渦輪機葉片尾流控制之實驗與計算探討
Study of Wake Control for Turbomachinery Blades (3/3)

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一、摘要

計劃三年進行總目的為使用最有效方式降低上游葉片(轉子)尾流對下游葉片(定子)非定常受力之影響。主要理念為在轉子葉片上進行控制，控制氣体由尾緣(trailing edge)射出。由尾緣射出主要目的為降低尾流之動量缺(momentum defect)。

本報告為第三年之成果。主要成果為完成在轉子/定子軸流壓縮机組合之轉子尾流量測及控制，並詳細評估受控制下之轉子尾流對下游定子非定常受力之影響。結果顯出在近尾流區域(15%弦長軸向間距時)，受控制下之尾流與葉片平均負載有密切之關係。在稍遠下游處(約 30%弦長)，此影響比較不明顯。原因在於尾流已有稍長時間被控制氣流所混合。實驗結果證實陣風參數(gust factor)與尾流動量缺參數(wake momentum defect factor)之基本關係為線性。所有實驗結果顯出計劃中使用之尾流控制方法確實有效降低尾流對定子葉片之非定常受力。

關鍵詞: 軸流壓縮機、流場控制、葉片尾緣噴氣。

Abstract

The purpose of the three-year project is to perform a series of experimental studies on flow control in a low-speed, large-scale, axial flow compressor. Specifically, air will be ejected from the rotor blade trailing edge in an attempt to interact with the stator downstream.

This third-year report presents detail experimental results for the rotor/stator axial compressor configuration with rotor trailing edge blowing under various circumstances, e.g. axial gaps, time-mean blade loading, and blowing parameters. Results show that near wake (15% chord) velocity defect is dependent on the time-mean blade loading; blowing is more effective for near design loading than at high loading in improving the velocity defect. Further downstream (30% chord), this effect diminished since the wake has more time to mix with the controlled flow. The gust factor shows an essentially linear relationship with the wake momentum defect factor. All results from this work reveal that the ejection from trailing edge is a viable method of flow control.

Keywords: axial compressor, flow control, trailing edge flow ejection.

二、緣由與目的

Wakes from blades are a fact of life. As a natural consequence of boundary layers from blade surfaces a wake makes few friends. It robs energy from the outer flow for its own gain, lowering the efficiency of turbomachines. Noise, a result of wake/blade interaction, can propagate to cause nuisance if not properly designed for. Blade vibration, due to forced response of the passing wake, may lead to high cycle fatigue and eventual disastrous blade failure.

This work focuses on wake control for the purpose of reducing the forced response on downstream blade rows in an axial flow compressor. Manwaring and Wisler[1] assessed various state-of-the-art computational tools to predict gust response in compressors and turbines, which clearly showed the importance of the wake in light of issues related to forced response. An earlier work, Hsu and Wo[2] (based on the gust decomposition methodology of Wo et al.[3]), demonstrated that for a rotor/stator/rotor configuration, "clocking" of the rotor rows can substantially offset the stator forced response due to the upstream rotor wake by the influence of the downstream rotor row. For one case tested, a 60% unsteady force reduced was achieved. Although this method of clocking poses no restriction on the rotor/stator count ratio the rotor counts for both rows need to be the same for maximum reduction of forced response. The present study deals directly with the wake, and its consequences, by blowing from the rotor trailing edge (see Fig. 1) using a large scale rotating axial compressor rig. Knowledge of the consequence of a particular wake profile on response of the downstream blade is deemed beneficial from a design point of view even though this method of flow control may or may not be directly utilized.

三、研究方法

A three-step approach is adopted. First, to characterize the rotor wake three-dimensional ensemble-averaged velocities with and without blowing is measured via a slanted hot-wire located at three downstream locations and two time-mean loadings in a compressor rig (Fig. 2). Second, with the wake data the transverse gust, $v+$, acting on the downstream stator is calculated. This provides a qualitative indication of the effect of flow control on the stator response since, the axial spacing in this work being 30% chord, the contribution from the rotor potential field towards the stator response is much less than the rotor vortical field (Hsu and Wo[2]). Third (third year effort), the effect of energized wake on stator unsteady response is quantified via unsteady pressure data on blade surfaces.

To quantify the gust in the rotor wake, define a *gust factor*, G, to characterize the overall level of gust that the downstream stator experiences over an unsteady cycle T, i.e.,

$$G \equiv \frac{\int_0^T v^+ dt}{\int_0^T v_0^+ dt}, \qquad (1)$$

where the subscript 0 represents the no blowing case. Hence, the gust factor G is unity (maximum gust) without flow control and zero (minimum gust) when control is applied so that v^- vanishes over a period.

