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Converged statistics for time-resolved measurements in low-speed axial fans using high-frequency response probes

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ABSTRACT

Fast-response probes in multistage turbomachinery are typically used to measure unsteady flows and turbulence in a number of traverse locations throughout the machine (rotor–stator inter-regions, inlet and outlet sections, tip clearance gaps...). When used intensively, they provide complete information of time-resolved flow structures, including wake patterns, wake mixing, wake–wake and rotor-wake interactions or turbulence transport in 2D planes and even 3D pictures if the raw signals are post-processed accurately.

The segregation between deterministic, unsteady features and turbulent scales is essential to understand the unsteady mechanisms responsible for the energy transfer and requires an accurate selection of the sampling frequencies and the total length of the measured traces to assure a valid statistical reduction. Similar considerations must be made if they are filtered in a frequency basis (for example, filtering low-scale turbulence or extracting only BPF components), employing well-designed periodograms or power spectra with minimum scatter and large periods of time integration.

This work presents the effect of number of periods (ensembles), resolution in which the averaged periods are reconstructed and turbulence intensity on the experimental accuracy of ensemble-averaged measurements in low-speed axial fans using fast-response probes. In particular, the statistical analysis is established in terms of convergence (residuals) between time-resolved traces retrieved using different sampling frequencies and number of total samples. The possible effects of three-dimensionality, the measured regions (hub, tip, midspan) or the sensibility to turbulence levels is also explored.

A technique to quantify the convergence of the phase-locked averaging (PLA) processes is applied to a low-speed axial fan, with twin configurations of rotor–stator and stator–rotor arrangements. As a starting point, a concise survey of usual practices employed by other authors in the literature for axial fans and compressors is firstly reviewed, in order to identify fundamental parameters and values typically adopted to guarantee convergence. Finally, typical requirements are given as a function of the variable analyzed, the wake pattern to be described or the global disorder of the flow structures inside axial flow fans.

1. Introduction

In the last two decades, the phase-locked averaging technique has been widely used in combination with hot-wire anemometry and fast-response pressure probes to study the flow inside axial turbomachinery. To segregate between deterministic and non-deterministic scales, it is necessary to pay particular attention to the number of samples adopted per blade passing period, as well as the total number of samples considered for an accurate statistical reduction of the velocity traces.

The number of samples for each blade passing period gives a good idea of the circumferential precision of the measurements. This value is related to both acquiring (sampling frequency) and blade passing frequencies (BPF), and also to the number of rotor blades. An accurate value is essential to obtain a precise description of the gradients associated to the wake shear layers when measuring with stationary probes. Depending on the subject of the study or the phenomena under study, this value may require a higher number (i.e., high-complex structures developed under near-stall conditions) or a lower number of samples (primary flow at design conditions). However, the own intrinsic limitations of the dynamic response of the instrumentation plays here a major role. Effectively, the resolution of the period strongly depends on the dynamic response of the measuring technique, which cannot be exceeded. This cannot be exclusively determined a priori on the only basis of post-processing considerations, and as a consequence, preliminary analysis in the frequency domain is

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Nomenclature

B	number of rotor blades
BPF	blade passing frequency (Hz)
CFD	computational fluid dynamics
D	wake depth (mm)
e	error (%)
f_s	sampling frequency (Hz)
k	current number of discrete samples or "classes"
m	m-th ensemble
M	total number of ensemble-averages (temporal discretization)
n	n-th sample
N	total number of angular phases (spatial discretization)
PLA	phase-locked averaging
ppd	points per degree
PSD	power spectrum density (W/Hz)
Q, Qn	flow rate and nominal flow rate (m^3/s)
R	residual
RMS	root mean square
RPM	revolutions per minute
t	time (s)
T_r	rotor blade passing period (s)
Tu	turbulence Intensity (%)
$\overline{Tu}$	mean turbulence intensity (%)
u	velocity (m/s)
U	maximum velocity (m/s)
$\tilde{u}$	ensemble-averaged velocity (m/s)
u'	random velocity fluctuation (m/s)
$\bar{u}$	mean velocity value (m/s)
W	passage width (mm)
y	transversal coordinate (mm)

Greek symbols

δ	wake width (mm)
δ^*, δ_p^*	displacement thickness (mm)

Superscripts and subscripts

~	ensemble-averaging operator
-	time-averaging operator
m	number of ensemble-average
n	number of angular phase
th	theoretical
max	maximum

mandatory to assure that the probes performance is consistent with the unsteadiness to be measured. Hence, it is necessary to be sure that frequency response of the anemometer is high enough to sample at the required rates.

