11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

SINUSOIDAL FORCING OF AN AXISYMMETRIC LEADING EDGE SEPARATION BUBBLE

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ABSTRACT

The leading-edge separation zone of a blunt circular cylinder was forced by single-frequency sinuous disturbances of different frequencies and levels at Reynolds numbers of the order of 10^5. The disturbance was introduced along the square-cut leading edge of the cylinder. For low levels of the forcing, the reattachment length attained a minimum at a forcing frequency which was approximately five times the frequency of shedding of large-scale vortices from the reattachment region, and a maximum at another forcing frequency which was approximately a half of the frequency of the Kelvin-Helmholtz instability immediately downstream of the separation edge. The reattachment length was independent of the forcing frequency if it was greater than approximately twice the Kelvin-Helmholtz frequency. For intermediate and high levels of the forcing, the reattachment length had a much complicated response. The modification of the rolling-up process of the shear layer was demonstrated by the power spectra of velocity fluctuations near the edge of the shear layer.

INTRODUCTION

Separated-and-reattaching flows (separation zones) are encountered in a number of fluid-flow systems. In turbomachinery the formation of separation zones is associated with unfavourable flow unsteadiness such as pressure fluctuations, structural vibrations, noise, etc. On the other hand, the separation zones enhance the heat transfer, mass transfer and mixing. Thus control of separation zones is expected to have a wide range of applications in fluids engineering. Previous studies on control of separation zones are summarized by Kiya (1989a). More recent studies are those by Sigurdson and Roshko (1988), Nishioka et al. (1990), and Kiya et al. (1991a).

The purpose of this paper is to control a turbulent leading-edge separation zone of a blunt circular cylinder by single-frequency sinuous disturbances uniformly introduced along the right-angled separation edge. This separation zone was employed because its turbulence structure without the forcing is clarified to a sufficient extent by the previous studies (Ota and Motegi, 1980; Kiya et al., 1991b).

EXPERIMENTAL APPARATUS AND METHOD

Wind tunnel and blunt circular cylinder. Experiments were performed in a closed-return wind tunnel with a 1.5 m wide, 1.2 m high and 6.0 m long working section. The ceiling of the working section was shaped so as to have zero longitudinal pressure gradient. The free-stream turbulence intensity was 0.2 -0.3% at speeds 5 - 20 m/s. The acoustic pressure level measured near an air breather at the end of the working section was 0.5-1.2 Pa in the same range of the speeds. No significant peaks were found in the spectrum of the velocity fluctuation in the main flow and that of the acoustic pressure.

A blunt circular cylinder constructed from a Plexiglass was 0.200 m in diameter d and 2.0 m long, having the flat face and the square-cut leading edge. Figure 1 shows a cross sectional view of the cylinder, and the definition of the coordinate system and main symbols. The front disk 1.0 cm in thickness was bevelled by 45° towards the back side, being set in position by a screw device. The front end of the cylinder was bevelled by 45° in a manner as shown in Fig. 1 so that a gap was formed between the back side of the front disk and the front side of the cylinder. In the present experiment the gap g was set to 2.77±0.05 mm. A woofer was installed inside the cylinder as shown in Fig. 1. The woofer produced sinusoidal velocity fluctuations at a point immediately upstream of the separation edge.

Velocity fluctuations were measured by constant temperature hot-wire anemometers using a single I-wire probe and a split-film probe (Thermo-Systems Inc. Model 1288). The I-wire probe was used to detect velocity fluctuations in regions where the intermittent reverse flow was not expected. The split-film probe measured the instantaneous longitudinal velocity near the surface to obtain the reverse-flow time fraction.

The experiments were performed at main-flow speeds U_∞ = 5.0 - 20.0 m/s, which corresponded to Reynolds numbers Re (= $U_\infty d/\nu$) = (0.69 - 2.76) × 10^5.