To quantify the degree that the blowing flow energizes the wake it is intuitive to define a *wake momentum defect factor* as

$$K_m \equiv \frac{\int \rho \left(W^2 - W_0^2\right) dy}{\int \rho \left(W_p^2 - W_0^2\right) dy}, \qquad (2)$$

where W stands for the rotor relative velocity and the subscripts 0 and p represent the no blowing flow and the wake outer flow, respectively. Physically, K_m equals *zero* for the no blowing case and *unity* when the energized wake acquires the same momentum as the 'wakeless' flow – an uniform flow with the same velocity as the wake outer flow.

四、結果與討論

Results of hot-wire measurement on wake profile has already been reported in the report last year. Thus, this report will focus on unsteady pressure and force data on the downstream stator blade.

With the upstream rotor wake well quantified, its effect on the downstream stator row can now be accessed. Figure 3 presents the chordwise variation of ensemble averaged unsteady pressure signature along the stator *suction* surface for all blowing flow rates at near-design loading. (The unsteady pressure amplitude on the *pressure* surface is essentially zero). The ordinate, normalized unsteady pressure, is defined as

$$\tilde{p}/0.5\rho V_b^2 ,$$

where $\tilde{p}$ is the local unsteady pressure (instantaneous pressure minus the time-mean) and V_b is the blade velocity. Data are presented for three time intervals within an unsteady cycle – normalized time t/T = 0.0, 0.4 and 0.8. The results at other times add little physical significance to that shown.

Figure 3 suggests that for all blowing flows the largest unsteadiness in pressure occurs at the forward portion of the blade chord, with the rest of the blade having a local normalized pressure fluctuation of only a few percent. The unsteady pressure fluctuation near the leading edge naturally will dominate the unsteady forced response. The large pressure excursion is also demonstrated in Hsu and Wo[7], who went one step further and showed that the maximum departure from the mean pressure occurs at the time when the upstream wake meets the stator suction surface near the leading edge.

Valkov and Tan[4] provide an excellent physical insight for this behavior, thanks to their spectral code which is able to capture fine flow features. Their Navier-Stokes results of upstream wake impinging upon the stator cascade show that as the wake interacts with the blade boundary layer 'B vortices' are being ejected from the boundary layer into the outer flow a few boundary layer thickness from the blade surface. As these 'B vortices' are convected downstream they induce large pressure fluctuation on the surface. The present data show that this effect is important near the leading edge region and decays rapidly downstream. However, hot-wire measurement near the stator leading edge is not available to definitively link their calculated result with data.

Figure 4 presents the excursion of unsteady force, integrated from the data of Fig. 3, on the stator for all cases of blowing mass flow considered at near-design loading. The ordinates for Figs. 4a, 4b and 4c represent, respectively, non-dimensional unsteady force *tangent* to the blade chord, $\tilde{F}_t/0.5\rho C V_b^2$; the non-dimensional unsteady force *normal* to the blade chord, $\tilde{F}_n/0.5\rho C V_b^2$; and the non-dimensional unsteady *moment* about the mid-chord, $\tilde{M}/0.5\rho C^2 V_b^2$. These three unsteady quantities, being obtained from integrating the unsteady pressure data (instantaneous pressure minus time mean), thus include all harmonic components. A glance at the figures reveals that the force normal to the chord, Fig. 4b, exhibits largest unsteady amplitude (note the expanded scale for Figs. 4a and 4c), with the amplitude of tangential force and moment less than 2%. This confirms that the transverse gust, v', is more important than the streamwise gust, u'. Intuitively, the transverse gust is more important than the streamwise gust since it is the transverse gust, which in essence acts in the direction normal to the blade chord, which contribute most to $\widetilde{F}_n$. This will still be the case even if u' and v' are equal in magnitude. The maximum amplitude in Fig. 4b with uncontrolled wake (K_m= 0) is about 6%, which is the largest for all cases examined, with the magnitude decreasing with increasing blowing flow. Data at high loading also exhibit the same qualitative trend.

To interrogate the data further, one needs to better quantify the reduction of unsteady loading as a result of flow control. Figure 5 shows a typical excursion of unsteady loading where the peak-to-peak amplitude without blowing (symbol A) is subtracted from the blowing case (symbol B), and presented as a percentage change reference to the no blowing case, defined as the *force reduction factor (B-A)/A*. Figure 6 presents this force reduction factor over the range of wake momentum defect factor, K_m, with control. An essentially linear relationship between the two factors for all cases tested suggests that trailing edge blowing technique is effective in decreasing unsteady loading due to gust over a broad range of wake profiles and time-mean blade loading. At the largest value of K_m tested reduction in the unsteady force is still achieved. (However, it is reasonable to believe that excessive blowing would become a *source* of gust rather than reducing it.) This methodology seems to be insensitive to the manner in which injection occurs since, as mentioned, the blowing air trajectory is quite biased towards the pressure surface. It seems reasonable that the rate of mixing, however, would depend on details of the flow control geometry. In other words, modification of blowing nozzle design should affect the development of wake profile downstream. Nevertheless, the force reduction achieved is a welcomed result.

