SECONDARY FLOWS AROUND OSCILLATING ASYMMETRIC CYLINDERS

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SECONDARY FLOWS AROUND OSCILLATING ASYMMETRIC CYLINDERS

By Masakazu TATSUNO*

An experimental investigation was made as to whether or not the secondary flow field involves a unidirectional flow component besides the circulatory streaming, when a cylinder with an asymmetric cross-section performs the sinusoidal oscillations. Experiments were carried out using several cylinders with a triangular, Joukowski and fan-shaped profiles and several containers of the fluid over the wide range of physical parameters $\omega d^2/\nu$, $\omega s^2/\nu$ and s/d, where ω is the angular frequency, d the maximum transverse dimension of a cylinder, ν the kinematic viscosity of a working fluid, and s the oscillation amplitude. No evidence could be found of the existence of a unidirectional flow. When the Joukowski profile oscillates sinusoidally, the distinctive feature appears in the flow patterns, which may be classified into three types depending on the values of $\omega d^2/\nu$.

Key words: Oscillating asymmetric cylinders, Secondary flow, Circulatory streaming, Unidirectional flow

1. Introduction

When a symmetric cylinder performs the sinusoidal oscillations, the secondary flow field is symmetric with respect to both directions of oscillation and perpendicular to it, and the streaming is circulatory, based on many investigations[1-6] up to date.

On the other hand, when the symmetric cylinder performs the inharmonic oscillations, a unidirectional flow is induced besides the circulatory streaming as reported by Miyagi *et al.*[7] theoretically and by Tatsuno** experimentally. The unidirectional flow has the same direction as that the cylinder moves faster, and the flow velocity on its side is considerably larger than that on the opposite side along the direction of oscillation.

Now, only two investigations have been reported about the streaming induced by asymmetric cylinders performing the sinusoidal oscillations as far

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as the author knows. Tamada *et al.* [8] made a theoretical analysis of the streaming induced by a symmetric Joukowski profile. Their analysis was based on the theory of Schlichting[3] and applicable to the case of $\omega d^2/\nu \gg 1$ and $\omega s^2/\nu \ll 1$, where ω is the angular frequency, d the maximum transverse dimension of the cylinder, ν the kinematic viscosity and s the oscillation amplitude. They reported that a uniform flow in the direction parallel to the oscillation direction is induced due to the asymmetry of the profile, and the flow is constituted by the circulatory streaming and the uniform flow component. On the other hand, Tatsuno[9] investigated the streaming induced by a triangular cylinder. In his experimental investigation, however, a flow pattern with a uniform flow is never obtained and the flow field is constituted by only the circulatory streaming.

Thus, the flow fields obtained by two reports are different from each other, though the cross-section of the cylinder is not equal.

It is one of the purposes of this work to investigate experimentally whether or not the flow field involves the uniform flow component besides the circulatory streaming when the asymmetric cylinder performs the sinusoidal oscillations. A cylinder with the same section as the Joukowski profile employed by Tamada *et al.* was prepared for this purpose. Furthermore, a cylinder with a fan-shaped section was used, which had no sharp edges and the profile had a more pronounced asymmetry than the Joukowski profile.

Another purpose is to clarify the characteristics of the streaming due to the asymmetry of the cylinder.

2. Apparatus and Experimental Method

The experiments were carried out with the same apparatus that the author used in the previous investigation about the streaming due to the saw-toothed oscillations. Figure 1 shows the photograph of the apparatus. A loudspeaker was used to oscillate cylinders. The deviation of the cylinder was measured optically using the pin-holes attached to the shaft connecting the cylinder and the speaker cone. An example of traces obtained is shown