RESULTS AND DISCUSSION

Reference position. The level of velocity fluctuation produced by the woofer should be measured near the separation edge with the main flow included (Kiya et al., 1992). An appropriate reference position was determined based on profiles of the time-mean and r.m.s. velocities measured along the minus x-axis with the I-wire probe normal to the xy-plane. These velocities are denoted by Q and q'. The reference position should be defined in terms of a dynamically significant position. In this sense the position where the time-mean velocity Q attains a distinct maximum is a reasonable choice. At this position, however, the r.m.s. velocity q' attained so high a value that the signal produced by the woofer

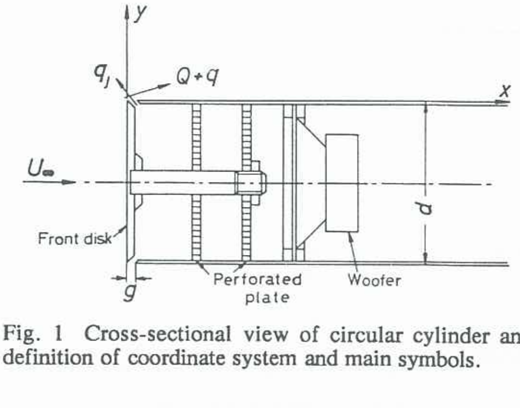

Fig. 1 Cross-sectional view of circular cylinder and definition of coordinate system and main symbols.

would be overcome by the turbulence. Thus the position where the value of Q was 90% of its maximum value was chosen as the reference position. At this position the r.m.s. velocity q' was less than 0.4% of the free-stream velocity U_∞. When the woofer was driven, the velocity fluctuation measured at the reference position was almost sinusoidal.

Reattachment length. The reattachment length of the separation zone x_R was defined as the distance between the separation edge and the position where the reverse-flow time fraction measured near the surface attained the value of 0.5. The measurement of the reverse-flow time fraction was made at a height y = 1 mm (y/d = 0.005) from the surface. The reattachment length of the unforced flow, x_{R0}, was x_{R0} = $(1.60 \pm 0.06)d$ in the Reynolds-number range.

Characteristic time scales. There are three characteristic time scales in the unforced separation zone (Kiya, 1989b). These time scales are associated with the Kelvin-Helmholtz instability immediately downstream of the separation edge, the fairly periodic shedding of large-scale vortices from the reattachment region, and the low-frequency flapping motion of the separated shear layer which is accompanied by the shrinkage and enlargement of the separation zone. The Kelvin-Helmholtz instability f_{KH} was $f_{KH}d/U_\infty$ = 45 at $Re = 1.38 \times 10^5$; the vortex-shedding frequency f_v was $f_v d/U_\infty$ = 0.32; the central frequency of the flapping motion f_l was approximately $f_l d/U_\infty$ = 0.063.

The value of the vortex-shedding frequency f_v can theoretically be obtained by assuming that the separation zone is a self-excited system: When a large-scale vortex impinges on the surface in the reattachment region, a pressure fluctuation is generated, propagating upstream with the velocity of sound a to be accepted at the sharp leading edge to modify the rolling-up process of the separated shear layer. The accepted disturbance is convected downstream with the velocity U_c which is approximately a half of the free-stream velocity U_∞. If the fundamental frequency of this self-excited system is assumed to be equal to the vortex shedding frequency in the reattachment region, one obtains

$$x_{R0}/U_c + x_{R0}/a = N/f_v \qquad (1)$$

where x_{R0} is the reattachment length of the unforced flow and N implies an integer. Noting that $U_c >> a$, and assuming that N=1, one has

$$f_v x_{R0}/U_\infty = U_c/U_\infty = 0.5 \qquad (2)$$

Since $x_{R0} = 1.6d$, one obtains $f_v d/U_\infty$ = 0.32. This is equal to the value obtained experimentally.

A physical mechanism which is responsible for the flapping motion is not known, although a few suggestions are made (Kiya, 1989b). The central frequency of the flapping is approximately 1/5 of the vortex-shedding frequency.

