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Design trade-off study between efficiency and rotor forcing attenuation in a transonic turbine stage

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ABSTRACT

A multi-objective optimisation procedure was applied to the 3D design of a transonic turbine vane row, considering efficiency and stator outlet pressure distortion, which is directly related to the forcing induced in the rotor. The characteristic features that define different individuals along the Pareto Front were described, analysing the differences between high efficiency airfoils and low interaction. Pressure distortion was assessed by means of a model that requires only of the computation the steady flow field in the domain of the stator. The reduction of aerodynamic rotor forcing was validated via unsteady multistage aerodynamic computations carried out with NUMECA *FINE*^{TM}/*Turbo*. A well known loss prediction method was used to perform total loss decomposition to quantify the influence on efficiency of reducing rotor forcing. Results show that when striving for efficiency, the rotor was affected by few, but intense shocks. On the other hand, when the objective was the minimisation of distortion, multiple shocks appeared.

1. Introduction

The objective of the present paper was the design and physical description of a high pressure turbine (HPT) vane operating in the transonic regime, which was aimed at reducing the interaction between rotor and stator, while preserving high efficiency. The main agent of turbine row interaction is the shock system that develops at the trailing edge of an airfoil. In spite of the common belief that reducing shock intensity will mitigate both rotor forcing and losses, this paper illustrates the physics governing both contradictory effects.

The relevance of the study is based on the increasing importance of row interaction effects in aero-engine systems. Current design trends focus on weight and size reduction in order to improve the efficiency of the whole aircraft, which can lead to reduced distance between components and a higher loading per stage. This implies increased flow perturbation per row and less space for its damping, which according to Li and He [1,2] can lead to forcing increments of first order importance. In order to tackle this problem, the inherent unsteadiness of the flow field should be taken into consideration in every stage of the design process, as proposed by Hodson et al. [3].

Several sources of flow unsteadiness have been identified, with comprehensive accounts found in Paniagua [4] and Payne [5]. These can be classified as pressure waves propagation or *potential effects*, viscous effects where convection of low momentum flow causes local pressure distortions, and shock waves. Supersonic flow is characterised by the limited

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Nomenclature

α	tangential flow angle
$\bar{u}$	velocity field
$\dot{m}$	mass flow
Ψ	spectral decomposition of ψ
ψ	forcing function according to the steady single row model
τ	stagnation pressure loss over inlet stagnation pressure
θ	angular coordinate for the pitch-wise direction of a turbine
a	sound speed
M_{is}	isentropic Mach number
p_0	stagnation pressure
p_s	static pressure
r	radial coordinate
r_{20}	radial coordinate at 20% span
r_{80}	radial coordinate at 80% span
S	shock function
T_0	stagnation temperature
w	coordinate of distance following the geometry of the leading edge of the rotor
Y	stagnation pressure loss over outlet dynamic head
EPR	events per revolution
HPT	high pressure turbine
LE	leading edge
LRS	left running shock
RRS	right running shock
Opt L	loss optimised geometry
Opt U	unsteadiness optimised geometry
PS	pressure side
SS	suction side
TE	trailing edge
U	resulting unsteadiness after integrating the forcing function over the risk region

attenuation of propagated perturbations. Therefore, the interaction between blade rows in transonic turbine stages will be of higher importance than in subsonic stages. Barter et al. [6] investigated numerically the propagation of shocks across a stage, both considering and neglecting wave reflections between rows. Results showed that the stator's trailing edge shocks, when reflected from the rotor, do have an important impact on the vane's loading, but successive reflections back to the rotor pose an influence of second order. Barter argued that only the unsteady frequency component corresponding to the first harmonic of the excitation is relevant. However, Kammerer and Abhari [7] demonstrated experimentally the importance of higher order harmonics.

Work on this topic has been carried out in the past at the von Karman Institute. Vascellari et al. [8] identified numerically the particularities of 2D profile velocity distributions that give rise to the trailing edge shock system. Joly et al. [9] set as objective the minimisation of vane outlet inhomogeneities using multi-objective optimisation techniques, revealing that efficiency and unsteady forcing are conflicting objectives. Multiple shock reflections may result in a reduced forcing at the expense of higher loss. Joly et al. described a geometry which achieves the same efficiency as a baseline one, while also minimising the outlet pressure distortion. The pressure side was heavily modified, generating a narrower channel with a divergent passage. The sonic line shifted upstream, resulting in a larger acceleration at the pressure side, coupled with a straight suction side rear part. This resulted in a reduction of the pressure difference at the trailing edge.

Previous research was focused in the study of 2D profiles, an approach that is not applicable to low aspect ratio turbomachinery flows, which are highly three-dimensional. Wang [10] concluded that the design of a 3D structure cannot be decoupled into 2D subproblems.

The novelty of the current research is the identification of various 3D flow field features present in an HPT vane that leads to low aerodynamic forcing in the downstream rotor, compared to a high efficiency one. The perspectives of improving both aspects are also explored.

2. Optimisation methodology

In order to reduce stator induced forcing in a turbine's rotor by a traditional design method, several trial and error iterations would be necessary. By designing a geometry using computational design and optimisation techniques, access is directly granted to a well performing geometry which can be investigated at length. Two objectives were set for the optimisation, efficiency and a measure of pressure distortion which will be described in detail in Section 4.1.