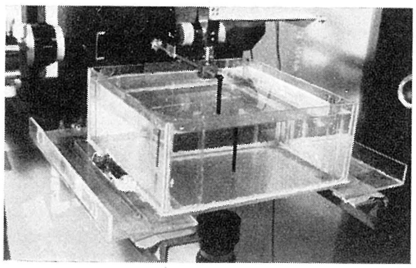

Fig. 1 Experimental apparatus

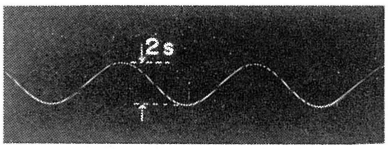

Fig 2 A trace of form of sinusoidally oscillatory motions of a fan-shaped profile. $f=20.0$Hz.

in Fig. 2, and the oscillation amplitude is estimated on this curve. Test cylinders with three different sections and several containers of the fluid will be shown in detail in the next section. Test cylinders were vertically held at the center of the container. A working fluid was a mixture of water and glycerine, and the kinematic viscosity ranged from 0.033 to 3.35 cm^2/s. In order to visualize the fluid motion, the aluminium dust or micro glass particles of about 10 μm in diameter were suspended uniformly in the fluid. A harmonic signal generator was used to oscillate cylinders sinusoidally. A projector or a stroboscope was used to illuminate a horizontal thin plane perpendicular to the axis of the cylinder, and photographs of the flow were taken by a camera placed underneath the container.

3. Experimental Results

The steady streaming induced by a circular cylinder performing the sinusoidal oscillations is shown in Fig. 3, where f is the frequency of the cylinder motion and t_e the exposure time. The double arrow indicates the direction of oscillations and the arrow the direction of the flow. If the cylinder section is symmetric, the streaming is symmetric with respect to both directions of oscillation and perpendicular to it, and is constituted by circulatory flows.

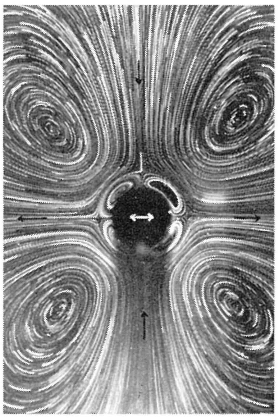

Fig. 3 Secondary flow by an oscillating circular cylinder.
$d=0.602$ cm, $f=60.0$ Hz, $s=0.0279$ cm, $\nu=0.49$ cm^2/s,
$\omega d^2/\nu=278$, $s/d=0.0463$, $\omega s^2/\nu=0.598$, $t_e=30$ s.

3.1. Case of a triangular cylinder

Figure 4 shows the flow patterns around a triangular cylinder at five different values of s/d. When the value of $\omega d^2/\nu$ is small, the flow field around the cylinder is occupied by the inner circulatory streaming, as seen from Fig. 4(a). The whole flow pattern is symmetric with respect to the

