is $\delta = 7.5$ mm, and the measurements are made in the boundary layer, 2.7 mm above the floor (that is, $y/\delta = 0.36$), and outside the boundary layer at $y/\delta = 1.5$. It is emphasized that in the present experiment the measurements are made in the same flow using the same hot wire operated under identical conditions with both CTA and CVA.

The hot wire is a tungsten wire of 5-μm diam and 1.2-mm length that is spot-welded to the prongs of a commercial DANTEC® 55P11 probe. A small amount of slack is used in attempt to avoid the strain-gauging effect, but as is evident from the spectra (Figs. 1–3), this was

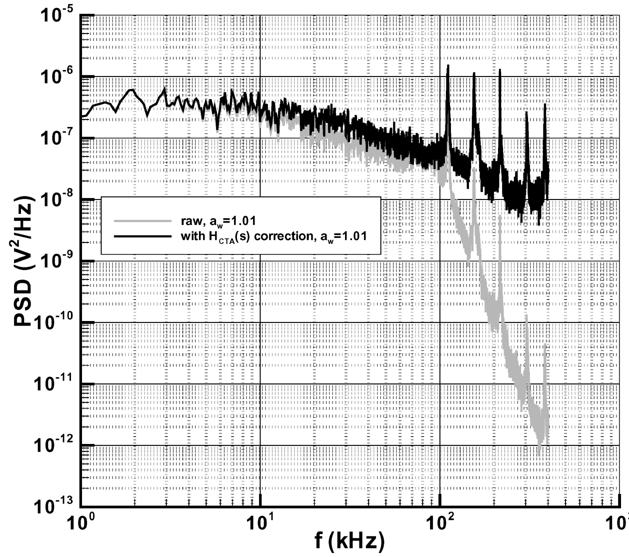

Fig. 1 Raw CTA spectra and corrected CTA spectra (y/δ = 0.36).

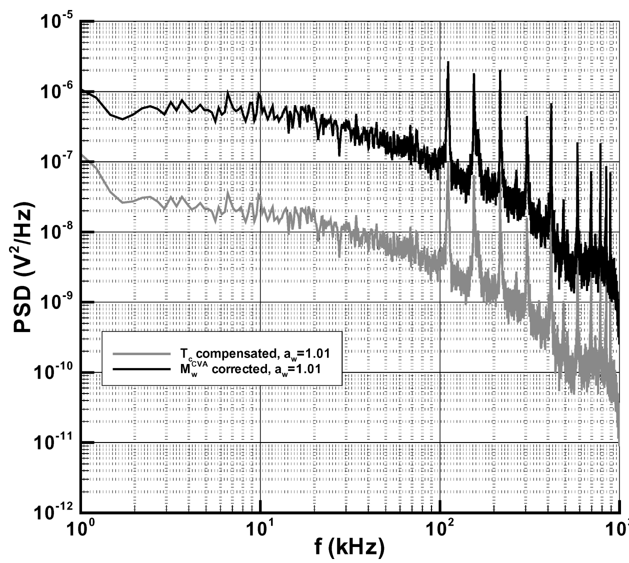

Fig. 2 Partial hardware T_c compensated and full software M_w^{CVA} corrected CVA spectra (y/δ = 0.36).

not successful. The Reynolds number based on the wire diameter and local flow conditions is 15 at $y/\delta = 0.36$ and 25 at $y/\delta = 1.5$.

In the experiment the following procedure was employed. First, the CTA measurements are made. These CTA measurements consisted of two phases: first, the fluctuation measurements including the measurement of the wire voltage are performed, followed by an electrical test to determine H_{CTA}. Following the CTA measurements, the CVA measurements are then also obtained in two phases, using the wire voltages measured in the preceding CTA tests: the CVA fluctuation measurements are first obtained, and then the in situ hot-wire time constant is measured.

The spectra were computed from the averaging of 16 blocks each of record length 8192; the spectral resolution is 0.24 kHz for the CVA and 0.1 kHz for the CTA.

Results

Figure 1 illustrates the effects of the correction procedure for the CTA, using H_{CTA}. It is clear that the shape of the spectra is quite different with and without the correction. The uncorrected spectra show a sharp decrease in amplitude above the roll-off frequency of the CTA. The absence of the correction for the anemometer's response in the commercial CTA system is the reason for the discrepancy between CTA results and CCA and CVA results that are reported in previous experiments.[8] The effect of strain gauging in the hot wire is quite apparent in the spectra.

The spectra of the fluctuating CVA output voltage with partial and full thermal lag correction are presented in Fig. 2. The corrected CVA spectra are obtained by applying Eq. (2). The partially (raw spectra) and the fully compensated CVA spectra show the same bandwidth. Furthermore, these CVA spectra differ only in their levels as can be inferred from the asymptotic limit of the software correction, which only involves the ratio M_w^{CVA}/T_c (Ref. 8). The effect of wire strain gauging is also observed in the CVA spectra, as in the CTA spectra, suggesting that strain gauging is only wire dependent and not a function of the anemometer type.