五、結論

With the present flow control scheme the development of the *near wake* is shown to be very much load dependent. At 15% chord the same amount of blowing momentum has an affect on the velocity defect at near design loading but not at high loading. This suggests that the effectiveness of a particular flow control scheme is dependent on details of how and where evaluation is made. Wake data for both loadings taken at 30% chord show clear reduction in the velocity defect. Generally, beyond the near wake region, increase in the blowing flow momentum would result in further decrease in the rotor wake velocity defect. The three-year project successfully completed study of trailing edge blowing on the wake and unsteady loading on blade row.

六、參考文獻

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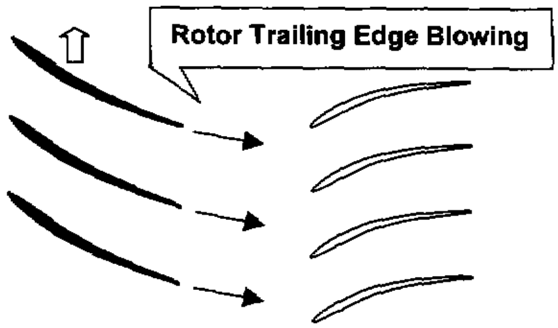

Fig. 1 Sketch of blowing flow from the rotor trailing edge in a rotor/stator axial compressor considered in this work.

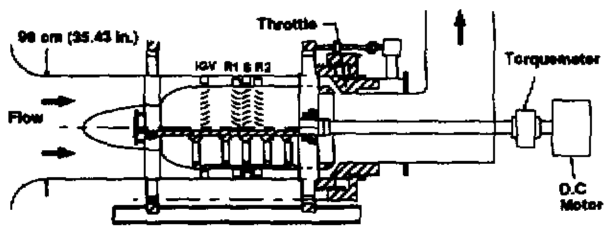

Fig. 2 The rotor/stator compressor rig used.

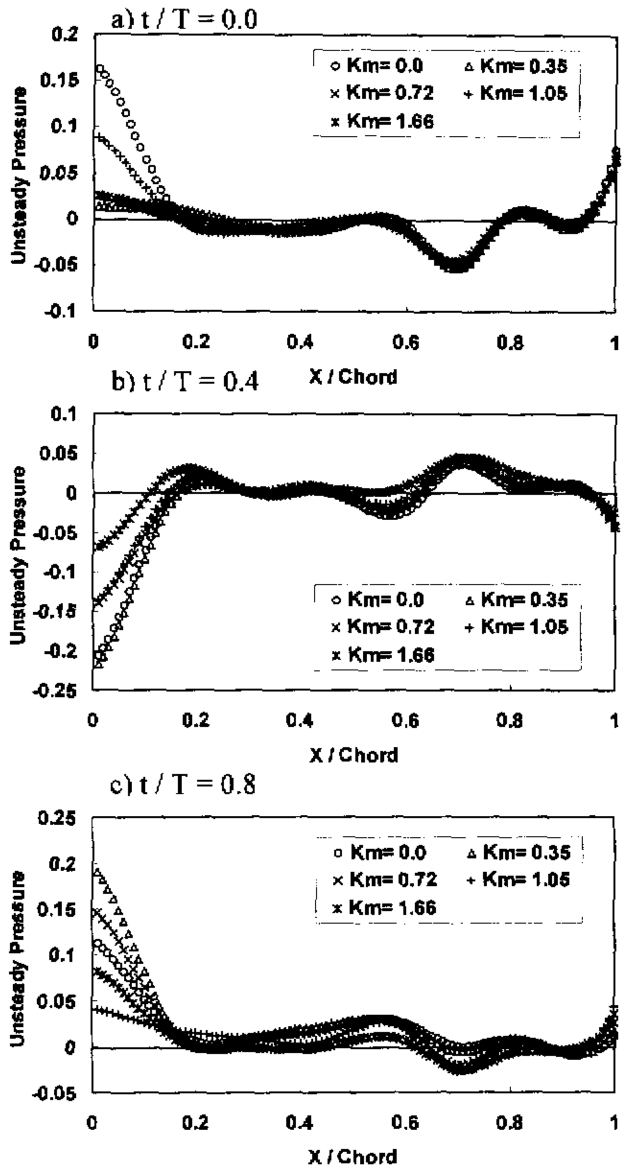

Fig. 3 Chordwise distribution of normalized unsteady pressure on the stator suction surface with various blowing flow at normalized time of a) t/T= 0.0, b) t/T= 0.4 and c) t/T= 0.8. Data taken at near design loading. See text for definition of the ordinate.