On the other hand, the total number of samples depends only on the length of the acquiring time. That is, more samples are stored if the acquiring time is increased. Unfortunately, this time cannot be indefinitely extended because the store space or the duration of the tests is limited. Although this is rarely a problem in the case of low-speed turbomachinery applications with blade passing frequencies at least in the order of 1 kHz (where a few hundred of ensembles are recorded in 1 s of acquisition), it could turn to be a limitation in terms of total amount of data recorded in the case of intensive measurements performed in multiple locations (i.e., traverse measuring planes). Furthermore, it can be a major concern in the case of short-duration facilities in which the measurement window is a few tenths of a second, or in the case of slow-rotating machines, like wind turbines. In such applications, the minimum number of samples that must be adopted to provide a converged description of the time-resolved flow structures can be valuable information.

Table 1 shows a concise review of typical parameters employed for data-acquisition techniques used in multistage environments of axial fans and compressors. Concerning the number of samples for each blade passing period, the tangential discretization is shown to be in the order of one point per degree. In particular, most of these studies adopted a number of points ranging from 50 to 100 samples per blade passing period. Maximum values, like Huyer and Snarski [1], employed 167 points corresponding to 0.36 points per degree for a six-bladed diagonal flow fan. Similarly, Kergourlay et al. [2] used 125 points in a single low-speed axial fan with a 6-blade rotor resulting in 2.08 points per degree. However, it is not unusual to consider even a lower number of samples: Read and Elder [3] employed 43 samples (8.95 points per degree); Mailach and Vogeler [4], 49 samples (8.57); Velarde-Suárez el al. [5], 32 samples (0.71) and Prato et al. [6], 20 samples (4.11); or more recently, Lepicovsky [7], introducing 16 samples to obtain 625 points for a complete revolution (1.73).

Complementarily, regarding the total number of samples to be used in the ensemble-averaging process, typical values range from 100 to 300 in the literature [8]. This disparity depends on the levels of turbulence, secondary flows and the global disturbance of the flow field. Note that maximum values reported in Table 1, like those by Henderson et al. [9] with 3072 ensembles, or Senkter and Reiss [10] with 3800, are related to turbulence measurements. Conversely, several authors have introduced a limited number of samples, in accordance to Brunn guidelines, without severe lack of fidelity. For example, Lakshminarayana [11,12] employed 80 ensembles; Camp and Shin [13] adopted 45 samples for a rotor periodicity; Huyer and Snarski stored 49 blade passages and Lepicovsky sampled a full-annulus with 65 samples in a 4-stage low-speed axial compressor.

Recently, the increasing use of experimental investigations based on optical measurement techniques has renewed the interest for converged statistics in unsteady flows. In particular, early contributions can be found in Uzol and Camci [14], Perrin et al. [15] or Ullum et al. [16] in the case of canonical flows like cylinder wakes or squared fences. In the case of pitching or rotating flows, Wernert and Favier [17] and Cavazzini et al. [18] had presented valuable procedures for validating turbulent unsteady flows in turbomachinery environments. In a similar fashion, taking advantage of the mimic between fully unsteady codes and time-resolved measurements, Clark and Glover [19] had also presented a quantitative method based on fuzzy logic to assess the level of convergence of a periodic-unsteady simulation for axial turbines. Following the same basic concepts, this investigation presents a rational technique to quantify the convergence of time-resolved measurements in multistage environments of axial flow fans and compressors using intrusive probes. Basic parameters in the data acquisition of the phase-locked averaging technique, related to the number of ensembles and the number of samples per blade passing period, are used to define indicators of convergence in terms of normalized residuals and discretization error. The methodology is afterwards applied within an experimental database for time-resolved measurements of unsteady flow and turbulence in a single-stage, low-speed axial fan with rotor–stator and stator–rotor configurations. Different convergence criteria are defined as a function of the variable of interest (velocity or turbulence intensity) and the influence of probe locations respect to boundary