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CONTROL OF TURBULENT SEPARATED AND REATTACHING FLOW BY PERIODIC PERTURBATION

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ABSTRACT

Flow over a backward-facing step is investigated experimentally when the separated flow is excited by a sinusoidally oscillating jet issued from a spanwise thin slit along the separation line. The flow properties are characterized by two principal parameters, i.e., the forcing frequency ($St_H = fH/U_o$) and forcing amplitude(A). In order to investigate the effect of local forcing, the structure of separated flow is scrutinized for both cases of unforced and forced flows. It is found that the overall flow characteristics are altered significantly. When the local forcing is perturbed, the shear layer growth is increased and it leads to the reduction of reattachment length(x_r). Especially, the particular frequency gives a minimum reattachment length. The present experiment reveals that the large-scale vortical structure is closely associated with the forcing condition and flow instabilities.

INTRODUCTION

Control of separated and reattaching flow is of prime importance in a wide range of applications in fluids engineering. Flow over a backward-facing step constitutes a basic problem. The presence of a separated flow, together with a reattaching flow, gives rise to unsteadiness, pressure fluctuations, structure vibrations and noise. It is therefore an essential task to gain a proper understanding of the phenomenon and seek possible ways to ameliorate the above-stated adverse impacts.

A literature survey reveals that there have been many attempts to control or lesson the unfavorable behavior associated with the separation. Among others, use of sound wave and vibrating flap to influence the separated shear layer were examined by several researchers[1~6].

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The purpose of the present experiment is to 1 the flow structure over a backward-facing step when the separated flow is locally perturbed. By utilizing a small-amplitude localized jet flow at the separation edge, it is attempted to control the turbulent separated and reattaching flow. The large-scale vortical structures in the reattaching flow is also scrutinized.

EXPERIMENTAL APPARATUS

Wind tunnel

The present experiment is performed in subsonic open-circuit wind tunnel. Air is driven by a centrifugal blower and introduced into a settling chamber prior to the test section. The dimension of inlet channel is 2000mm L, 100mm H, and 620mm W in x, y and z directions, respectively. The inlet flow condition is assumed to be a fully developed two-dimensional turbulent channel flow. The dimension over a backward-facing step is the dimension of 2100mm L, 150mm H, and 620mm W with the aspect ratio of 12.5 and the step height H=50mm. Along the centerline of the bottom wall from the separation point, 1.0mm diameter holes are drilled 10mm apart to measure the wall static pressure distributions.

The free stream turbulence intensity is less than 0.6% at speeds 4.0~14.0m/sec. No significant peaks are found in the spectrum of velocity fluctuations. Figure 1 shows a cross sectional view of the test section with the several definitions. All working sections are constructed from Plexiglas.

Local forcing technique

The local forcing is introduced by a sinusoidally oscillating jet which is driven by a 300mm diameter woofer issued from a spanwise thin slit along the separation line (Fig.1). The slit is located at the separation point, so that it turns out to be most effective

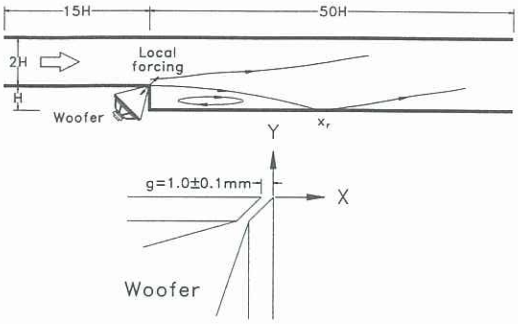

Figure 1: Cross sectional view of test section

to control the separated flow.

The forcing amplitude A is determined as the ratio in terms of the increasing total velocity due to the local forcing over the mean free-stream velocity. The amplitude A is represented by $A = \frac{Q_{forced}-Q_{unforced}}{U_o}$, where the total velocity Q means the issuing velocity from the slit in the free-stream. This definition represents the momentum change between the unforced flow and the forced flow in the initial boundary layer. The forcing frequency f is adjusted by the input signal into the woofer. In the present experiment, f is less than 1kHz and $Q_{forced} - Q_{unforced}$ is less than 7% of the free-stream velocity.