Reattachment length versus frequency of excitation. Figure 2(a) shows the reattachment length plotted against the forcing frequency in a normalized form S (= $f_{ex}d/U_\infty$) - x_R/x_{R0}. The forcing was at a low level q_f'/U_∞ = 0.01, where q_f' is the root-mean square amplitude of the sinusoidal velocity fluctuation with the forcing frequency f_{ex}. Figure 2(b) extends the range of the forcing frequency up to S = 175. In Fig. 2, zero forcing frequency implies the case of no forcing.

The reattachment length attains a distinct minimum approximately at the non-dimensional frequency S = 1.6. This frequency is approximately five times the frequency of shedding of large-scale vortices from the reattachment region f_v. The forcing by the vortex-shedding frequency produces much weaker effect on the separation bubble, as can be seen from Fig. 2(b). The forcing by the frequency of the flapping motion produces further weaker effect.

Wavelengths of the disturbances can give us a clue to estimate the position where the the rolling-up of the shear layer

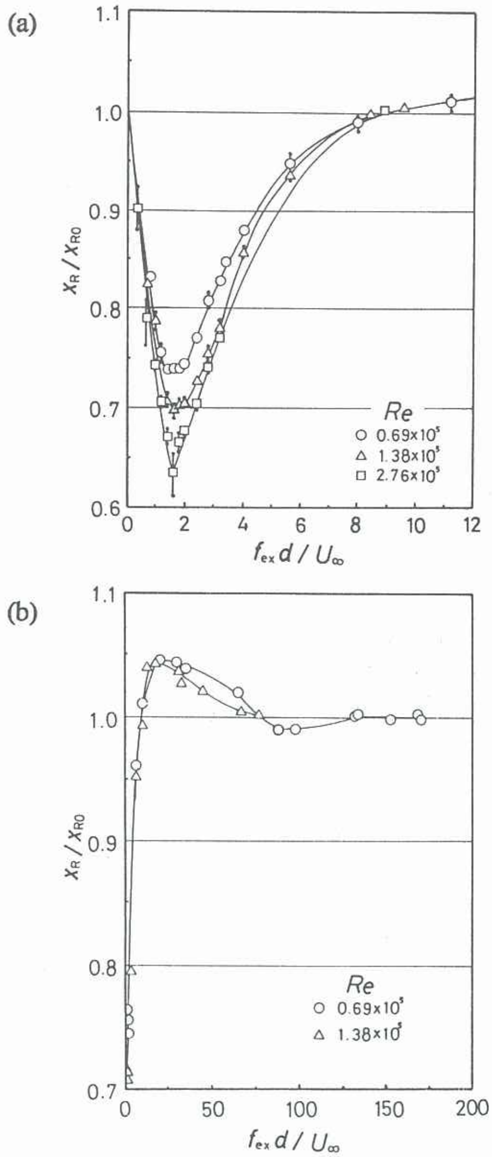

Fig. 2 Reattachment length x_R versus forcing frequency f_{ex} in range (a) 0 < $f_{cx}d/U_\infty$ < 175 and (b) 0 < $f_{cx}d/U_\infty$ < 11 at different Reynolds numbers. Forcing level is q_f'/U_∞ = 0.01.

was first modified by the excitation. If the disturbance is assumed to be convected downstream with the velocity 0.50 U_∞ (Kiya et al., 1991b), the wavelength of the disturbance with S = 1.6 is $\lambda_{1.6} = (0.22 \pm 0.06)x_{R0} = (0.35 \pm 0.10)$d . The first modification of the rolling-up was realized within a distance $\lambda_{1.6}$ from the edge, as demonstrated by the evolution of the spectra of the longitudinal velocity fluctuations measured at the outer edge of the separated shear layer, which are shown in Fig. 3 together with the spectra of the unforced flow. The spectrum at x/d = 0.20 for the forced flow has a single peak at the forcing frequency which is lower than the peak frequency of the unforced flow. This demonstrates that the forcing produced larger vortices in the forced flow than in the unforced flow at a distance of approximately a half of the forcing wavelength. A peak of the spectrum corresponding to the subharmonics emerges at x/d = 0.40, becoming more dominant at x/d = 0.80. This means that the first merging of the rolled-up vortices associated with the forcing frequency

