渦輪機葉片尾流控制之實驗與計算探討
Study of Wake Control for Turbomachinery Blades (2/3)

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一、中文摘要

總計劃欲分三年進行，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)。本報告為第二年之成果(在第一年中已完成轉子葉片之加工及噴氣品質之驗證)，主要成果為完成安裝加工後之轉子葉片、改裝軸流壓縮机設備使氣源可經過空心軸進入轉子葉片之根部、及轉子葉片尾流有、無噴氣時之量測。流場量測使用斜熱線在尾緣下游 15%弦長、30%弦長及 60%弦長處量測三維角位平均流速。量測在葉片設計點及高負荷點進行，為深入瞭解本控制方法之使用範圍。噴氣結果顯示對所有情況下之尾流有明顯之效果。在近尾流區域(near wake region)，即 15%弦長處，噴氣對尾流流速缺(velocity defect)之效果在設計點時比高負荷佳。在 30%弦長及 60%弦長處結果更明顯示此流速控制之益處。分析結果顯示陣風參數(gust factor)與尾流動量缺參數(wake momentum defect factor)之基本關係為線性。

關鍵詞: 軸流壓縮機、流場控制、葉片尾緣噴氣。

Abstract

This work (second year of a three-year project) aims 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. Fabrication of the rotor blade to be used for blowing is already complete in the first year as well as testing of flow quality. The second year effort was on mounting the instrumented blades (3 total) on the compressor rig, routing shop compressed air to the blades through the hollow main shaft, and measurement of the wake with and without control. Results show that blowing from trailing edge is an effective form of wake control overall. Near wake (15% chord) velocity defect is somewhat dependent on the time-mean blade loading; blowing is more effective for near design loading than at high loading in improving the velocity defect. Data at 30% and 60% chord both definitively show blowing is effect. The gust factor shows an essentially linear relationship with the wake momentum defect factor.

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

Data of the rotor wake with and without blowing flow will first be presented. Wake profiles at three locations – 15% chord, 30% chord and 60% chord – downstream of the rotor trailing edge are measured. These locations are chosen since the wakes measured characterize the gust on the closely coupled, downstream stator blades. The blowing cases considered correspond to K_m= 0, 0.35, 0.72 and 1.05 for near design loading, and K_m= 0, 0.35 and 0.72 for high loading cases, since K_m= 1.05 at high loading case being out of the range of slanted hot-wire calibration.

Figure 3 presents the wake *axial* velocity at near design loading (C_x/V_b = 0.60). The abscissa represents the instant when the wake sweeps pass the hot-wire. Figure 3a shows the wake profile at 15% chord aft of the trailing edge. The uncontrolled wake result (K_m= 0) shows the largest velocity defect compared to other blowing cases, as might be expected. The 'spike' at the left side (pressure surface side) of the velocity profile for the energized wake of K_m= 1.05 is the signature of the blowing flow. There are two sources that contribute to the bias of the blowing flow towards the pressure surface side of the wake: (1) the blowing air slot is fabricated principally along the camber line near the trailing edge, however, angular variation is difficulty to confirm and (2) the presence of flow deviation for a loaded blade which would 'shift' the entire wake towards the suction side. The first reason alone might cause the 'spike' to bias towards the pressure surface but the flow deviation further aggravates this situation. It is reasonable to believe that if the blowing slot were vectored towards the suction boundary layer or even place *on* the suction surface an increased rate of mixing would be achieved. Nevertheless, the blowing spike, which is an unwanted source of gust, only appear at fairly large injection flow and that all blowing flows resulted in lowered maximum velocity defect. This suggests that this form of blowing control in itself is effective regardless of fine details of the blowing slot design.

The development of the wake further downstream is shown in Figs. 3b and 3c. At 30% chord aft, Fig. 3b shows similar trend except that substantial portion of the energized wake has attained higher momentum in contrast to that of Fig. 3a. (The entire wake is right shifted in time due to the rotor stagger angle.) At 60% chord aft, Fig. 3c suggests that the transient effect of the blowing flow has subsided and that each wake 'gets what it deserves'; wake with larger blowing momentum injected resulted in smaller velocity defect.

Wake profiles at high loading ($C_x/V_b = 0.53$), just prior to the onset of rotating stall, are presented in Figs. 4a, 4b and 4c. At the 15% chord location, Fig. 4a, the maximum velocity defect with or without blowing flow is approximately the same. This suggests that the injected flow has not yet impacted the base flow (no blowing case). This is understandable since the velocity defect at high loading is much more severe than the near design case of $K_m = 0$ (Fig. 3a). At 30% chord aft of the trailing edge, Fig. 4b shows that the effect of the blowing flow on the velocity defect can be clearly seen. Further downstream at 60% chord, similar to that of Fig. 3c, Fig. 4c suggests that different rate of blowing flow has a distinct impact on the wake velocity defect.