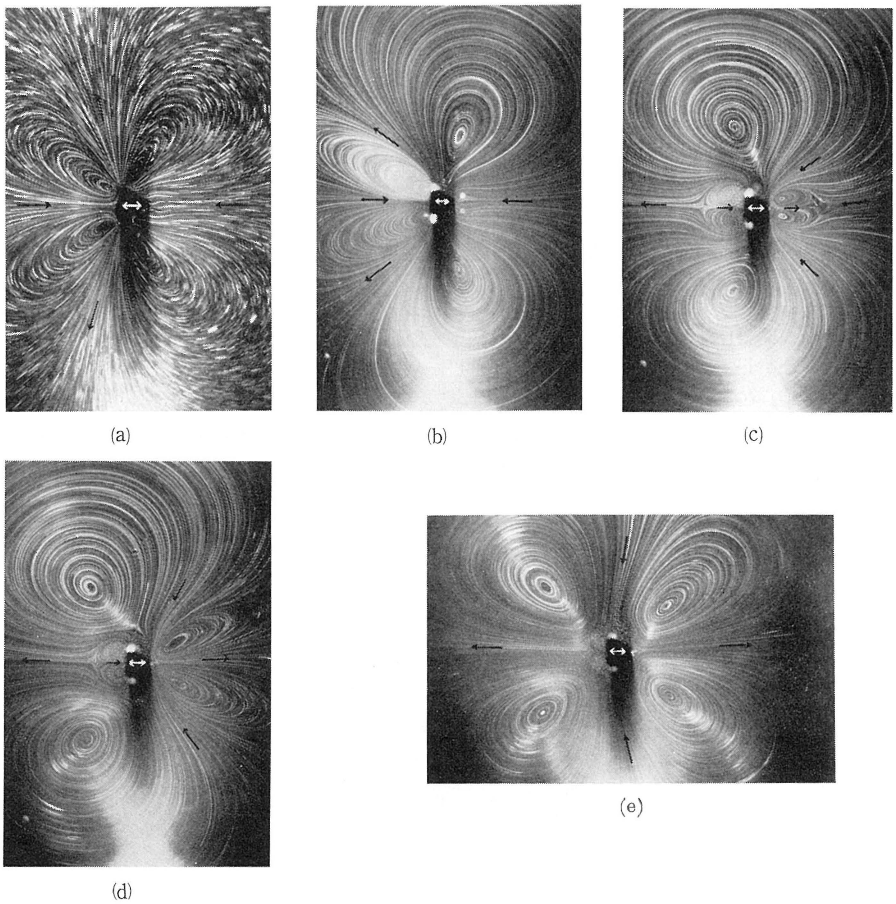

Fig. 4 Secondary flows around a triangular cylinder at various values of s/d.
$d=0.514$ cm, $f=49.9$ Hz, $\nu=0.53$ cm^2/s, $D=12.2$ cm, $\omega d^2/\nu=156$, $D/d=23.7$, D is the representative width of the container.
(a) $s/d=0.0238$, $\omega s^2/\nu=0.088$, $t_e=30$ s,
(b) $s/d=0.176$, $\omega s^2/\nu=4.81$, $t_e=30$ s,
(c) $s/d=0.249$, $\omega s^2/\nu=9.69$, $t_e=20$ s,
(d) $s/d=0.263$, $\omega s^2/\nu=10.8$, $t_e=20$ s,
(e) $s/d=0.308$, $\omega s^2/\nu=14.8$, $t_e=20$ s.

direction of oscillation but asymmetric with respect to that perpendicular to the oscillation direction. Thus, if the cylinder is asymmetric, the flow pattern grows to be asymmetric. According as s/d is increased, this trend becomes conspicuous, and the inner circulatory streaming at the side of the obtuse edge shrinks suddenly, but the streaming at the side of the sharp edge grows large, as seen from Fig. 4(c). In this stage, it will be seen that the flows parallel to the oscillation direction on both sides of the cylinder take the same direction and the streaming seems to have a unidirectional flow component. This streaming, however, does not correspond to the streaming that Tamada *et al.* chose as the subject of the study. Such streaming appears temporarily in the process of the transition of the streaming. The streaming shown in Fig. 4(c) finally turns into the streaming shown in Fig. 4(e) with the increase of s/d. It seems to involve no uniform flow component.

In Fig. 5, the photograph of the streaming at a large value of $\omega d^2/\nu$ is shown for a triangular cylinder.

After all, it is evident from these figures that the uniform flow or the unidirectional flow is not induced and only the circulatory streaming is induced around the triangular cylinder.

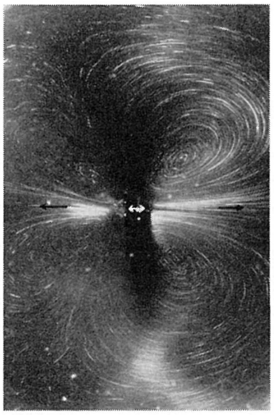

Fig. 5 Secondary flow by an oscillating triangular cylinder. $d=0.514$ cm, $f=70.0$ Hz, $s=0.0218$ cm, $\nu=0.0495$ cm²/s, $\omega d^2/\nu=2345$, $s/d=0.0424$, $\omega s^2/\nu=4.22$, $t_e=30$ s.