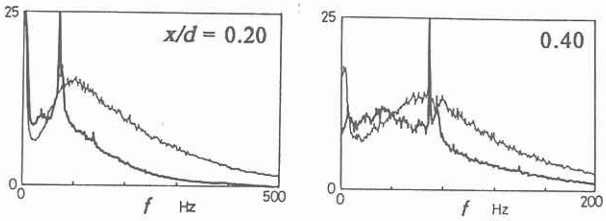

Fig. 3 Evolution of amplitude spectra of velocity fluctuation q near edge of separated shear layer. Vertical axis is arbitrary linear. Thin lines are for unforced flow, while thick lines are for forced flow. Forcing frequency and level are $f_{ex}d/U_\infty = 1.4$ and $q_f'/U_\infty = 0.085$. $Re = 1.32 \times 10^5$.

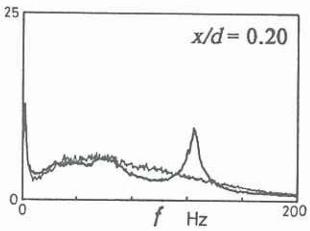

Fig. 4 Amplitude spectrum of velocity fluctuation q for forcing which yields maximum reattachment length at $Re = 0.69 \times 10^4$. Thick line is for forced flow with $q_f'/U_\infty = 0.01$ and $S = 20$ ($f_{ex} = 500$ Hz), while thin line for unforced flow.

is completed within two wavelengths of the forcing. The second merging perhaps occurred between the positions x/d = 0.8 and 1.6.

On the other hand, the wavelengths corresponding to the forcing frequencies $S = 0.32$ ($f_{ex} = f_v$) and $S = 0.063$ ($f_{ex} = f_l$) are $\lambda_v/x_{R0} = 1.0$ and $\lambda_l/x_{R0} = 5.0$. These wavelengths are so large that the corresponding disturbances cannot modify the rolling-up process of the separated shear layer unless the level of the excitation is sufficiently high.

The reattachment length attains a maximum which is approximately 5% greater than x_{R0} at the forcing frequency of approximately a half of the Kelvin-Helmholtz frequency f_{KH}, viz. at $S = 20$ ($f_{ex} = 500$ Hz for $Re = 0.69 \times 10^5$). The spectrum at the position $x/d = 0.2$, which is shown in Fig. 4, has a dominant peak at the subharmonic frequency $f_{ex}/4$, and another broad peak approximately at the frequency $f_{ex}/8$. The latter peak frequency is approximately the same as that of the unforced flow. This spectrum suggests that smaller vortices were produced at the position $x/d = 0.2$ by the forcing than in the unforced flow. Such smaller vortices have lower rate of entrainment so that they tend to increase the reattachment length. The spectra for the forced and unforced flows were almost the same more downstream of approximately $x/d = 0.4$.

The reattachment length is almost independent of the forcing frequency if the forcing frequency is greater than approximately $2f_{KH}$. General shapes of the spectra for the unforced and forced ($S = 64.8$) flows were almost identical for the longitudinal distances greater than $x/d = 0.15$. In an earlier region x/d = 0 - 0.05 the spectra contain a number of peaks corresponding to subharmonics of the excitation frequency. These peaks, however, quickly disappeared with increasing x/d.

Effect of Reynolds number. Figure 2(a) shows the effect of Reynolds number on the relation between the forcing frequency and the reattachment length. The 'most effective' forcing frequency at which the reattachment length attains a minimum value is independent of Reynolds number, while the minimum value itself becomes smaller with increasing Reynolds number. The Reynolds-number effect is most significant at the most effective frequency, being probably associated with thinner shear layers for higher Reynolds numbers.