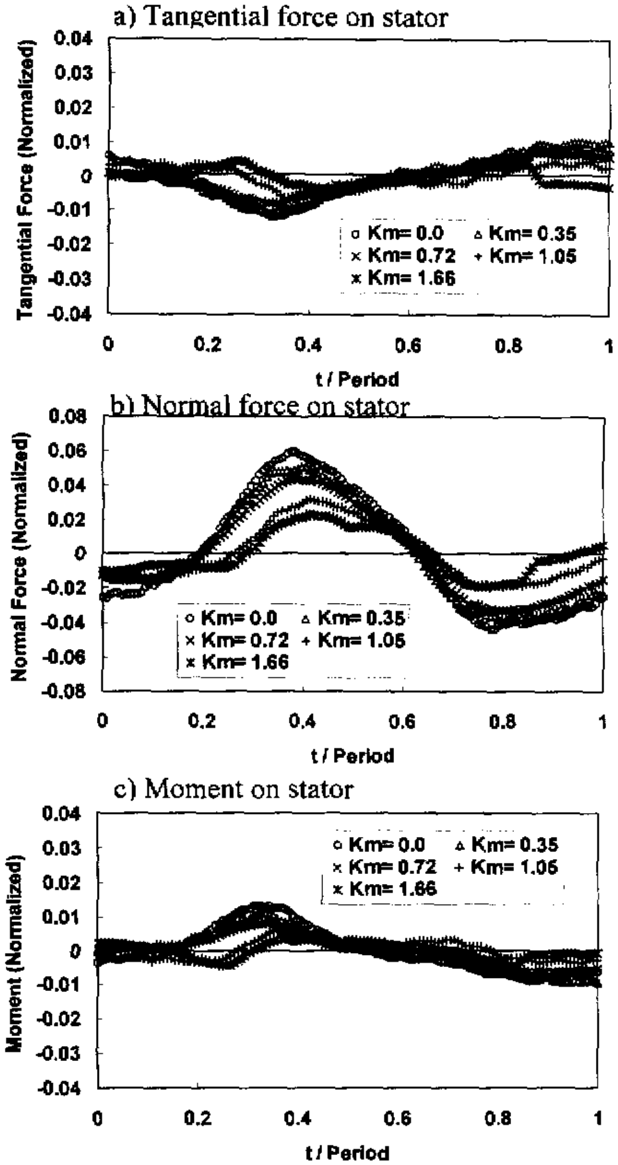

Fig. 4 Excursion of stator a) tangential force (along the chord), b) normal force (perpendicular to chord) and c) moment at various blowing flows. (Note: expanded ordinate scales for plots a and b.) Data taken at near design loading. See text for definition of the ordinate.

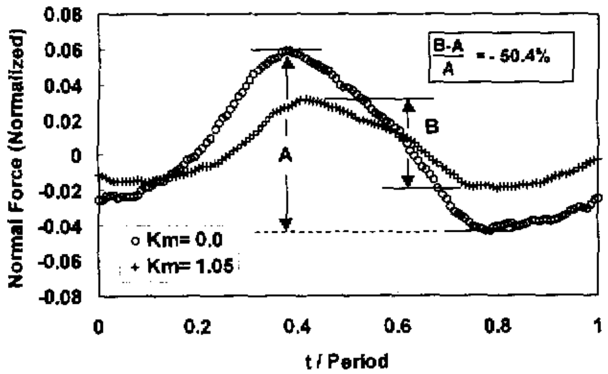

Fig. 5 Define the force reduction factor (B-A)/A to quantify the reduction of stator unsteady force with blowing compared to the no blowing case (Km= 0).

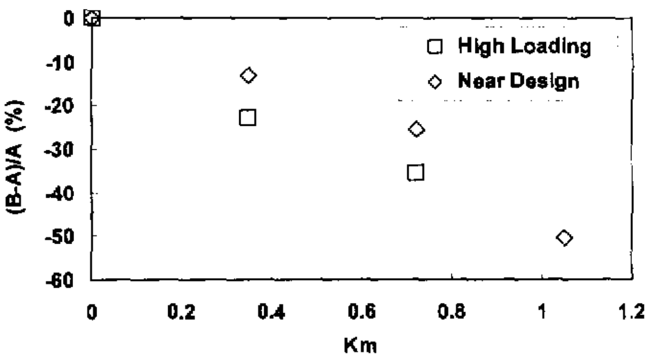

Fig. 6 Reduction of unsteady force amplitude on the stator over a range of blowing flows for two blade time-mean loadings. (See Fig. 5 for definition of ordinate.)