1. INTRODUCTION

1.1 Background

Separation is mostly an undesirable phenomenon because it entails large energy losses. In order to reduce drag and pressure losses it would be necessary to inhibit flow separation by suppressing boundary layer development. For this reason methods have been devised for the artificial prevention of separation. Boundary layer control has been used widely in aerodynamic applications to inhibit flow separation. The simplest method, for example, from the physical point of view, is to adopt a streamline shaped body in order to reduce the velocity difference between the stream and the flow near the solid wall, though this method sometimes has design restrictions in engineering practice. Another effective method for the prevention of separation is boundary layer mixing. In this method, the fluid particles which have large energy of the freestream are supplied to decelerated fluid particles in the boundary layer by longitudinal vortices. The techniques using longitudinal vortices are classified as passive and active methods. The passive control technique with solid vortex generators (rectangular, ramp, delta-shaped winglets, etc.) has advantages such as simplicity, ruggedness, and low cost. It has practical applications in stall control on airfoils and in diffusers. For example, solid vortex generators placed on the airfoils are useful to improve flight performance during aircraft take-off and landing. Furthermore, the generators placed in diffusers make the diffuser length shorter than those of the usual type. However, solid vortex generators have fatal shortcomings. Their disadvantages are that 1) they do not have the ability to provide a time-varying control action and therefore they can not be adopted for highly maneuverable aircraft and 2) they add parasitic drag in flow situations where stall suppression is not needed (e.g., an airfoil operating near its design condition). It is desirable for the control devices to be operated only when flow separation occurs. However, solid vortex generators are always exposed in the flow and they have increased drag.

On the other hand, pitched and skewed jets issuing through small holes in a wall into a freestream have proven effective regarding the control of boundary layer separation. Longitudinal vortices are produced by the interaction between jets and a freestream. This technique is known as the vortex generator jet method. The vortex generator jet method as an active control technique provides a time-varying control action to optimize performance under a wide range of flow conditions. For vortex generator jets, the strength of the longitudinal vortices are controllable by varying the jet speed. Furthermore, for flow situations where stall control is not needed, parasitic drag can be avoided with the jet flow turned off. The vortex generator jet method may accomplish separation control only when it is necessary and therefore it is available for both design and off-design conditions. Stall control with airplane or fluid machinery is not needed in usual operations because they are designed to produce no separation. If the control device operates only when it is necessary and can adaptively suppress flow separation, the ideal flow corresponding to the flow under its design condition is always attained without any changes in design of airfoils or diffusers.

1.2 Literature Review

The vortex generator jet method was first examined by Wallis [1] in the 1950's. However, solid vortex generators which were suggested by Taylor [2] some years earlier than that, had been energetically investigated at that time in comparison with vortex generator jets. They have practical applications in the stall control of airfoils and diffusers. It is not going too far to say that the vortex generator jet method has been neglected. Therefore, aspects for study related to the vortex generator jet method still remain.

A large body of literature describing studies of solid vortex generators exists. The principle of controlling a boundary layer using solid vortex generators such as those shown in Fig. 1.1 was first suggested by H. Bruynes and H. D. Taylor of the United Aircraft Corporation in 1947. Bruynes (1951) obtained U.S. Patent 2,558,816 for his fluid mixing device. H. D. Taylor [2] reported on the manner in which these solid vortex generators might be used in diffusers. This began a period during which wind tunnel testing was performed to determine the effects of solid vortex generators on suppressing boundary layer separation. Schubauer and Spangenberg [3] studied forced mixing in boundary layers. They investigated various types of solid vortex generators to determine which were more effective in suppressing boundary layer separation. Mehta [4] studied the effects of longitudinal vortices on the turbulent mixing layer. He reported that the mixing between the two streams was enhanced due to longitudinal vortices without significant decay in the vortex strength due to the mixing layer. He also studied the effects of vortices on separated subsonic [5] and supersonic boundary layers [6]. He concluded that the longitudinal vortex delayed separation on the downwash side and encouraged separation on the upwash side of a vortex for subsonic flow. For supersonic flow the longitudinal vortex reduced the entire region of separation, not just in the downwash region.

