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On the structure of turbulence in a low-speed axial fan with inlet guide vanes

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Abstract

This paper analyzes the structure of turbulence in a single stage, low-speed axial fan with inlet guide vanes. Turbulence intensity values and integral length scales have been obtained using hot-wire anemometry for three different operating points and two different axial gaps between the stator and the rotor. These measurements were carried out in two transversal sectors, one between the rows and the other rotor downstream, covering the whole span of the stage for a complete stator pitch. Since total unsteadiness is composed of the contribution of both periodic and random unsteadiness, a processing data method was developed to filter deterministic unsteadiness in the raw velocity traces. Velocity signals were transformed into the frequency domain by removing all the contributions coming from the rotational frequency, the blade passing frequency and its harmonics. Consequently, coherent flow structures were decoupled and thus background levels of turbulence – RMS values of random fluctuations – were determined across the stage. Additionally, this unsteady segregation revealed further information about the transport of the turbulent structures in the unsteady, deterministic flow patterns. Therefore, anisotropic turbulence, generated at the shear layers of the wakes, could be identified as the major mechanism of turbulence generation, rather than free-stream, nearly isotropic turbulence of wake-unaffected regions. Finally, spectra and autocorrelation analysis of random fluctuations were also used to estimate integral length scales – larger eddy sizes – of turbulence, providing insight on the complete picture of the turbulent flow.

Keywords: Turbulence; Low-speed axial fan; Stator–rotor; Unsteadiness; Integral length scale; Hot-wire anemometry

1. Introduction

Total unsteadiness in a multistage environment is a key parameter in the performance of any axial turbomachine. In case of axial compressors, much effort has been focused on understanding the boundary layer transition from laminar to turbulent on blade surfaces [1]. The vortical disturbances that are created by wakes convected from blade rows further upstream may lead to boundary layer transition. This periodic impinging of incoming wakes onto the blades is a well-known ''wake-induced'' transition. In addition, a high level of turbulence, rather than those periodic disturbances on the blade surfaces, can also be responsible for the turbulent shear layer to be set on [2]. Therefore, in order to achieve a good description for both mechanisms, it is necessary to segregate its relative influence on the development of the unsteady boundary layers on the blades.

The flow field inside a turbomachine is characterized by its complex unsteadiness. When this unsteadiness is considered as a whole unique fluctuation, this total variation leads to the establishment of the classical Reynolds stresses into the mean flow. However, the total unsteadiness can also be considered as the contribution of both periodic and random components. The periodic fluctuation, usually known as ''unsteadiness'', consists of all nonuniformities

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Nomenclature

ACF	autocorrelation function
B	number of rotor blades
BPF	blade passing frequency [s^{-1}]
b.c.	blade chord
E	spectrum of turbulent energy [m^2/s^2]
FFT	fast Fourier transform
k	frequency or eddies wavenumber [s^{-1}]
L	integral length scale [m]
LE	leading edge
M	total number of stored rotor blades periods [–]
N	total number of samples per blade passing period [–]
P	pressure [Pa]
PS	pressure side
Q, Qn	flow rate and nominal flow rate [m^3/s]
q	turbulent kinetic energy [m^2/s^2]
$\vec{r}$	spatial position in cylindrical coordinates
r	radial coordinate [m]
Re	reference Reynolds number [–]
SS	suction side
t	time [s]
T_r	rotor blade passing period
Tu	turbulence intensity [%]
TE	trailing edge
TKE	turbulent kinetic energy
u	instantaneous velocity [m/s]
u'	random velocity fluctuation [m/s]
u_L	characteristic velocity scale of largest eddies [m/s]
$\widetilde{U}$	deterministic velocity component [m/s]
$\underline{U}$	deterministic velocity fluctuation [m/s]
$\overline{U}$	mean velocity [m/s]
z	axial coordinate [m]

Greek letters

α	Kolmogorov's constant [–]
ε	energy dissipation rate [m^2/s^3]
ϕ	flow coefficient [–]
ϕ	rotor blade phase [°]
η	overall efficiency [–]
θ	angular coordinate [rad]
ϑ	rotor phase [°]
ρ	density [kg/m^3]
τ	time lag [s]
ψ	pressure coefficient [–]
Ω	rotational speed [rad/s]

Superscripts and subscripts

$\langle\ \rangle$	FFT filtering
$\sim$	ensemble-averaging
$-$	time-averaging
$_t$	tip
$_{1,2}$	inlet and outlet

and unsteadiness clocked with the shaft speed and the blade passing frequency (BPF). It can be addressed by means of an average-passage technique, in which the Navier–Stokes equations are transformed into a set of steady, full 3-D viscous equations, separately for each row [3]. As a result, the effects of phase-dependent unsteadiness are accounted for through additional terms in the equations, known as "deterministic stresses". Its solution provides the average-passage flow which is a time-averaged flow field, periodic over the pitch of the blade row of interest. On the other hand, the closure problem is completed with those remaining stresses due to the random and chaotic component. Actually, the Reynolds stresses appear in the final equations taking into account just purely stochastic fluctuations, referred to as "turbulence".

The segregation of "unsteadiness" from "turbulence" in multistage turbomachinery can be easily observed in any velocity trace, rather than in the complex, non-linear set of Navier–Stokes equations. Previous works have dealt with this idea, using velocity traces obtained through hot-wire anemometry [4], or even pressure signals from rapid response transducers [5]. The simplest method to remove periodic fluctuations consists in ensemble-averaging the velocity trace and then subtracting this processed signal from the original data [1,3,5]. Unfortunately, though this is an exact definition which gives useful results, it is just filtering all the unsteadiness related to the BPF. Other "large-scale" unsteadiness with periodic features like vortex shedding, unsteadiness of separation points, misalignment of the blades or fluttering of separated flows is not removed by using this method. In practice, this is because there is no exact frontier separating the periodic unsteadiness of large-scale fluctuations from the large-scale eddies of random turbulence. Consequently, it is also necessary to include some other filtering procedure to remove clearly the effects of all the periodic unsteadiness from the raw data. Some authors have defined a cut-off frequency to extract just "small-scale" fluctuations ([6], with single hot-wire anemometry, and [7,8], with dual hot-wire probes), neglecting much of the turbulent energy of large-scale eddies. In order to avoid this inconvenience, a method with a frequency domain basis is used to identify peaks (at the rotational frequency, at the BPF and all the relevant harmonics) in the Fourier transform of the signal. These peaks, representing periodic events, are digitally filtered out by setting its amplitudes to zero. The truncated power spectrum is then transformed back into the time domain to give the turbulent signal [4,9].

This paper analyzes the structure of turbulent data, obtained using hot-wire anemometry, in a single-stage,