Measurement 91 (2016) 1–11

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Effects of prong-wire interferences in dual hot-wire probes on the measurements of unsteady flows and turbulence in low-speed axial fans

K.M. Argüelles Díaz *, J.M. Fernández Oro, M. Galdo Vega, E. Blanco Marigorta

Universidad de Oviedo, Área de Mecánica de Fluidos, Campus de Viesques, 33271 Gijón, Asturias, Spain

ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form 23 July 2015
Accepted 10 May 2016
Available online 11 May 2016

Keywords:
Hot-wire anemometry
X-array probes
Prong-wire interference
Time-resolved measurements
Turbulence intensity
Axial turbomachinery

ABSTRACT

Support needles of Dual Hot Wire (DHW) anemometers induce significant inaccuracies for flow angle and turbulence measurements in the case of X-array probes with prongs perpendicular to the flow plane. At certain angular ranges of the incident flow, a wake interference is established between the sensors which leads to a practical limitation of the device. In the case of turbomachinery environments, this is even more critical due to the inherent unsteadiness of the flow direction rotor downstream.

In the present work, the measurement deviation caused by hot-wire probes operated under interference effects has been studied and evaluated, in both steady and unsteady conditions, especially for turbomachinery flows. New designs of DHW probes without prong-wire interference effects in their operative angular ranges were developed for validation. In particular, both V-type and Z-type interference-free probes are compared to a classic X-type probe susceptible for prong-wire interferences. Firstly, a steady calibration is performed to show the baseline deviation of the X-array probe in the measurement of the velocity magnitude, the flow angle and the turbulence intensity. Typical errors up to 10–13% in velocity, 5.5–7 deg in angle and 1.5–2.5 points overestimation in turbulence levels are observed. Also, unacceptable inaccuracies are found in the turbulence spectra of the measurements.

Following, the impact of the interference for unsteady flow measurements is highlighted comparing the performance of the three probes within the single stage of a low-speed axial fan. The unsteady measurements of the X-array probe have revealed similar averaged discrepancies to those observed in the steady performance, but the instantaneous deviations can be as high as a 20% in velocity and 16–18 deg in flow angle in those regions (rotor wakes) with large unsteady velocity gradients and turbulence generation. Turbulence intensity measured in the rotor wakes is also excessively higher.

1. Introduction

Thermal anemometry is a measuring technique that retrieves the flow velocity through heat transfer variations in a small sensor that it is electrically heated while exposed to a moving fluid. The most common thermal anemometer is the hot wire thermal device, which it is composed by a single or multiple tiny wires mounted on the probe tip. Every wire is weld to a couple of prongs, usually of stainless steel, incrusted to the probe support, which are also employed as electrical contacts to heat the wire to a temperature in the range of 200–300 °C.

Wire's diameter must be extremely reduced for a high frequency response. Typical wire diameters are ranged between 2 and 5 μm, resulting in extremely low Reynolds numbers which lead to consider the incident flow over the wires as symmetric and quasi-steady. Additionally, the wire's length must be also quite reduced to enlarge the probe's spatial resolution. Optimal values are found when the length-to-diameter ratio is about 200 [1], although it must be kept in mind that the spatial resolution is also conditioned by the existing distance between the wires [2].

When the flow impinges on a hot wire, part of its heat energy is advected by the flow (forced convection [3]). Because of the wire thermal inertia, its frequency response to flow velocity variations is dumped, so it needs to be electronically compensated using, for instance, a constant temperature anemometer (CTA). This kind of equipment is an amplifier device that feeds back the wires to maintain its temperature independent of the variations in the flow velocity [4]. Using this technique, the frequency limit can be significantly raised, up to 1000 times higher [5,6].

Every probe must be calibrated before it can be used to measure a particular flow. The calibration determines a relationship between the output voltage of every single wire and the magnitude and direction of the flow velocity vector. A sensitivity function is

* Corresponding author.
E-mail address: arguelleskatia@uniovi.es (K.M. Argüelles Díaz).

http://dx.doi.org/10.1016/j.measurement.2016.05.031
0263-2241/

Nomenclature

Acf	angular calibration coefficient (–)
BPF	blade passing frequency (Hz)
CTA	constant temperature anemometer
E	output voltage (V)
e_α	error in angle (deg)
e_v	error in velocity (%)
e_t	error in turbulence (points)
f	transfer function
f	frequency (Hz)
M	total number of ensemble-averages (phase-averaging)
N	total number of angular phases (spatial discretization)
PSD	power spectrum density
RMS	root mean square
t	time (s)
T	temperature (°C)
T_R	rotor blade passing period (s)
Tu	turbulence intensity, $Tu = \sqrt{\overline{u'^2}}/\bar{u}$ (%)
u, *v*	velocity (m/s)
u'	random velocity fluctuation (m/s)
$\bar{u}$	mean velocity value (m/s)
U_{eff}	effective velocity (m/s)

Greek symbols

α	flow angle (deg)

Superscripts and subscripts

$\bar{}$	time-averaging operator
1, 2	wire 1, 2
a	air
real	real value
meas	measured value
w	wire

then introduced to retrieve the velocity magnitude, while an angular calibration provides the directional response of the probe. Depending on the number of wires, pitch and/or yaw variations should be performed to obtain the angular range [7].

