EXPERIMENTAL INVESTIGATION

OF THE WAKE OF AN OSCILLATING CYLINDER

A Thesis

Presented to

the Faculty of the Department of Mechanical Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

---

by

Andre Joseph Heinzer

January, 1968

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ABSTRACT

The wake of a circular cylinder oscillating with simple-harmonic motion was investigated experimentally. Oscillations with amplitudes ranging from 0.4 to 4.8 cylinder diameters and frequencies smaller than 60 cycles per minute were considered. Flow visualization and photographic techniques were used to obtain pictorial sequences of the flow phenomena. The existing experimental results have been reviewed. The experimental apparatus and the flow visualization technique used for this investigation are described.

Photographic results are presented for various oscillatory conditions. The results indicate that the dimensions and characteristics of the cylinder wake depend strongly on the relative amplitude of the oscillatory motion. The frequency of oscillation, on the other hand, has very little effect on this same wake.

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CHAPTER I

INTRODUCTION

The steady uniform flow of a fluid around a circular cylinder is characterized by the presence of vortices in the wake of the cylinder. Morkovin[1]*, Lagerstrom[2] and Taneda[3] give excellent reviews of the phenomena associated with steady flow around a circular cylinder.

For very small Reynolds numbers R (R is UD/ν, where D is the diameter of the cylinder, U is the velocity far removed from the cylinder and ν is the kinematic viscosity of the fluid), the fluid flows in a smooth regular fashion around the cylinder. At about R equal to 5, separation occurs at the rear stagnation point and two tiny vortices appear at that point. As the Reynolds number is increased, these two symmetrical eddies grow and become more and more elongated in the flow direction but they adhere stably on the cylinder until a Reynolds number of about 45 is reached. There is a vortex sheet which appears as a straight line connecting the ends of the two vortices and extending downstream. This vortex sheet is called the trail. Thus, at Reynolds numbers between 5 and 45, the wake behind a circular cylinder consists of two parts, the twin-vortices and the trail.

At Reynolds numbers greater than 35, a remarkable

*Numbers in brackets refer to references.

phenomenon is observed. Small concentrated vortices appear in the outboard boundaries of the twin-vortices, move downstream along the boundary line until they reach the rear end of the twin-vortices, tremble there for a short time and die out. This small irregular motion however does not produce any effect on the flow behind the twin-vortices until a Reynolds number of about 45 is reached.

The trail, on the other hand, begins to oscillate sinusoidally some distance downstream at R equal to about 30, and its amplitude becomes larger as the Reynolds number is increased. When a Reynolds number of about 45 is reached the oscillation of the trail begins to exert an influence upon the twin-vortices. At Reynolds numbers above 45, the small concentrated vortices are elongated along the trail and shed alternately from each of the vortices with a very definite frequency and pass downstream, where they arrange themselves in a configuration known as a Karman vortex street. But a large portion of the twin-vortices is still stably attached to the cylinder. The size of the small concentrated vortices which travel downstream increases with the Reynolds number until for Reynolds numbers above 150 a large portion of the twin-vortices are shed alternately. At the same time turbulence appears for the first time in the wake. The turbulence is intermittent at first, some of the vortices which are shed are purely viscous, while others contain turbulent fluid. By about R equal to 300, the wake turbulence is well established.

The characteristics of the vortex formation and shedding as they appear above R equal to 45 remain essentially unchanged up to a Reynolds number of about 10^5. Below this Reynolds number the boundary layer is laminar and separates on the front of the cylinder at about 80° from the forward stagnation point. Between 10^4 to 10^5, a point of turbulence transition occurs in the shear layer just downstream of the separation point and, as the Reynolds number is increased past 10^5, the transition point moves ahead of the separation point. The boundary layer becomes turbulent and a new equilibrium is established with the separation point on the back of the cylinder at 120° to 140° from the stagnation point. Vortices are still formed and shed periodically but the shedding frequency is much higher than with separation in front.