The processes of Reynolds stress modification and streamwise vorticity transport are important in understanding the development of the embedded vortices. The structure of turbulent boundary layers with embedded longitudinal vortices has been studied by Bradshaw and his co-workers at Imperial College [7]. Vortices were generated by placing half-delta-wing vortex generators in a wind tunnel settling chamber. These vortices pass through the contraction and into the test section with no significant wake remaining, and are embedded in the boundary layer. Their studies concentrated on the turbulent structure modification in the boundary layer due to interaction with the embedded longitudinal vortices. Mehta et. al. [8] reported the early results of these studies. A detailed data presentation and an analysis of the results were summarized in several parts. For a single longitudinal vortex embedded in a boundary layer, the results appeared in Shabaka, Mehta, and Bradshaw [9] or Mehta [10]. The vortex interaction with common flow between the vortices directed toward the wall was the most extensively studied, because it caused a strong distortion of the boundary layer. Results for the vortex pair with common flow-up were reported by Mehta and Bradshaw [11]. Pauley and Eaton [12] provided more detailed data for a variety of configurations with respect to rotational direction and strength of longitudinal vortices. They reported that higher skin friction was observed in the region with secondary flow toward the lower wall for the common-flow-down vortex pair and lower skin friction was observed in the region with the secondary flow away from the lower wall for the common-flow-up vortex pair. Shizawa and Eaton [13] indicated the suppression effect and the downstream development of longitudinal vortices. Matsumoto [14] measured the mean flow and Reynolds stress in the vicinity of an embedded common-flow-up vortex pair. He noted distortion of the boundary layer velocity profiles, particularly a decrease in the shape factor due to the vortices. The streamwise vorticity was mostly concentrated in the vortex core region, and this was accounted for as being produced by the anisotropy of the normal Reynolds stresses term in the streamwise vorticity transport equation. He observed the mean and fluctuating velocities in a turbulent boundary layer with no pressure gradient, but with longitudinal vortices introduced artificially by a series of vane-type vortex generators.

On the other hand, the image of generating longitudinal vortices using vortex generator jets is shown in Fig. 1.2. Jets issue through small holes in a lower wall into a freestream. Longitudinal vortices are generated by the interaction between the jets and the freestream. The vortex generator jet method was first examined almost 40 years ago by Wallis [1] and Wallis and Stuart [15] in Australia. Wallis' work indicated that a single vortex, which is similar to one from a solid vortex generator, might be formed by a jet which was skewed with respect to the freestream direction and was pitched to the lower wall. The vortex generator jet method was examined primarily for the purpose of delaying shock-induced separation of turbulent boundary layers. For vortex generator jets, the beneficial effect of separation control is obtained only if the pitched and skewed jets are issued. A more recent study by Ball [16] on stall suppression for jet-engine-inlet diffusers employed vortex generator jets alone and together with solid vortex generators.

Johnston and Nishi [17] examined five configurations of jet directions. They provided engineering design data (e.g., minimum jet speeds and angles) for effective utilization and showed that jet arrays which give counter-rotating vortex pairs can cause significant spanwise variations. Compton and Johnston [18] investigated the strength and decay rate of a longitudinal vortex for seven cases of jet skew angle. They concluded that the maximum vorticity levels are strongly dependent on jet velocity and skew angle, and an optimal jet skew angle may be between 45 and 90 degrees to the downstream direction. Furthermore, they indicated that the property of longitudinal vortices produced by vortex generator jets is different from that by solid vortex generators. The suppression effect of flow separation using pulsed vortex generator jets in a stalled two-dimensional diffuser was demonstrated by McManus et al [19]. In order to realize pulsed flow, they used a pulsed valve which was driven by a timing controller. A comparison between pulsed and steady flow jets was performed in order to confirm the relative efficiencies of the two techniques. It was indicated that the mass flow requirements for effective separation control using pulsed vortex generator jets were greatly reduced over those for steady jets.

Nishi et al. [20, 21] examined the applicability of vortex generator jets to suppressing separation in a conical diffuser which had a diffuser's divergence angle of 14 degrees. Selby et al. [22] performed a parametric study on controlling flow separation associated with low-speed turbulent flow over a two-dimensional rearward-facing ramp. In their study, they investigated the effects of several parameters such as the jet orifice diameter, jet orientation, jet speed, jet skew angle, and jet pitch angle on separation control. Furthermore, they made a comparison between slot blowing and vortex generator jets. A computational study was performed for the longitudinal vortices produced by a single jet and co-and contra-rotating jets in a turbulent cross flow by Zhang [23]. He selected control parameters such as jet angle, jet-to-cross flow velocity ratio, and jet spacing. The longitudinal vortices have the ability of convecting kinetic and thermal energy in the lateral plane. The ability could be utilized to enhance the film cooling efficiency of turbine blades (Honami et al. [24]) and heat transfer (Zhang and Collins [25]). Leylek and Zerkle [26] made a comparison of computational results with experiments on discrete jet film cooling and obtained reasonable agreement. Goldstein and Eckert [27] indicated that the effect of jet orifice geometry on the film cooling downstream of the secondary gas injection. Johnston and Khan [28] made a visual study using fluorescent dyes in a water flow channel in order to investigate the origin of the dominant vortex formed from a pitched and skewed jet.

