Experimental study of boundary-layer transition on an airfoil induced by periodically passing wake

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Abstract Hot-wire measurements are performed in boundary-layer flows developing on a NACA 0012 airfoil over which wakes pass periodically. The periodic wakes are generated by rotating circular cylinders clockwise or counterclockwise around the airfoil. The time- and phase-averaged mean streamwise velocities and turbulence fluctuations are measured to investigate the phenomena of wake-induced transition. Especially, the phase-averaged wall shear stresses are evaluated using a computational Preston tube method. The passing wakes significantly change the pressure distribution on the airfoil, which has influence on the transition process of the boundary layer. The orientation of the passing wake alters the pressure distribution in a different manner. Due to the passing wake, the turbulent patches are generated inside the laminar boundary layer on the airfoil, and the boundary layer becomes temporarily transitional. The patches propagate downstream at a speed smaller than the free-stream velocity and merge together further downstream. Relatively high values of phase-averaged turbulence fluctuations in the outer part of the boundary layer indicate the possibility that breakdown occurs in the outer layer away from the wall. It is confirmed that the phase-averaged mean velocity profile has two dips in the outer region of the transitional boundary layer for each passing cycle.

1 Introduction
Unsteady boundary-layer flows over the blades in turbomachinery have received attention since they strongly affect fluid-dynamic performance, flow loss and heat transfer on the blades. In a multi-stage axial compressor and turbine, periodic passing-wakes from an upstream blade impose a considerable influence on boundary-layer development and especially on the transition process over the downstream blade surface, in which it is known that wake-induced transition occurs. Therefore, correct understanding and accurate prediction of the wake-induced transitional flow are important to design a highly efficient blade.

A number of experiments on wake-induced transition in turbomachinery were reported by Dong and Cumpsty (1990a, b), Mayle and Dullenkopf (1991), Halstead et al. (1997), Schulte and Hodson (1998), and Walker et al. (1999) (see also the reviews by Mayle (1991) and Walker (1993)). Although these compressor and turbine experiments provided important aspects of unsteady boundary-layer flows in practical environments, various unsteady disturbances in complex turbomachine flows made it difficult to investigate the effect of the passing wakes on the boundary-layer development. Complex geometries of conventional turbomachines also made it difficult to obtain high quality data near the blade surface. To overcome such technical limitations, a number of investigators have performed hot-wire measurements for wake-induced transition on a flat plate in a wind tunnel (Pfeil et al. 1983; Liu and Rodi 1991; Orth 1993; Funazaki and Koyabu 1999; Funazaki and Aoyama 2000). In their experiments, the periodic unsteady blade-row disturbances were simplified as periodic passing-cylinder wakes, which were generated upstream of the plate by a rotating squirrel wheel. Liu and Rodi (1991) measured time- and phase-averaged mean and fluctuating streamwise velocity profiles in wake-affected boundary layers for four different wake-passing frequencies. Funazaki and Koyabu (1999) focused on the effects of periodic passing wakes on boundary-layer transition on a flat plate under the favorable and adverse pressure gradients. With the same facilities and experimental conditions, Funazaki and Aoyama (2000) measured two component velocities using a split-film probe. On the other hand, numerical simulations were also carried out to predict flow and heat-transfer characteristics in wake-affected transitional boundary layers (Cho et al. 1993; Fan and Lakshminaraya 1996; Chakka and Schobeiri 1999; Kim and Crawford 2000). Very recently, Wu et al. (1999) conducted a three-dimensional, time-accurate direct numerical simulation of wake-induced boundary-layer transition. They reported detailed behavior such as generation, growth, and
coalescence of wake-induced turbulent patches in the boundary-layer flows, and provided many useful time- and phase-averaged flow data.

As mentioned in previous work, the wake-affected boundary-layer transition strongly depends upon the characteristics of wake-induced turbulent patches. When wakes pass over a laminar boundary-layer flow, turbulent patches are generated inside the boundary layers and the flow becomes temporarly transitional. When going downstream, the patches grow and merge with each other due to different propagation speeds of their leading and trailing edges. When the patches coalesce sufficiently at the far downstream station, the boundary-layer flow becomes fully turbulent. Initial turbulent patches at the leading edge of the test plate are mainly subjected to turbulence intensities and mean velocity defects of passing wakes. On the other hand, their growth is affected by various internal and external flow conditions such as the characteristics of the initial turbulent patch and trailing wake, the streamwise pressure distribution, the free-stream turbulence intensity. Hence, understanding the behavior of the turbulent patch under certain external flow fields is required to predict the wake-induced transitional boundary-layer flows.

This work is a fundamental study of wake-induced transition employing a NACA 0012 airfoil with zero angle of attack instead of a real turbomachine blade. The passing wakes are generated by rotating circular cylinders clockwise (CW) or counterclockwise (CCW) around the airfoil, so the wake passes consecutively over the airfoil at each passing period. The time- and phase-averaged streamwise mean velocities and turbulence fluctuations in the boundary-layer flows are precisely measured using a single hot-wire probe. The phase-averaged wall shear stresses are evaluated using a computational Preston tube method (Nitsche et al. 1983). From the measured data, we investigate the characteristics of the wake-affected turbulent patch in connection to the phenomena of wake-induced transition.

2 Experimental set-up and method

2.1 Apparatus and instrumentation
The experiments were conducted in a closed-type wind tunnel. The test section was a rectangle of 0.6 m wide, 0.3 m high, and 2.0 m long. At the free-stream speed of 10 m/s, the uniformity of the streamwise mean velocity and turbulence intensity at the test section was less than 0.4 and 0.5%, respectively. The zero streamwise static pressure gradient in the test section without the airfoil was obtained by adjusting the side walls.

Figure 1a shows a schematic of the airfoil, the wake-generating wheel and the traverse unit for the hot-wire probe in the test section. A rotating disk of the wheel was at the bottom wall of the test section and was driven by a continuously adjustable DC motor at the exterior of the wind tunnel. Eight circular cylinders of 3 mm diameter were vertically installed and equally spaced along the circumference of the rotating disk. The cylinders in the wheel moved along the circular path with a radius of 0.27 m perpendicular to the incoming flow in front of the airfoil, so the periodic two-dimensional passing wakes were generated and affected the flow over the downstream airfoil. As shown in Fig. 1b, the cylinders rotated CW or CCW (when seeing the wheel over the test section) around the airfoil at the same speed to the incoming flow velocity of 10 m/s. Therefore, the wake-generating frequency was 47.2 Hz and the Strouhal number based on airfoil chord length \( (St_c = f C / U_\infty ) \) was 1.416. When the cylinder was positioned just in front of the airfoil, the distance between the center of the cylinder and airfoil leading edge was 0.12 m. The test blade made of an aluminum alloy was a NACA 0012 airfoil and its chord length and width were 0.3 and 0.29 m, respectively. The Reynolds number based on the chord length and the incoming free-stream velocity was \( 2 \times 10^7 \). Forty holes of 0.8 mm diameter were made on the airfoil to measure static pressure. The airfoil was vertically mounted with zero angle of attack at the center of the test section and detached from the rotating disk with a gap of 5 mm. The height of the near-wall flow disturbed by the rotating disk was found to be less than 10% of airfoil width at 10 m/s. Therefore, this disturbance did not affect the wake-induced boundary-layer flows over the mid-span of the airfoil in real experiments.

![Fig. 1a, b. Schematic of the test equipment: a a 3-D view, b an overview](image-url)