3.2. Case of a symmetric Joukowski profile

In Fig. 6, the section of a model, one of the fluid containers and the co-ordinate system of the flow field are shown schematically. The uniform flow predicted by Tamada *et al.* takes the negative value in the direction of oscillation on the basis of this co-ordinate system. The profile of the model section closely resembles to that of Tamada *et al.* There is only one difference between two profiles. The profile of Tamada *et al.* has a mathematical cusp on the one side. As it is impossible to make a mathematically cuspidal edge in practice, the model has an approximately cuspidal edge; the edge was sharpened as much as possible.

An example of the flow at a small value of $\omega d^2/\nu$ is shown in Fig. 7. The flow field around the cylinder is almost occupied by the inner circulatory streaming.

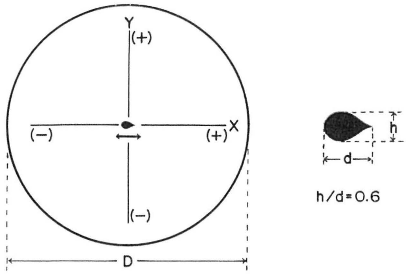

Fig. 6 Sections of a model and a container, and co-ordinate systems.

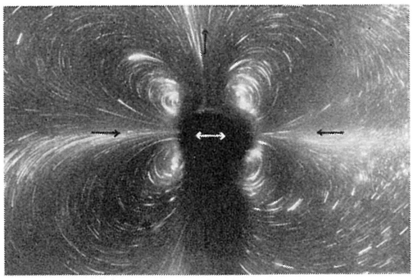

Fig. 7 Secondary flow by an oscillating Joukowski profile. $d=1.00$ cm, $f=10.0$ Hz, $s=0.064$ cm, $\nu=1.14$ cm^2/s, $D=18.3$ cm, $\omega d^2/\nu=55.1$, $s/d=0.064$, $\omega s^2/\nu=0.225$, $D/d=18.3$, $t_e=60$ s.

Photographs in Fig. 8 show the steady streaming at four different values of s/d at a moderate value of $\omega d^2/\nu$. The flow pattern is considerably complicated at small s/d. The inner streaming close to the obtuse edge is greater than that close to the cuspidal edge. Here, the velocities of the outer streaming were measured at $x=\pm 3d$ on the x-axis in order to examine the velocity field quantitatively, where u_1 is the velocity at $x=+3d$ and takes always the positive value, and u_2 is that at $x=-3d$ and takes the negative value. The dimensionless values of them at two different values of $\omega d^2/\nu$ are shown in Fig. 9. On the other hand, the velocities along the x-axis calculated from the theory of Tamada *et al.* are shown in Fig. 10. It indicates that if the unidirectional flow component is induced, the absolute value of u_2 is considerably larger than u_1. In the experimental results, however, $|u_2|$ is evidently smaller than $|u_1|$, as seen in Fig. 9. After all, we can get no clear evidence of the existence of the unidirectional flow.

Now, the difference in the magnitude between $|u_1|$ and $|u_2|$ shown in Fig. 9 will not indicate the existence of the unidirectional flow with the positive value. As the transverse distance between the two vortex centers of the outer circulatory streaming on the negative side of the x-axis is larger than that on the positive side, as seen in Fig. 8(d), the total momen-