As has been seen above, the effect of boundary layer control using vortex generator jets has begun to be understood in recent years. However, studies with respect to the vortex generator jet method have not been sufficiently carried out in comparison with those on solid vortex generators. In particular, the mechanism of the active boundary layer control by vortex generator jets and the generation mechanism of longitudinal vortices by the pulsed jets are not yet understood. Although the optimal jet skew angle which can strengthen the maximum vorticity level at a pitch angle of 45 degrees has already been reported, the effect of the jet pitch angle on separation control is unknown. The advantage of the vortex generator jet method is that it has the ability to adaptively control the various flow conditions. However, applications of vortex generator jets to time-varying flow fields have not been reported.

1.3 Objectives of This Study

The purpose of present study was to investigate the effects of active separation control using vortex generator jets on suppressing flow separation. The more specific objectives of this study were the following:

1. To understand the mechanism of boundary layer control by using vortex generator jets [29, 30],

2. To determine the effects of the jet pitch angle on separation control [31, 32],

3. To understand the difference between the steady and pulsed jets in the downstream development of longitudinal vortices, and

4. To develop an active separation feedback system which can adapt time-varying flow fields and confirm the effectiveness of this system for changes in the flow fields of this experimental facility [33].

In this paper, the description is arranged in the following way: we begin in Chapter 1 by introducing the background and objectives of this study. In Chapter 2 we give an outline of the fundamental physical principles of the boundary layer and diffuser. The experimental apparatus are explained in Chapter 3 with a description of the velocity and pressure measurement instruments. In Chapter 4 we examine whether flow separation control is influenced by the boundary layer condition. In Chapter 5 the mechanism for suppressing flow separation using vortex generator jets is studied by making a comparison between the steady and pulsed jets in order to obtain data on the optimal conditions of longitudinal vortices for effective separation control. Furthermore, we make clear that the downstream development of longitudinal vortices for pulsed jets is different from that for steady jets. For these reasons we prepared Chapter 6. In Chapter 7 we describe the effect of the jet pitch angle on separation control in order to obtain effective engineering design data. In Chapter 8 we take up the application of the active boundary layer control system which utilizes the data on the mechanism for the prevention of separation of the longitudinal vortices and the jet pitch angle. Finally, Chapter 9 contains a summary of the paper.

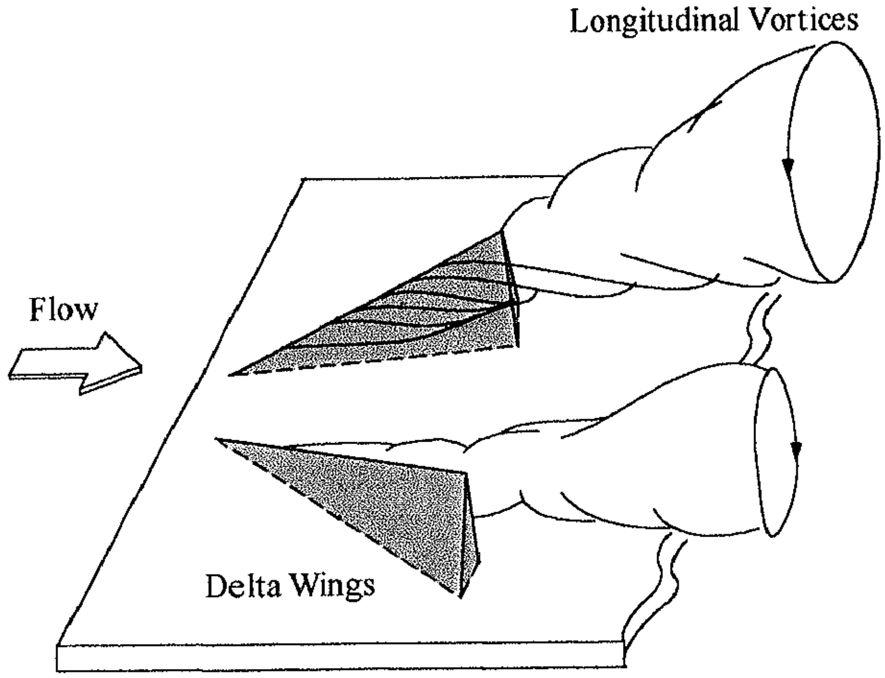

Figure 1.1 Longitudinal vortices generated by solid vortex generators.

