International Journal of Heat and Fluid Flow 70 (2018) 28–40

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Identification and quantification of losses in a LPT cascade by POD applied to LES data

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ARTICLE INFO

Keywords:
LES
Loss production rate
POD

ABSTRACT

A POD based procedure has been developed to identify and account for the different contributions to the entropy production rate caused by the unsteady aerodynamics of a low-pressure (LP) turbine blade. LES data of the extensively studied T106A cascade have been used to clearly highlight the capability of POD to identify deterministic incoming wake related modes, stochastic fine-scale structures embedded within the bulk of the wake carried during migration, and coherent structures originating in the boundary layer as a consequence of the wake-boundary layer interaction process. The POD modes computed by a kinematic kernel generate a full and complete basis, where both the velocity and enthalpy fields have been projected through an extended POD procedure to determine the relative coefficients. This allows to separately compute orthogonal sets of contributions to turbulent kinetic energy production, enthalpy-velocity correlation and turbulent dissipation of resolved structures, thus clearly identifying the dominating modes (i.e. phenomena) responsible for the overall entropy production rate. Moreover, low-order truncation of these different contributions have been grouped into three different parts: those arising from the deterministic incoming wake, those due to the turbulence carried by the wakes and its interaction with the boundary layer, and those related to boundary layer events. The spatial integration of these low-order truncations restricted to the time-mean boundary layer, wake mixing and the potential flow regions of the blade passage allows gathering further information on the unsteady loss generation mechanisms, and where they mainly act. Particularly, results show that the procedure is able to decompose losses into the dominant contributions, thus providing a new tool for a rapid and clear identification of the different sources of losses in complex unsteady flow fields.

1. Introduction

The development of the flow field in turbine and compressor rows of multistage turbomachines is a complex three dimensional and unsteady phenomenon. The wakes shed from upstream rotating blades induce periodic (deterministic) and stochastic oscillations at the entrance of the downstream rows, while the potential field induces additional time-varying flow distortion, making the propagation of turbulent quantities generated by upstream wakes strongly inhomogeneous and spatially and temporally dependent. During migration the upstream wakes diffuse in the blade row gaps and in the downstream passage, they give rise to turbulent and viscous losses due to superposition of different phenomena. The identification and quantification of the various contributions to the overall loss remain a difficult task, as also pointed out by van de Wall et al. (2000) and Praisner et al. (2006).

In the last years detailed high fidelity computations and accurate experiments (see Wu and Durbin, 2001; Michelassi et al., 2003; Stieger and Hodson, 2005; Hodson and Howell, 2005 for example) have given deep insight into the unsteady wake migration process. Approaching the downstream cascade, the planar-like (2-D like) structure of the incoming wake undergoes strong bowing, tilting, dilatation and stretching processes, and it finally becomes fragmented into segments as a consequence of the relative motion between the stator and rotor rows (Binder et al., 1985, 1989).

The Direct Numerical Simulation (DNS) of Wu and Durbin (2001) described in detail the stretching, dilatation and compression processes of wake filaments evolving in a LP turbine passage through a strain rate tensor principal axes analysis. They clearly showed that the wake filament developing close to the pressure side is almost aligned with the stretching direction, while on the other hand the wake centerline at the

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https://doi.org/10.1016/j.ijheatfluidflow.2018.01.011
Received 12 September 2017; Received in revised form 21 November 2017; Accepted 24 January 2018

bow apex is mainly aligned with the compression direction. Moreover, as also shown in Michelassi et al. (2003), the largest eigenvalues are localized on the suction side of the channel, where the strongest reorientation of the jet-like structure takes place. The eigenvalue and eigenvector decomposition of the shear and strain tensors reported in Michelassi and Wissink (2015) shows that the largest (compression related) strain eigenvalues dominate the turbulent kinetic energy production due to wake migration, with a maximum in the flow region where stress and strain principal axes are almost aligned. These observations agree well with Rogers (2002) who discusses the effects of different strain magnitudes and orientations on the turbulence produced in a planar wake. He clearly highlights that the condition with the wake axis aligned with the eigenvector of the velocity gradient tensor associated with compression represents the most influencing for turbulence production, similar to what happens in the bow apex of the wake migrating through the LPT passage (see also Stieger and Hodson, 2005).

The incoming wakes are also responsible for transporting the finer structures embedded in the bulk of the wake into the suction side boundary layer, further contributing to the excitation of the boundary layer and the consequent excitation of the transition process (see Wu et al., 1999; Lengani et al., 2017b). The isocontour surfaces of the λ_2 criterion and instantaneous flow vorticity reported in Zaki et al. (2009) and Sarkar and Voke (2006) give a clear view of the finer structures carried by the wakes. These structures are responsible for the generation of a dense population of streaky structures in the footprint of the region perturbed by wakes, as observed both numerically or experimentally (Wu et al., 1999; Nagabhushana Rao et al., 2013; Coull and Hodson, 2011; Lengani et al., 2017b). Moreover, for highly loaded turbine blades the boundary layer growing between successive wakes may undergo an intermittent separation (depending on the loading and diffusion level (Satta et al., 2014), that evidently imposes an inviscid-like instability (Sarkar and Voke, 2006; Simoni et al., 2013). In this case large scale coherent structures are shed as a consequence of the separated shear layer rollup during wake-boundary layer interaction, with dynamics similar to those characterizing the separated flow transition mechanisms observed in cases without incoming wakes (Alam and Sandham, 2000; Jones et al., 2008).