Measurement instrumentation

Velocity components are measured with a CTA system with I-type, X-type hot-wire sensors and a split-film sensor. The I-type sensor is used to measure the local issuing velocity from the thin slit. The X-type sensor is used to measure the turbulent properties except the recirculating region. The split film sensor is used to measure the forward flow fraction γ_p, which is used for the measurement of reattachment length. Probes are moved in x and y directions by a remote controlled traverse system, the resolution of traverse system being within 0.025mm.

RESULTS

Initial boundary layer

One of the most important parameters characterizing the turbulent separated and reattaching flows is the reattachment length x_r, which varies generally between x_r/H=5.0 and x_r/H=8.2 in the literature. It is known that the principal parameter affecting x_r is the conditions of initial boundary layer, i.e., δ, $\sqrt{\overline{u^2}}$ and $Re_H(= U_oH/\nu)$[7]. The initial conditions are listed in

Forcing condition	δ	δ^*	θ	x_r
A=0	20.6	2.62	2.03	7.8
$A = 0.07, St_H = 0.275$	17.6	2.49	1.96	5.0
$A = 0.07, St_H = 1.00$	21.1	2.48	1.94	8.1

Table 1: Initial conditions (Re_H=33000)

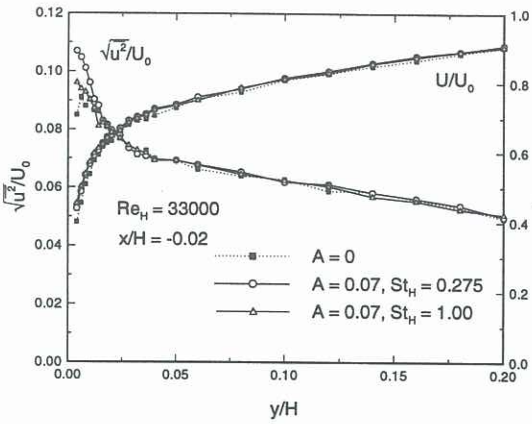

Figure 2: Initial boundary layer

Table 1 at Re_H=33000. The reason of selecting three forcing conditions will be described later.

To evaluate the effect of the initial conditions on the flow, U/U_o and $\sqrt{\overline{u^2}}/U_o$ are displayed in Fig.2. As a result of local forcing($A = 0.07, St_H = 0.275$), the mean velocity is slightly increased in the region of $0 \leq y/H \leq 0.05$. However, the turbulent intensity is shown to be a significant increase for $0 \leq y/H \leq 0.02$. Especially, a closer inspection reveals that the peak of turbulent intensity increases from 0.09 to 0.11. This increase is closely related to the reduction of the reattachment length.

In the experiment of Isomoto & Honami[8], the reattachment length can be reduced by the increase of turbulent level in the entire region of initial boundary layer. In the present experiment, however, the increase of turbulent level is localized in the vicinity of the separation edge. This gives rise to the stimulation of forming and merging of vortices due to the local controlled forcing. It is found that the turbulent level is increased due to the promotion of forming and merging of vortices when a free shear layer is perturbed by a controlled frequency[2][9].

Forward flow fraction, γ_p

Figure 3 shows typical distributions of γ_p near the bottom surface. The value of γ_p is measured close to the wall($y/H = 0.02$). x_r can be determined by the point where γ_p is attained the value of 0.5. (Fig.3).

As shown in Fig.3, the flow structure significantly varies with the forcing conditions. For the case of A=0.07, St_H=0.275, x_r decreases approximately 36%. Based on the distribution of γ_p in Fig.3, the size of corner flow near the edge can be predicted. It shows that the secondary recirculating zone near the edge for A=0 is larger than those of forcing cases. For A=0, the shear layer is reattached at x/H=7.8 and the recirculating region exists in $0 \leq x/H \leq 7.8$. The strong reverse flow, which is located below γ_p=0.1, appears in $3 \leq x/H \leq 6$, but in $0 \leq x/H \leq 1$, γ_p has above 0.5, so the flow is toward downstream. This phenomenon represents the generation of corner flow in this region. However, for