The gust factor G allows one to access the effect of flow injection on transverse gust. With velocity profiles measured, the gust factor can now be calculated, which is shown in Fig. 5 for all blowing cases tested. Results clearly show that as the blowing momentum defect factor (K_m) increases, due to increase in blowing mass flow, the gust factor (G) decreases, which is the case for both loading levels. The two shaded lines define the bounds of overall trend of monotonic decrease in the gust factor. With this data at hand one can expect a decreased unsteady loading on the stator since the unsteady loading is mainly due to the upstream wake.

五、結論

This paper addresses flow control via rotor trailing edge blowing in a rotor/stator axial compressor with 30% chord axial spacing between blade rows and two time-mean blade loadings. Focuses are on the resulted wake kinematics at various blowing momentum defects and its effect on the unsteady gust response of the downstream stator.

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 (compare Fig. 3a with 4a). 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 (Fig. 3b and 4b) 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.

六、參考文獻

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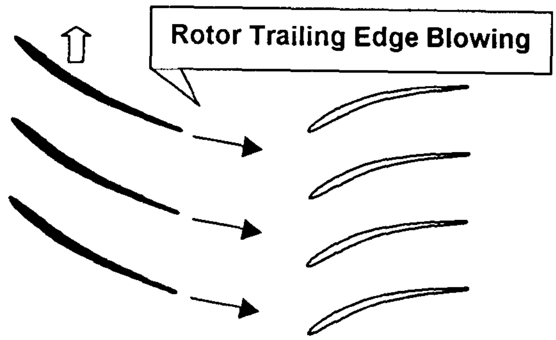

Fig. 1 Sketch of blowing flow from the rotor trailing edge in a rotor/stator axial compressor considered in this work.

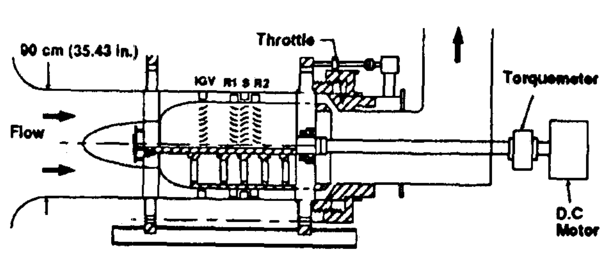

Fig. 2 The rotor/stator compressor rig used.

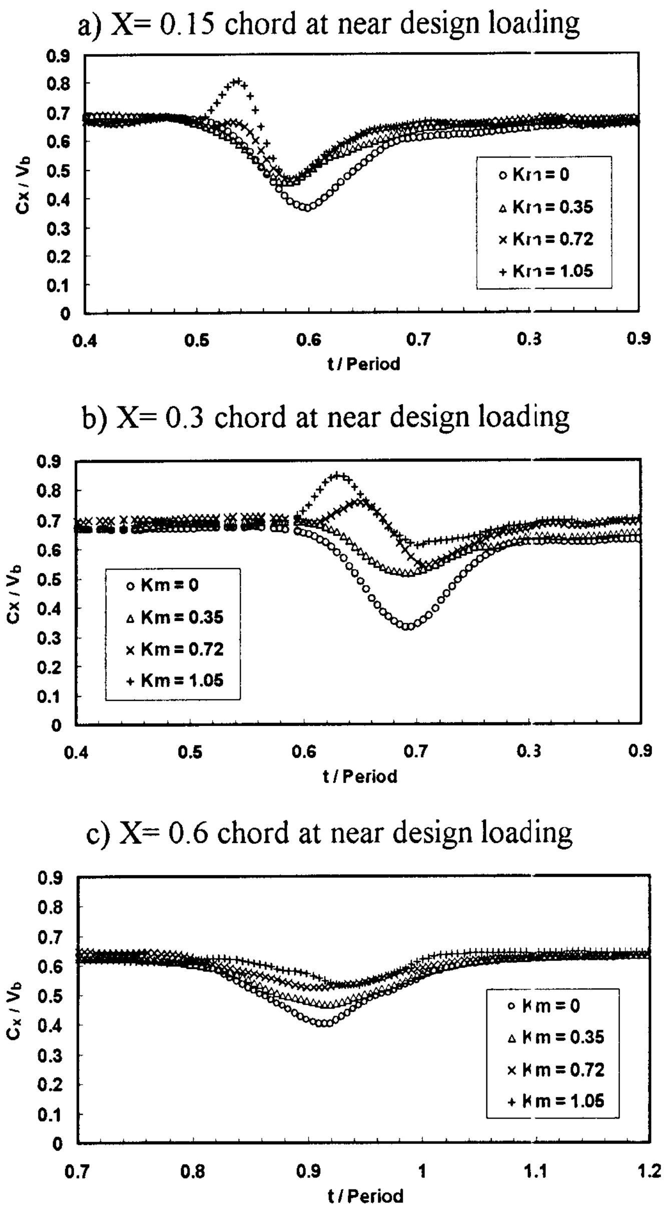

Fig. 3 Measured axial velocity wake profile with hot-wire located at a) 0.15 chord b) 0.3 chord and c) 0.6 chord aft of the rotor trailing edge. Blowing flow is applied at various wake momentum defect factors.