When a cylinder is started from rest, the same succession of flow patterns takes place in its wake, however the Reynolds number at which separation, oscillation of the trail, asymmetry of the twin-vortices and the Karman vortex street successively make their appearance is much higher than for the case of steady state flow. This behavior is true for both an impulsive start from rest and for a uniform acceleration from rest. Sarpkaya[4] performed an investigation of the impulsive start of a circular cylinder to a constant velocity and found that the wake developed gradually until a new phenomenon took place. The symmetrical vortices that formed at the start of the motion began to oscillate back and forth, mainly in the direction of the ambient flow, and grew and diminished in intensity prior to the actual shedding of the first vortex and subsequent formation of a vortex street. Sarpkaya and Garrison[5] analysed the strength, growth, and motion of the vortices behind a circular cylinder in a two-dimensional constant-acceleration flow from rest. Again, it was shown that the wake region of the cylinder developed gradually. As the twin-vortices became asymmetric, one of the vortices began to grow rapidly while the other vortex continued to grow only at a much slower rate. The bigger vortex was then shed, starting the alternate shedding process. Sarpkaya and Garrison showed also that, while the unsteady flow which started from rest with uniform acceleration is still nearly of potential nature, the steady flow at the corresponding Reynolds number has a fully-developed wake. It is seen, therefore, that one cannot compare the characteristics of the two types of flow, steady and unsteady, solely on the basis of Reynolds number.

The flow pattern around a cylinder submitted to a periodic motion depends on the amplitude and frequency of oscillation. The present investigation has been conducted in order to obtain a better understanding of the flow phenomena occuring around a circular cylinder when the cylinder, or the fluid around the cylinder, is submitted to a simple-harmonic motion. The main goal was to obtain a visual representation of the flow pattern around the cylinder. This representation could best be achieved in the form of pictorial sequences.

The flow pattern around the circular columns supporting off-shore drilling platforms is identical to the flow patterns investigated here since these columns are submitted to the periodic motion of the waves. The information obtained here could, therefore, be of use in understanding the effect of the wave motion on the supporting legs. This information could also be of help in determining the forces acting on these columns and, ultimately, could affect the design of these columns.

Literature Survey

A review of the literature reveals that many experimental investigations have been performed for steady-state conditions and for models accelerated from rest while very little experimental work has been conducted on models subjected to a periodic motion.

In 1931, Schlichting[6] presented an analytical solution to the problem of an oscillating circular cylinder and its attached boundary layer, but valid only for small amplitudes of oscillation, that is, for amplitudes smaller than the cylinder diameter. To test his solution, Schlichting conducted an experiment using a circular cylinder with a radius R of 4 cm, which was oscillating with a circular frequency ω of 3.1 sec^{-1} and with an amplitude A of 0.9 cm. The amplitude was defined by Schlichting to be one half of the distance between the extreme positions of oscillation. Due to this small amplitude of oscillation, no separation occurred. In order to render the stream-lines visible, small particles of tinfoil were spread on the water surface.

Photographs of the flow pattern showed that an oscillating boundary layer formed around the cylinder and that a steady circulation slowly set in with fresh liquid drawn in to the cylinder at right angles to the direction of oscillation. The path followed by the particles after many oscillations can be seen in Figure 1. A particle starting from point A moves slowly toward the cylinder and as the distance to the cylinder decreases, the velocity of the particle increases. The distance BC along the quarter of the cylinder periphery is covered relatively rapidly and with diminishing velocity the particle moves away from the cylinder toward point D.