Using Dual Hot Wire (DHW) probes, we can obtain in-plane velocity components of the flow. The most common configuration is the so-called X-probe (a.k.a. X-array), consisting in a hot wire anemometer with two crossed wires, either in an orthogonal or a non-orthogonal disposition. If the wires are orthogonal to each other, the maximum angular range cannot exceed 90 deg, while higher angle between the wires (i.e. 120 deg) may provide an extended angular range [8,9]. Anyway, whatever the angle selected, if the X-probes are built with the supporting prongs in a perpendicular orientation respect to the measuring plane (Fig. 1), there are certain angular positions where interference effects between the first wire and the prongs of the second wire arise. These effects are superimposed to the self interference of one wire with its own prongs, which is clearly less important than crossed interferences [10].

This effect, which has been already identified and studied by several authors [11,12], is known as "wake interference effect", and implies that the wire affected by the prong wake (i.e. in a region with a notable velocity deficit) is measuring flow velocities significantly lower than those of the real flow. Additionally, the measured turbulence level is also higher than the true value because the shedding vortices from the upstream prong are sensed by the downstream wire [13]. The direct consequence is a reduction in the measuring angular range of the probe and a severe limitation for turbulence measurements. To overcome these problems, the probes can be designed with the supporting prongs placed in a plane parallel to the one of the incident flow. Hence, the wake interference effect vanishes, remaining exclusively the interference effect of the wires with their own prongs, and increasing the angular range accordingly.

For the present investigation, two DHW probes have been built, denoted as Z-type and V-type, with the wire prongs placed in a parallel plane to the flow to avoid interferences. These probes have been compared with a classic 120 deg X-type probe in both steady and unsteady conditions. It is found that both Z-type and V-type calibrations are similar (for probes with identical geometrical characteristics in terms of wires diameter, wires lengths and overall probe size), presenting accurate calibration coefficients. On the other hand, the X-array probe retrieves significant errors up to 10–13% in velocity, 5.5–7 deg in angle and 1.5–2.5 points overestimation in turbulence levels under steady flow. Additionally, the impact of the interference is analyzed also for unsteady conditions in the case of a low-speed axial fan. In this case, though averaged errors are quite similar with respect to steady deviations (in accordance to bibliography [14]), instantaneous deviations can be as high as a 20% in velocity and 16–18 deg in flow angle, especially in those regions with large unsteady gradients (rotor wakes).

2. Probes geometry and calibration setup

Three different probe geometries have been considered for the present investigation. The original design is a classical X-type probe with the supporting prongs perpendicular to the flow plane. This means that the inner wire suffers wake interferences coming from the prongs of the outer wire. The remaining probes, designated as Z-type and V-type probes, are improved versions developed to eliminate interference effects, with the prongs placed in

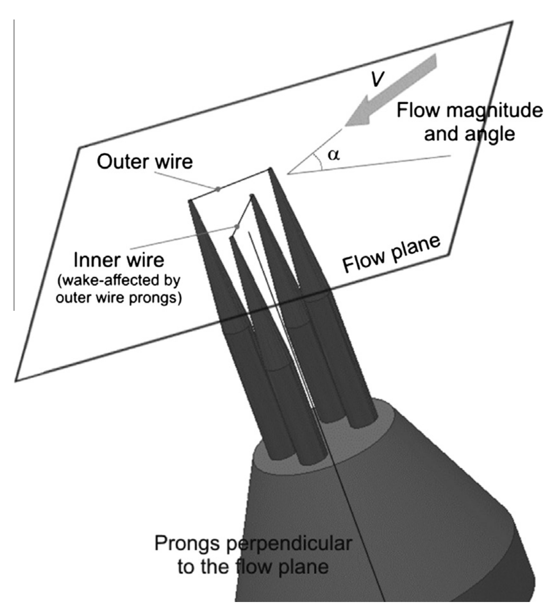

Fig. 1. Typical X-type DHW probe with prong-wire interference.