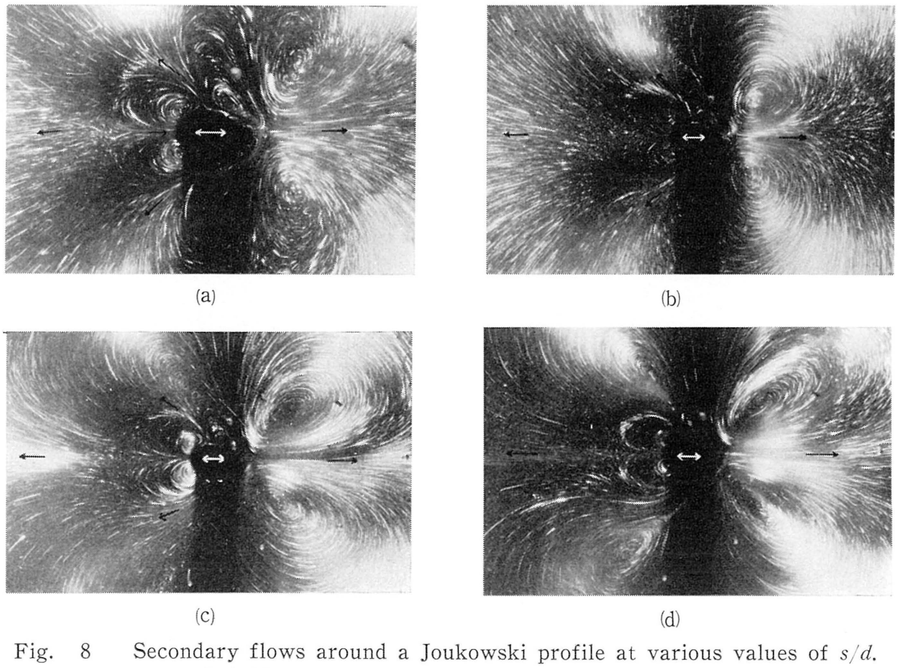

Fig. 8 Secondary flows around a Joukowski profile at various values of s/d.
$d=1.00$ cm, $f=69.9$ Hz, $\nu=2.13$ cm²/s, $D=18.3$ cm,
$\omega d^2/\nu=206$, $D/d=18.3$.
(a) $s/d=0.0091$, $\omega s^2/\nu=0.0171$, $t_e=120$ s,
(b) $s/d=0.0131$, $\omega s^2/\nu=0.0354$, $t_e=120$ s,
(c) $s/d=0.0251$, $\omega s^2/\nu=0.130$, $t_e=120$ s,
(d) $s/d=0.0457$, $\omega s^2/\nu=0.430$, $t_e=60$ s.

tum flux toward both directions may be equal to each other.

A photograph in Fig. 11 shows the steady streaming at a large value of $\omega d^2/\nu$. It is evident from the photograph that the greater part of the flow field is occupied by the outer circulatory streaming and there is little difference in length of the loci of particles on both sides of the x-axis. There is no evidence to demonstrate the existence of the unidirectional flow.

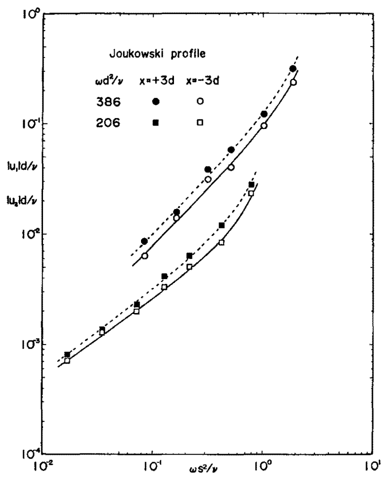

Fig. 9 Relationships among $|u_1|d/\nu$, $|u_2|d/\nu$ and $\omega s^2/\nu$ at $x=\pm 3\,d$.
$D/d=18.3$.

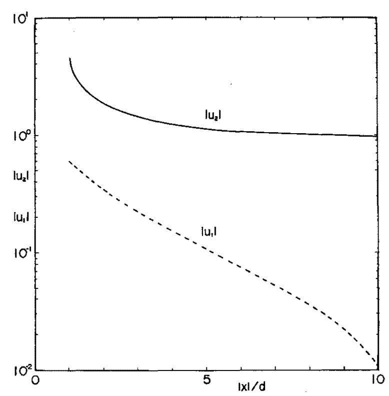

Fig. 10 Theoretical velocity values calculated from eq. (29) in ref. (8). The value u_1 indicates the velocity on the positive x-axis and all values are positive, and u_2 the velocity on the negative x-axis and all are negative.