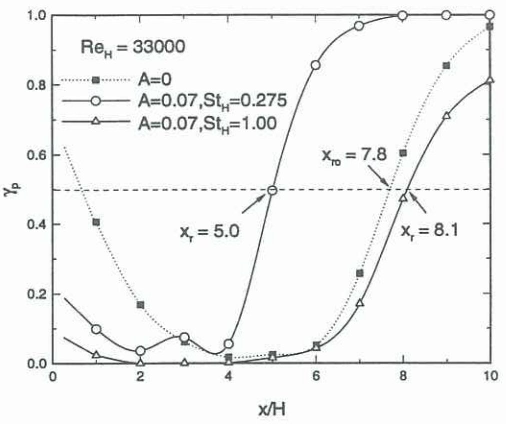

Figure 3: Typical plot of forward flow fraction

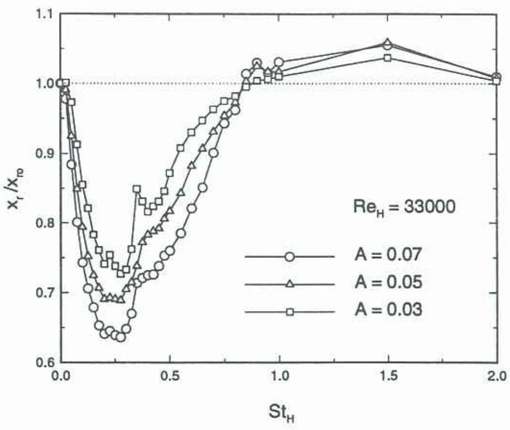

Figure 4: Variation of reattachment length

A=0.07 and St_H=0.275, γ_p is relatively small and most flow is toward upstream. Thus, the corner flow is eliminated or suppressed by the specific forcing frequency($St_H = 0.275$).

Reattachment length, x_r

It is known that the reattachment length is affected by the reduced forcing frequency St_H, the non-dimensional forcing amplitude A, and Re_H. The measurements are performed at $Re_H = 33000$. Three amplitudes(A=0.07, 0.05, 0.03) are selected for the investigation of the influence of amplitude (Fig.4). The range of St_H used in the present study is from 0.025 to 5.0 which are equivalent to 5Hz∼1kHz. A=0 is henceforth designated as the flow state without forcing. Figure 4 explains the variation of x_r against St_H and A at Re_H=33000. x_r decreases in the region of $0.2 \leq St_H \leq 0.6$ and increases in $1.0 \leq St_H \leq 1.8$.

In Fig.4, x_r has a minimum value at St_H=0.275 for Re_H=33000. The frequency is called the most effective frequency[4]. It is found that the vortex merging is taken place actively and the turbulence level increases in free shear layer over the range of reduced frequencies of 0.136 ∼ 0.55[9]. This result is consistent with the present reduced frequencies, 0.1 ∼ 0.5. It suggests that the separated shear layer is controlled effectively by the specific forcing and it leads to the increase of the growth rate of shear layer and the vortex merging. These effective reduced frequencies are very similar to the separated shear layer as well as the free shear layer. However, when the separated shear layer is perturbed by the highly reduced forcing frequency, e.g., $St_H \geq$0.8, the reattachment length is rather increased than that of no forcing. It is seen that any pairing event for perturbation is not observed in above 0.8[10]. As a result, the perturbation at the high forcing frequencies suppresses the forming and merging of vortex and the growth of shear layer. Accordingly, three typical cases are selected in the present experiment: The first condition is A=0, the second forcing is A=0.07 and St_H=0.275 which gives the minimum x_r at Re_H=33000 and the third is A=0.07 and St_H=1.00 which gives the larger x_r than that of A=0.

These frequencies are correlated with the instability frequency of shear layer. In a backward-facing step flow, the frequency of vortex formation is about St_H=0.27 which is measured near the shear layer edge at x/H=1. The most effective reduced frequency for the control of separated shear layer corresponds to the instability frequency of shear layer. Also it is shown that the most effective forcing frequency is equal to the shedding frequency of the shear layer[5]. When the forcing frequency is equivalent to the instability of separated shear layer, the instability is emphasized by a perturbation, the forming and merging of vortices are promoted. The growth rate of shear layer is increased and the reattachment length is reduced.