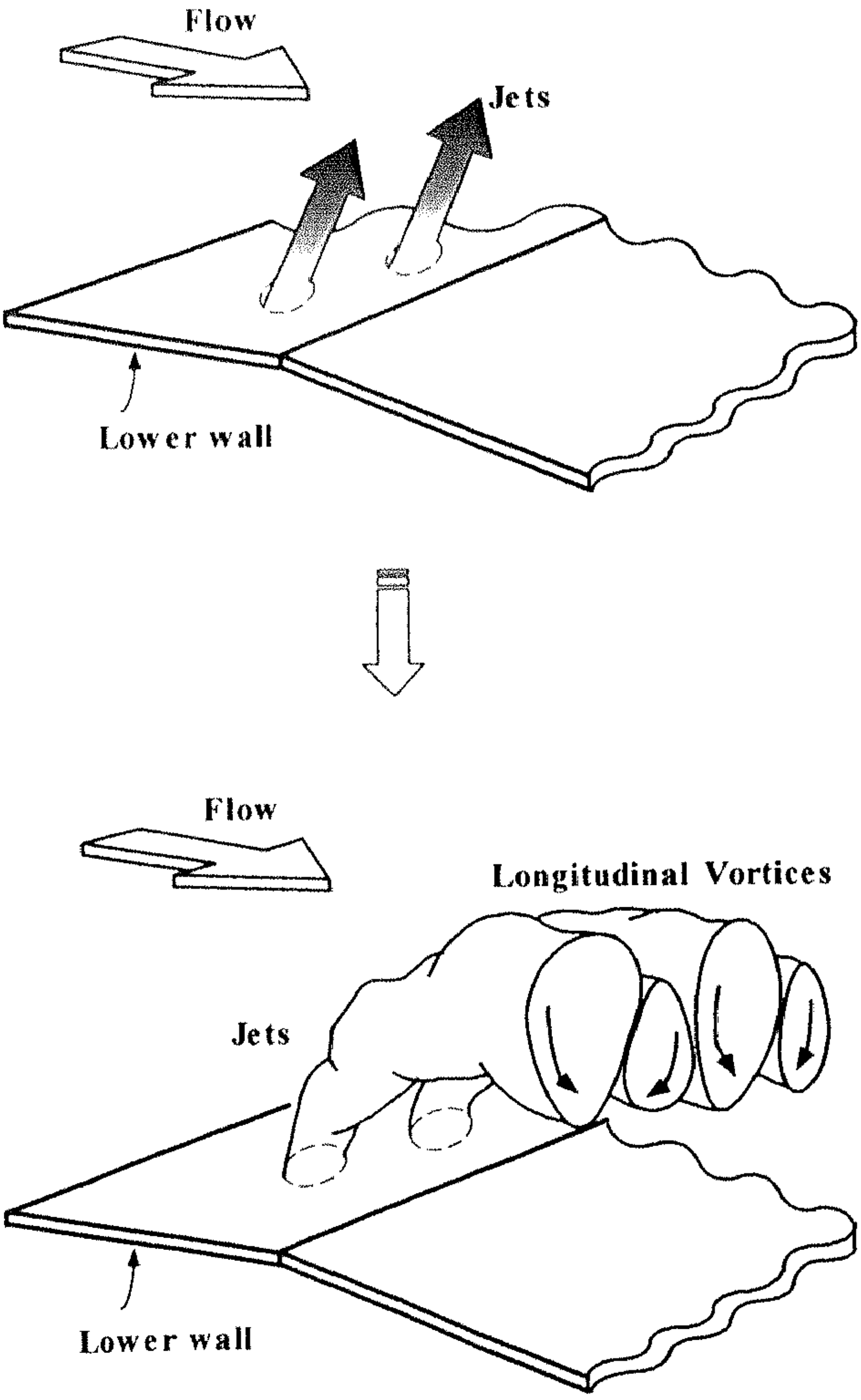

Figure 1.2 Longitudinal vortices due to jets issuing into freestream.