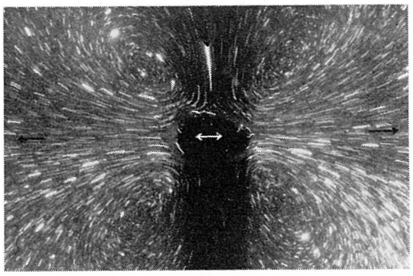

Fig. 11 Secondary flow by an oscillating Joukowski profile.
$d=1.00$ cm, $f=70.1$ Hz, $s=0.0052$ cm, $\nu=0.33$ cm^2/s, $D=18.3$ cm, $\omega d^2/\nu=1334$, $s/d=0.0052$, $\omega s^2/\nu=0.0361$, $D/d=18.3$, $t_e=60$ s.

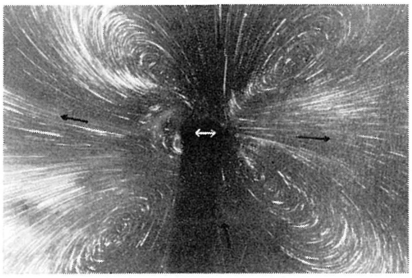

Fig. 12 Secondary flow in a large container.
$d=1.00$ cm, $f=80.0$ Hz, $s=0.020$ cm, $\nu=1.75$ cm^2/s, $\omega d^2/\nu=287$, $s/d=0.020$, $\omega s^2/\nu=0.115$, $t_e=60$ s, 40 cm $\times$ 60 cm container.

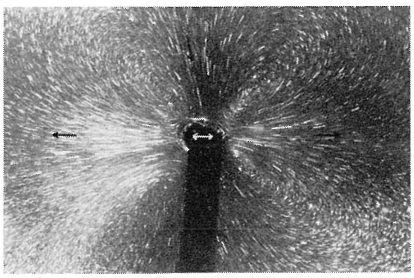

Fig. 13 Secondary flow in a large container.
$d=1.00$ cm, $f=80.0$ Hz, $s=0.0046$ cm, $\nu=0.85$ cm^2/s, $\omega d^2/\nu=591$, $s/d=0.0046$, $\omega s^2/\nu=0.0125$, $t_e=90$ s, 40 cm $\times$ 60 cm container.

The experiments mentioned above were carried out in the container of the fluid of 18.3 cm in diameter. In the next place, a large container of 40×60 cm in side lengths was used instead of the former. Two examples of the photographs of flows are shown in Figs. 12 and 13. In both cases, it will be seen that the inner circulatory streaming and the outer are induced around the cylinder and there exists no unidirectional flow component.

Moreover, experiments were carried out using a container with a different setup. Figure 14 shows the section of the container equipped with double-return channels. If a unidirectional flow is induced substantially, it may be observed more easily in this container. An example of the photograph of the flow is shown in Fig. 15. The flow velocities measured at $x=\pm3d$ on the x-axis are shown in Fig. 16 at two large values of $\omega d^2/\nu$.

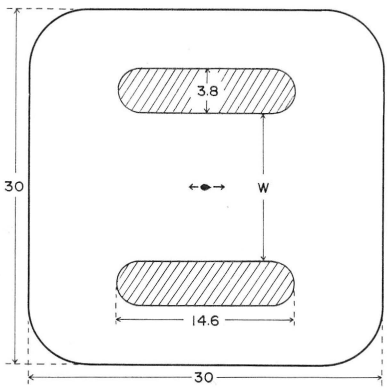

Fig. 14 Section of a container with double-return channels. All the dimensions are in cm.