Wall pressure distribution, C_p

Distribution of $C_p(=\frac{P-P_o}{0.5\rho U_o^2})$ is measured in a number of positions along the centerline at the bottom wall. Figure 5 shows the variation of C_p, as compare with the results of no forcing and forcing at two different forcing conditions, A=0.07, St_H=0.275 and A=0.07, St_H=1.00. In Fig.5, a strong adverse pressure gradi-

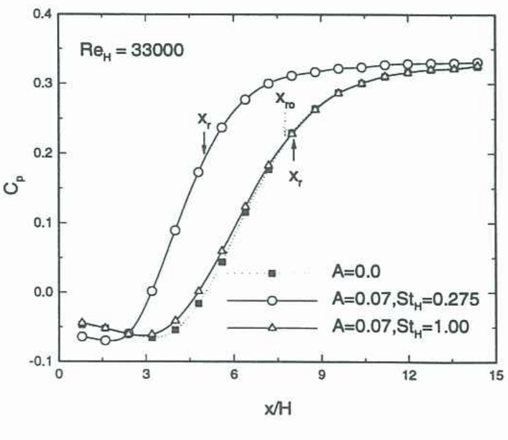

Figure 5: Wall static pressure distribution

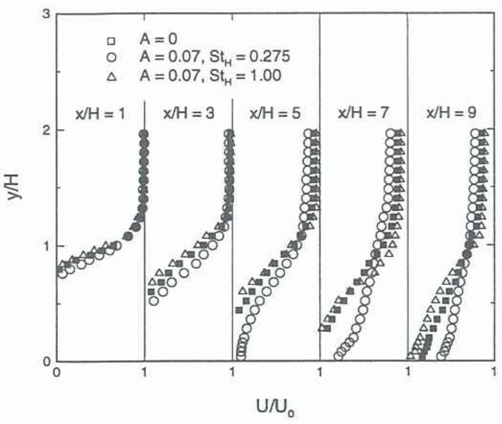

Figure 6: Mean velocity profiles(Re_H=33000)

ent is seen in the region immediately after the separation, $0 \leq x/H \leq 3$, followed by a moderate increase up to x/H=12 for A=0 and at A=0.07, St_H=1.00. But the variation of C_p at A=0.07, St_H=0.275 shifts approximately 3 step heights upstream and changes in the entire flow field. The rate of pressure recovery is larger than those of above two cases. The maximum C_p values decrease slightly from 0.32 to 0.31. It is noted that the C_p value is not altered with increasing turbulence level, suggesting only an upstream shift of the entire flow[11], but the change of C_p values result from perturbation[12]. As a consequence, the recirculating region decreases with the controlled forcing but the wall pressure distribution is not changed.

Time-averaged flow structure

The profiles of time-averaged streamwise velocity component and turbulence level are presented in Fig.6 at several locations along the test section. The results from the perturbed cases(St_H=0.275, St_H=1.00) are compared with that of no forcing at Re_H=33000. The forcing amplitude is set as A=0.07 for both forcing conditions.

In Fig.6, no significant change of the mean velocity profile is found near the step edge, x/H=1. However, a big significant deviation is apparent in the reattachment region, $x/H = 5 \sim 7$. The tendency of variation is discernible clearly in the separated shear layer. Especially, the value of mean velocity for St_H=0.275 increases about 20% or 30% at the same vertical position in the shear layer. These increases of mean velocity represent that the separated shear layer is rapidly entrained into the recirculating region by the controlled forcing. But the opposite phenomenon occurs for the higher forcing frequency, St_H=1.00, i.e. the recirculating region expands by the perturbation.

CONCLUSION

A local controlled forcing gives a significant influence on the separated and reattaching flows. The large-scale vortical structures are promoted with increasing turbulent levels and decreasing the reattachment length by a controlled forcing in the separated shear layer. When the forcing frequency is the same as the instability frequency of separated shear layer, the instability is emphasized by a perturbation, so the forming and merging of vortices are promoted, the growth rate of shear layer is increased. This gives the reduction of the reattachment length. Especially, this change is intensified within the recirculating region.

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