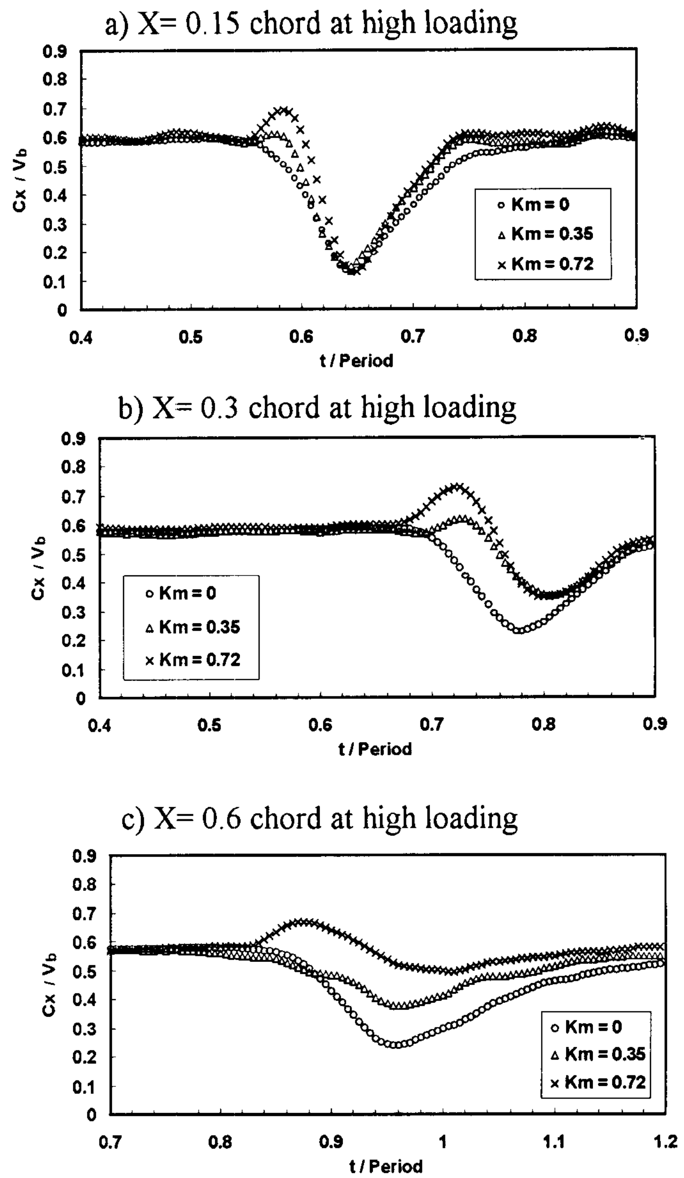

Fig. 4 Measured axial velocity wake profile with hot-wire located at a) 0.15 chord b) 0.3 chord and c) 0.6 chord aft of the rotor trailing edge at high blade loading.

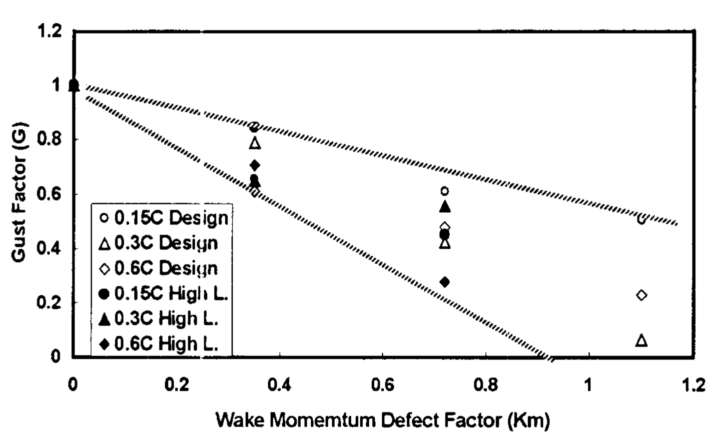

Fig. 5 Gust factor verses wake momentum defect factor over the entire range of data taken. The two shaded lines form the boundaries of the data, which suggests that the gust factor decreases monotonically with increasing wake momentum defect factor.