Overall, the unsteady aerodynamics of a LP passage is the result of the superposition of different phenomena acting in the different parts of the passage with different temporal and spatial scales. Each of them differently affects the loss (i.e. entropy) production mechanisms in the entire downstream passage (i.e. inside and outside the blade boundary layers) that up to now have usually been evaluated as a whole. The possibility to split and detect the different sources of losses represents one of the main engineering goals for further increasing the efficiency of modern new generation LPT blades. Optimization procedures aimed at selectively reducing losses could be easily and efficiently implemented observing the effects of design parameters on the different loss sources, instead of the effect on the overall loss. The entropy rate of change split allows determining the loss contribution due to wake diffusion in the downstream passage and differentiate it from those being generated as a consequence of the wake boundary layer interaction, due to both large and finer scales carried during wake migration. Due to the aforementioned (turbulent) stress-strain interaction mechanisms, wake migration in the potential flow region of the downstream passage gives rise to deterministic stress production, following the terminology reported in van de Wall et al. (2000), that can contribute a significant portion of energy degradation. The identification of this additional loss source will also be important for correcting RANS predictions of multistage machines, since in this numerical method the wake shear-stress interaction process producing losses is not resolved. Michelassi et al. (2015, 2016) used DNS and LES to show that entropy generation due to wake migration represents a non-negligible contribution to overall losses. The different sources of losses were quantified by a control volume method (following Denton, 1993) and not directly quantified from the dataset due to the difficulty in separating boundary layer from wake migration related events. Neither phase-averaged (Hussain and Reynolds, 1970) nor generalized phase-averaged methods (Bourgeois et al., 2013) can achieve such a separation, since all phenomena not directly locked with the passing wake forcing are smeared out by the averaging operation and cannot be directly resolved.

Among other data analysis approaches, Proper Orthogonal Decomposition (POD), that was introduced by Lumley (1967), is now a mature approach that has been often used to identify the different dynamics driving complex turbulent flows (e.g. Liu et al., 2001; van Oudheusden et al., 2005; Perrin et al., 2007; Kurelek et al., 2016). However, it has rarely been applied to the analysis of turbine blades perturbed by unsteady wakes. In the work of Sarkar (2008), POD was applied to LES data describing the unsteady flow field of the T106 turbine cascade with $Re = 160{,}000$, $f^+ = 0.68$. Here, the author paid attention to the dynamics through which the large scale deterministic structures attached to the leading and trailing boundaries of the incoming wakes interact with the separated shear layer growing between wakes. In Lengani et al. (2017b), POD was applied to experimental data in order to discuss the flow physics of the transition induced by the periodic passing wakes. It has been shown that POD can be used to identify the large scale structures of the passing wake, as well as observing the effect of the turbulence carried by the wake and its effects on the boundary layer.

In the present paper, POD has been applied to high fidelity Large Eddy Simulation (LES) data of the T106 LPT cascade with unsteady incoming wakes generated by a set of moving bars to mimic a stator-rotor interaction. The aim is to determine if the POD applied to LES data can identify and discern the different loss mechanisms in the presence of unsteady incoming wakes. This is accomplished by a new POD based procedure, that follows the idea reported in Lengani et al. (2017a), that allows the identification and characterization of the different dynamics that contribute to loss generation, analyzing their contribution to the entropy rate of change. The bi-orthonormality condition of the POD modes and related temporal coefficients is considered to compute the contribution of the individual mode dynamics to the Reynolds stresses and hence to the rate of change of total pressure. An extended POD projection (Borée, 2003) on the kinematic basis also allows computing the rate of change of total enthalpy, thus the possibility to account for single mode contribution to the entropy rate of change. Losses generated in the boundary layer region as a consequence of streaky structures and wake-boundary layer interaction mechanisms are clearly captured and separated from losses due to wake migration and distortion in the potential flow region due to both large and finer scales.

The paper is organized as follows: in Section 2 the numerical method, the geometrical configuration and the flow parameters are described in detail; in Section 3 the basic equations and the decomposition procedure for the moment statistics are presented; in Section 4.1 the LES results are presented; in Section 4.2 results from POD are described in order to clearly identify the different dynamics acting in the different regions of the LP turbine passage; once recognized, in Section 4.3 a limited number of POD modes has been used for the identification of the contributions to the entropy rate of change due to wake migration and boundary layer related processes. Finally, in Section 4.4 spatial integration in the different parts of the channel allows a quantitative analysis of the different sources causing an entropy change in the different regions.

2. Large eddy simulations

The low-pressure turbine data-set analyzed in this paper was obtained by performing large eddy simulations (LES) using the in-house compressible multi-block structured Navier–Stokes solver HiPSTAR. A comprehensive description of the algorithm and validation for turbomachinery applications is given in Sandberg et al. (2015) and here only