Figures 1 and 2 illustrate also the frequency above which the signal-to-noise ratio (SNR) becomes less than one, around 200 kHz for the CTA and 450 kHz for the CVA.

Figure 3 compares the CTA and CVA spectra with the respective posttest software corrections, namely, correction for the anemometer's response for CTA and full thermal lag correction for CVA. The

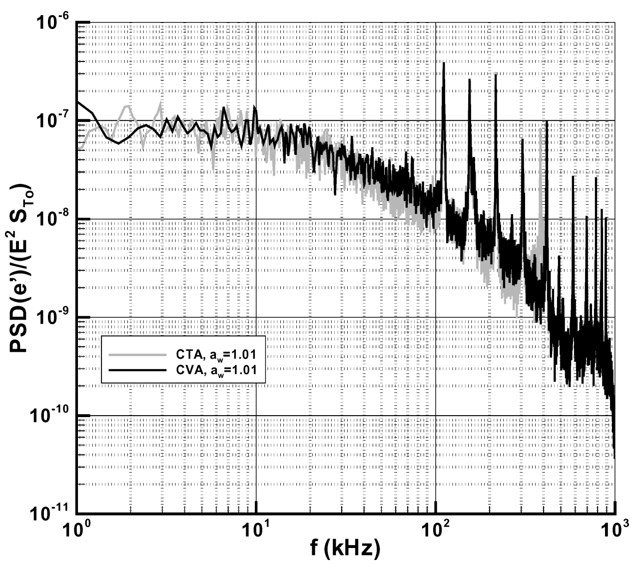

Fig. 3 Comparison of CTA and CVA spectra with respective software corrections ($y/\delta = 0.36$).

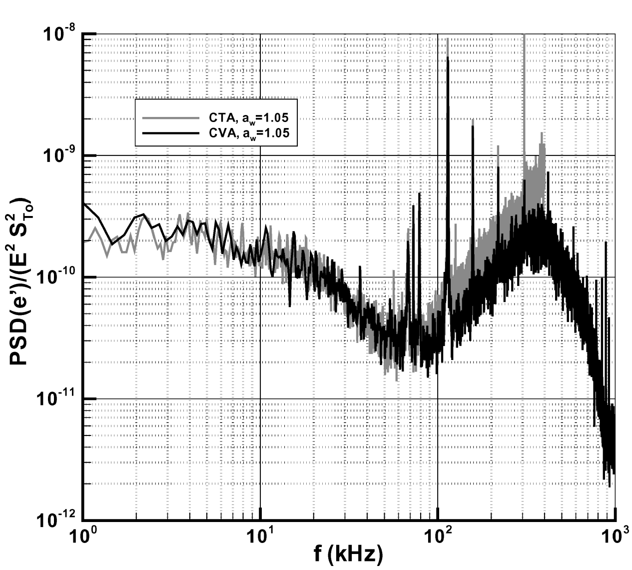

Fig. 4 Comparison of CTA and CVA spectra with respective software corrections (freestream measurements: $y/\delta = 1.5$).

importance of the correction for the CTA bridge response for large bandwidth measurements is clearly evident, as the general features of the software corrected CTA spectra are in very good agreement with the CVA spectra.

Figure 4 compares, in the freestream of the wind tunnel ($y/\delta = 1.5$), the CTA and CVA spectra with their respective posttest software corrections. The lower fluctuation levels in the freestream, compared to the boundary layer, provide a good source to assess the relative SNR behaviors of the two anemometers. Because of the lower fluctuation level in the freestream, the spectra of both anemometers show the characteristic f^2 rise at high frequency that is caused by electronic noise.[12–14] To the authors' knowledge, Fig. 4 is the first such comparison of the electronic noise behavior in CTA and CVA at large bandwidths.

Conclusions

In summary, a systematic comparison of constant-temperature anemometer (CTA) and constant-voltage anemometer (CVA) fluctuation measurements in supersonic flow is made. The same hot wire is operated at the same locations under the same conditions with both systems. A posttest software correction is applied to the fluctuation measurements in both systems. For the CTA the frequency response is obtained; this is then used to correct the measured data for the bridge's dynamic behavior. In the case of the CVA, the in situ time constant of the hot wire is measured; the measured time constant is then applied to CVA measurements obtained with a fixed compensation. The software-corrected CTA and software-corrected CVA spectra are in very good agreement when the signal-to-noise ratio is above unity for both systems. This demonstrates that accurate large-bandwidth CTA measurements are possible without the need for either a 1:1 bridge or a time-consuming adjustment procedure.

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