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Vane Clocking in a Three-Stage Compressor: Frequency Domain Data Analysis

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Blade row interactions affect compressor performance and durability. As design systems expand to account for these interactions, a better understanding of the underlying physics is necessary. In this paper, results from a vane clocking experiment in a three-stage compressor are discussed. Efforts are focused on the second stage, specifically the change in stator 2 wake profiles with respect to the placement of the stator 1 wake. The two clocking conditions presented position the wake from stator 1 at the leading edge of stator 2 and in the middle of the stator 2 passage. The time-accurate data are Fourier decomposed to determine the relative magnitudes of the frequencies in the spectrum. With data acquired at 50 circumferential locations spanning one vane passage for each clocking configuration, an enormous amount of data is collected, and a useful method for synthesizing this information is presented. Results show that, by placing the stator 1 wake at the leading edge of stator 2, the stator 2 boundary-layer response to the large incidence variations associated with the rotor 2 wakes is dampened, resulting in a thinner and more shallow stator 2 wake.

Nomenclature

CL_{LE} = clocking configuration that positions stator 1 wake at leading edge of stator 2
CL_{MP} = clocking configuration that positions stator 1 wake in the middle of the stator 2 passage
f = frequency
m_c = corrected mass flow rate
P_o = total pressure
R = rotor
S = stator
U = wheel speed
V = flow velocity in the absolute reference frame
α = absolute flow angle
η = adiabatic efficiency

I. Introduction

AS INDIVIDUAL blade rows are driven to higher loadings and moved in closer proximity to one another, blade row interaction phenomena, both potential and vortical effects, are magnified and have become the focus of several research investigations [1–4]. Potential disturbances from both the upstream and the downstream blade rows decay exponentially and thus typically only affect adjacent blade rows. As a rotor blade passes in front of the leading edge of a downstream vane, the higher static pressure causes a slight increase in the back pressure of the rotor and thus causes a change in the work done. The viscous wakes shed from upstream blade rows convect with the mean flow and can persist for several blade rows downstream. Wakes created in one reference frame (rotating or stationary) are manifested as changes in flow angle in the other. Thus, when an airfoil chops the wake shed from the upstream blade row, it experiences a periodically varying incidence leading to a change in circulation, apparent in the structures shed in the airfoil's wake. Interactions between the wakes of similar airfoils (vane–vane wake interactions) depend on the relative circumferential position of the vanes and the vane count in each row.

Vane clocking is the circumferential indexing of adjacent vane rows with a common vane count. Proper circumferential positioning of the vanes allows for a reduction in the sound pressure level of discrete frequency noise at the compressor inlet by 10–15 dB [5,6]. Vane clocking also affects the unsteady blade forces on the downstream vane [7,8]. In turbine stages, variations on the order of 0.5–1.0 points in adiabatic efficiency are associated with vane clocking. The turbine stage maximum efficiency condition occurs when the wake from the upstream vane row is positioned such that it impinges on the leading edge of the downstream vane. The minimum efficiency condition, typically out of phase with the optimum configuration by half a passage, occurs when the wake convects through the middle of the downstream vane passage [9–13].

The results from experimental investigations on the performance benefits of compressor vane clocking have not been as conclusive. Barankiewicz and Hathaway [14] concluded that the impact of vane clocking on the change in overall efficiency was small and within the band of uncertainty associated with manufacturing, assembly, and passage-to-passage variations in a three-stage low-speed compressor. In some of the first published vane clocking experiments in a high-speed stage-and-a-half test compressor, Saren et al. [15] measured changes in efficiency on the order of 1 point. However, spanwise measurements showed that local variations were much larger than the integrated effects, with end wall efficiencies varying by as much as 7–8 points.

In this paper, vane clocking is used as a method to perturb the flowfield to study vane–vane interactions. Part of the motivation for this study is that steady multistage calculations that model blade row unsteady interactions by techniques such as mixing planes or deterministic stresses are limited by the fidelity of the blade row interaction models. Improvements in such models can be realized by detailed flow measurements in multistage machines. Experimental investigations on multistage compressors (more than a stage and a half) are quite limited in the open literature. Some past work on multistage compressors includes that by Zierke and Okiishi [16], who used total pressure measurements to map out both rotor–stator and stator–stator wake interactions in a three-stage compressor. Also, Prato et al. [17] and Suryavamshi et al. [18] used unsteady velocity

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