Effect of forcing level. Figure 5 presents the effect of the forcing level on the reattachment length; the forcing level was in a range q_f'/U_∞ = 0.005 - 0.10. The reattachment length generally decreases with increasing excitation level. Especially at the highest forcing level $q_f' = 0.10$, the minimum reattachment length is only 35% of that of the unforced flow. A surprising result is that two minima appear at intermediate forcing levels q_f'/U_∞ = 0.03 and 0.05. At high forcing levels q_f'/U_∞ = 0.06 and 0.10 a single minimum of the reattachment length is recovered but at a slightly higher forcing frequency.

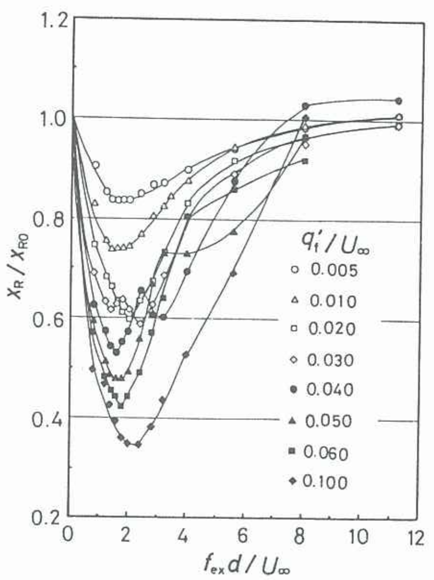

Fig. 5 Effect of forcing level on reattachment length at Reynolds number $Re = 0.69 \times 10^5$.

The above complicated response of the separation zone to the forcing is caused by the fact that the forcing levels are higher than those which can excite the linear or exponential stage of growth of the shear layer; that is, the linear stage is bypassed. Such a high level forcing has an important impact on the dynamics of the finite-amplitude disturbance that eventually evolves; evolution of the disturbance is generally a function of the forcing level.

The effect of the forcing level on the vortex structure of the shear layer is demonstrated in Fig. 6 which compares the evolution of the spectra for two different levels $q_f'/U_\infty = 0.005$ and 0.02 at the most effective frequencies. The main difference is that the subharmonic frequency component $f_{ex}/2$ is much stronger for the high forcing level $q_f'/U_\infty = 0.02$ than for the low forcing level $q_f'/U_\infty = 0.005$. Thus the vortex merging is enhanced for the former.

Universality of vortex-shedding frequency. Figure 7 shows the vortex-shedding frequency f_v in the form suggested by the feedback mechanism, together with results of Kiya et al. (1991a) are included in Fig. 6. The vortex-shedding frequency normalized by the diameter of the cylinder d and the main-flow velocity U_∞ is also included in this figure for reference. The non-dimensional frequency $f_v x_R/U_\infty$ has a fairly universal value 0.51±0.09 at different excitation frequencies.

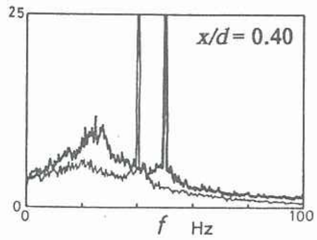

Fig. 6 Amplitude spectra of velocity fluctuation q for different levels of forcing at Reynolds number Re = 0.69×10^5. Thick line is for $q_f'/U_\infty = 0.02$, $S = 2.0$ ($f_{ex} = 50$ Hz), while thin line is for $q_f'/U_\infty = 0.005$, $S = 1.6$ ($f_{ex} = 40$ Hz).