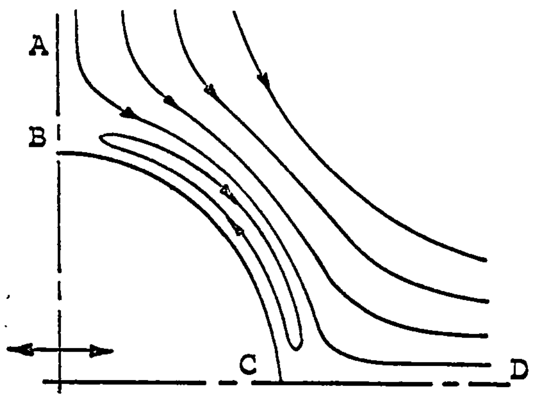


Figure 1. Pattern of Stream-lines of Secondary Motion

Similar photographs were published by Andrade [7] who investigated the circulation caused by the vibration of air around a circular cylinder placed in a tube. The oscillations were induced by standing waves and the secondary flow was made visible by the addition of smoke.

In 1958, Keulegan and Carpenter[8] conducted an investigation which was directed toward determining the inertia and drag coefficients of cylinders and plates in simple-sinusoidal currents. The test apparatus was a rectangular basin in which a standing wave motion was established. The cylinders were fixed horizontally below the water surface. The flow patterns around the model for varying conditions were examined because it was felt that these flow patterns may have had a bearing on the fact that the nature of the forces during a cycle is significantly affected by the period parameter UT/D, where U is the maximum intensity of the sinusoidal current, T is the period of the wave and D is the diameter of the cylinder. Values of the period parameter UT/D between 2.7 and 120 were considered. The flow patterns were made visible by the introduction of a jet of colored liquid and were recorded by a motion-picture camera. Several photographs corresponding to different period parameters were presented. For small period parameters up to about 4, no separation occurred and the liquid passed around the cylinder in a smooth regular manner. As the period parameter was increased, separation at the top of the cylinder occurred as can be seen in the photographs corresponding to a period parameter of 10 and 17. A completely different picture was obtained for a period parameter of 110 where one is confronted with the regular Karman vortices, the eddies separating from above and below.

Very recently Baird[9] investigated the flow conditions around a rigid cylinder fixed in a liquid which oscillated transversely with respect to the cylinder axis. Baird's main interest being heat transfer, relatively low frequencies and high amplitudes of oscillation were used as these are typical of the pulsators which are available for large scale industrial application. Baird used brass cylinders of 1/2 inch and 1 inch in diameter; each cylinder was 1/2 inch long and was mounted in a plexiglass test section 4 inches wide and 1/2 inch thick. Liquid pulsations were generated by an air driven pulsator which produced frequencies of 1 to 2.5 cycles per second and amplitudes up to 4 cm. The flow patterns were observed using fine aluminum powder as a tracer, with back illumination of the test section. Baird characterized the oscillations by means of the maximum Reynolds number with respect to the cylinder. At very low Reynolds numbers the liquid was oscillating in a smooth regular manner about the cylinder and no streaming motion could be detected by the unaided eye. At higher Reynolds numbers, separation occured for part of the cycle and viscous vortex pairs were seen to detach from either side of the cylinder in the direction of oscillation. At very high Reynolds numbers the vortex shedding became asymmetrical and turbulence extended for a considerable distance around the cylinder. Baird published photographs depicting these last two flow conditions but, unfortunately, they are very unclear.

In summary, no presentation was found which visualized properly the flow phenomena around an oscillating circular cylinder extending perpendicularly into a fluid, especially not for the range of investigation proposed for this work.

In order to visualize the flow phenomena occurring around a circular cylinder when the cylinder or the fluid around it is submitted to a periodic oscillatory motion an experimental apparatus was designed. Since the case of a cylinder oscillating in a fluid at rest is kinematically similar to a fluid oscillating uniformly about a cylinder at rest, either of the two cases could be used in conducting the investigation. It was found easier to obtain the desired flow conditions in oscillating the cylinder in a fluid at rest than in moving the fluid periodically about a fixed cylinder.

CHAPTER II

EXPERIMENTAL APPARATUS

In order to visualize the flow around an oscillating cylinder, an experimental apparatus was built. As can be seen in Figure 2, the test stand was composed of three different parts: (1) the water tank, (2) the mechanical drive producing the oscillatory motion, and (3) the oscillating frame supporting the model and the camera.