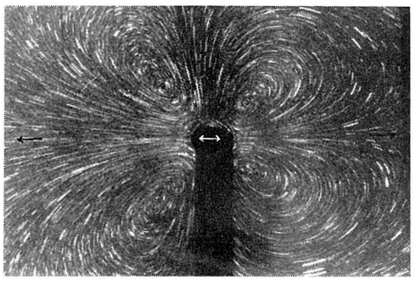

Fig. 15 Secondary flow in a container with double-return channels. $d=1.00$ cm, $f=40.0$ Hz, $s=0.017$ cm, $\nu=0.26$ cm^2/s, $\omega d^2/\nu=966$, $s/d=0.017$, $\omega s^2/\nu=0.279$, $t_e=120$ s, $w=11.0$ cm.

Figure 16 shows that the two values of $|u_1|$ and $|u_2|$ are almost equal to each other for all $\omega s^2/\nu$ and the relationship between them is different from that predicted by Tamada *et al.* shown in Fig. 10.

As mentioned above, after all, we can get no clear evidence to demonstrate the existence of the unidirectional flow in all combinations of $\omega d^2/\nu$, $\omega s^2/\nu$ and containers of the fluid.

Flow patterns of the circulatory streaming induced by a Joukowski profile are classified into three types as shown schematically in Fig. 17. The range that each type of flow appears is shown on the basis of $\omega d^2/\nu$ and $\omega s^2/\nu$ in Fig. 18.

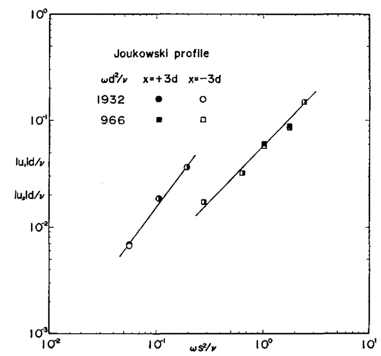

Fig. 16 Relationships among $|u_1|d/\nu$, $|u_2|d/\nu$ and $\omega s^2/\nu$ at $x=\pm 3d$. The container shown in Fig. 14 was used.

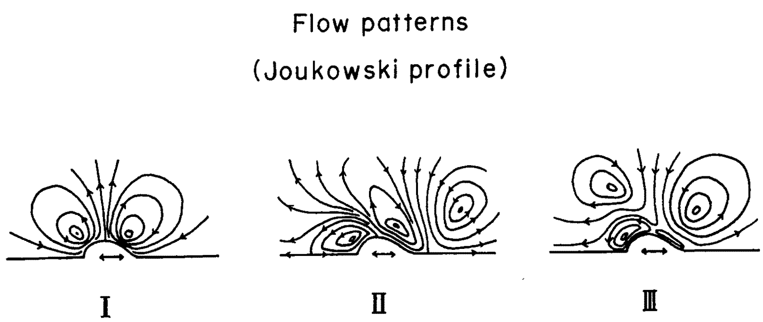

Fig. 17 Classification of flow patterns.