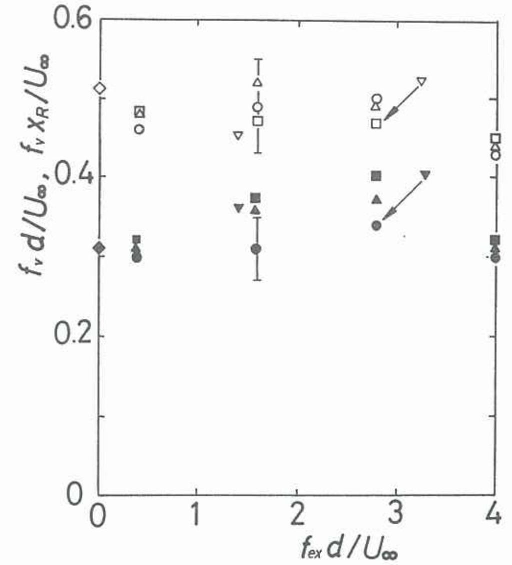

Fig. 7 Frequency of shedding of large-scale vortices from reattachment region versus excitation frequency at Reynolds number $Re = 1.32 \times 10^5$. Open symbols are for $f_v x_R U_\infty$ and solid symbols are for $f_v x_R U_\infty$. Different symbols imply different levels of forcing.

FURTHER DISCUSSION

The feedback mechanism has explained the universal, non-dimensional value of frequency of vortex shedding from the unforced separation zone. The universal value was found in a wide range of separation bubbles (Cherry et al., 1984). Figure 7 suggests that the feedback mechanism also prevails in the forced flow. This is surprising because the forcing is of such a high level that the process of vortex merging might hardly be influenced by the disturbance which is produced by the impinging vortices and propagates upstream to be accepted at the sharp separation edge. However it is possible that the role of the forcing is to give rise to the first rolled-up vortices within its wavelength, and that the subsequent merging of these vortices is governed by the accepted and downstream propagating disturbance originally produced by the impinging vortices.

The value of the most-effective forcing frequency f_{min} is approximately 1/5 of the vortex-shedding frequency f_v. If the experimental uncertainty is included, one has that $f_{min}/f_v = 5.0 \pm 1.3$. This relation can be obtained by assuming (i) that the non-dimensional vortex-shedding frequency of the excited flow is given by

$$f_v x_R/U_\infty = U_c/U_\infty \quad (3)$$

in the same manner as Eq. (2), and (ii) that the final vortex shed from the reattachment region is created by the n-th amalgamation at a longitudinal position x_n which is the reattachment position; the minimum reattachment length is realized for the smallest possible value of n. If the wavelength corresponding to the forcing frequency f_{min} is denoted by λ_{min} ($= U_c/f_{min}$), one has $x_n = x_R = 2^n \lambda_{min}$, assuming that two vortices are involved in each merging. Thus one has

$$x_R f_{min}/U_\infty = 2^n U_c/U_\infty \quad (4)$$

Equations (3) and (4) yield $f_{min}/f_v = 2^n$. Within the framework of this theory, the value of n cannot be determined. For n = 0, 1, 2, 3, one has f_{min}/f_v = 1, 2, 4, 8. Thus the choice $n = 2$ yields a fair agreement between the theory and the experiment. This value of n is also consistent with the evolution of the energy spectra of Fig. 3. It is possible that for sufficiently high levels of the forcing the lower values of n is realized.

CONCLUSION

Main results of the present study may be summarized as follows.

(1) The frequency of shedding of large-scale vortices from the reattachment region was derived by assuming that the separation bubble is a self-excited system maintained by a feedback mechanism.

(2) If the forcing level is less than 2 percent of the main-flow velocity, the reattachment length attains a minimum at a forcing frequency which is approximately one-fifth of the vortex-shedding frequency.

(3) For the forcing levels between 3 - 5 percent two minima of the reattachment length occur at different forcing frequencies, while a single minimum of the reattachment length is recovered for the forcing levels of 6 - 10 percent.

(4) For the forcing frequency at which the reattachment length attains a single minimum for levels less than approximately 2 percent, there exist basically two stages of merging of the vortices formed by the forcing between the separation edge and the reattachment region.

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