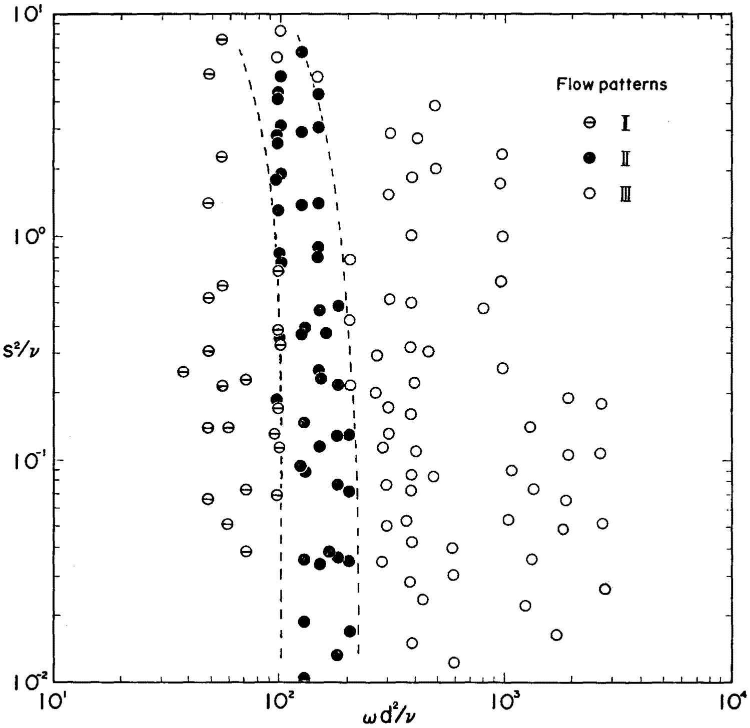

Fig. 18 Classification of flow patterns on the basis of $\omega d^2/\nu$ and $\omega s^2/\nu$.

3.3. Case of a fan-shaped profile

The model cross-section has no sharp edges and has a more pronounced asymmetry than the Joukowski profile, as shown in Fig. 19. An example of the photograph of the flow is shown in Fig. 20. The outer streaming forms four circulatory flows, and the unidirectional flow component is not observed in this case, also.

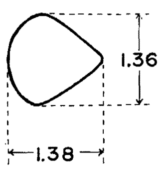

Fig. 19 A fan-shaped profile.

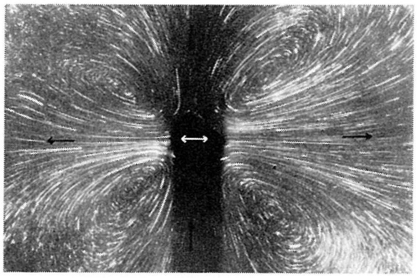

Fig. 20 Secondary flow by an oscillating fan-shaped profile. $d=1.38$ cm, $f=20.0$ Hz, $s=0.0514$ cm, $\nu=0.056$ cm^2/s, $\omega d^2/\nu=4270$, $s/d=0.0372$, $\omega s^2/\nu=5.92$, $t_e=30$ s, 30 cm$\times$30 cm container.

4. Conclusion

An experimental investigation was made as to whether or not the secondary flow field involves a unidirectional flow component besides the circulatory streaming, when a cylinder with an asymmetric cross-section performs the sinusoidal oscillations. Experiments were carried out using several cylinders with a triangular, Joukowski and fan-shaped profiles and several containers of the fluid over the wide range of physical parameters $\omega d^2/\nu$, $\omega s^2/\nu$ and s/d. No evidence could be found of the existence of a unidirectional flow. The flow field of the steady streaming is asymmetric with respect to the same axis as the cylinder is asymmetric. When the Joukowski profile oscillates sinusoidally, the distinctive feature appears in the flow patterns, which may be classified into three types depending on the values of $\omega d^2/\nu$.

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References

1) Carrière, Z. : J. Phys. et radium **6, 10** (1929) 198.
2) Andrade, E. N. DA C. : Proc. Roy. Soc. L. **A 134** (1931) 445.
3) Schlichting, H. : Z. Phys. **33** (1932) 327.
4) Holtsmark, J., Johnsen, I., Sikkeland, T. and Skavlem, S. : J. Acoust. Soc. Am. **26** (1954) 26.
5) Raney, W. P., Corelli, J. C. and Westervelt, P. J. : J. Acoust. Soc. Am. **26** (1954) 1006.
6) Tatsuno, M. : J. Phys. Soc. Jpn. **35** (1973) 915.
7) Miyagi, T. and Nakahashi, K. : J. Phys. Soc. Jpn. **39** (1975) 519.
8) Tamada, K. and Miyagi, T. : J. Phys. Soc. Jpn. **37** (1974) 249.
9) Tatsuno, M. : J. Phys. Soc. Jpn. **38** (1975) 257.

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