Water Tank

The experiments were conducted in a water tank made of wood and with the following dimensions: 2 feet wide by 3 feet long by 1.5 feet deep (see Figure 3). The width of 2 feet was chosen in order to keep D/H, the ratio of the cylinder diameter to the tank width, smaller than 0.05. For D/H less than 0.05, the effect of the confining walls of the tank on the stability of the wake of a circular cylinder can be neglected. The depth of 1.5 feet allowed the model to be immersed more than 1 foot; in this way end effects could be neglected and the motion at the water surface could be considered to be two-dimensional. The tank was fitted with an overflow cutout extending nearly over the whole width of the end wall. A drain valve was placed at the bottom of the tank. A scale was placed slightly above the water surface allowing the position of the model to be determined at any time.

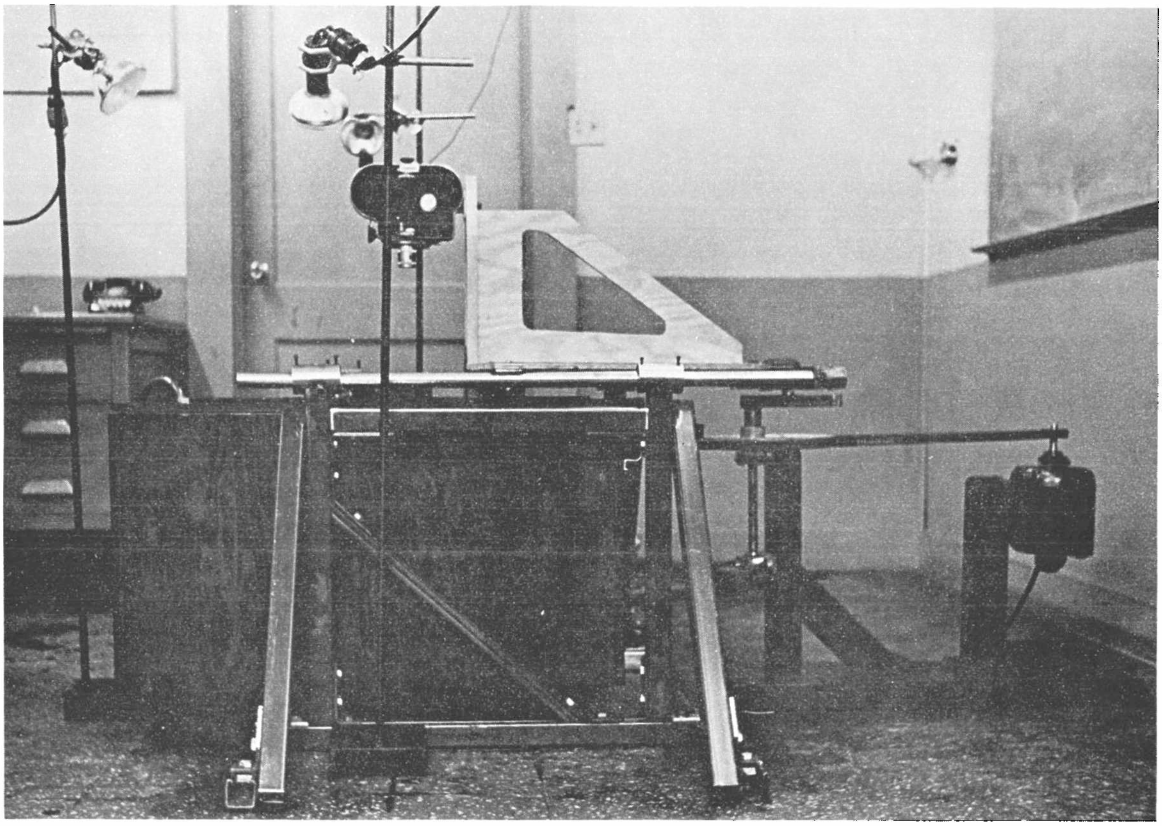


Figure 2. Experimental Apparatus

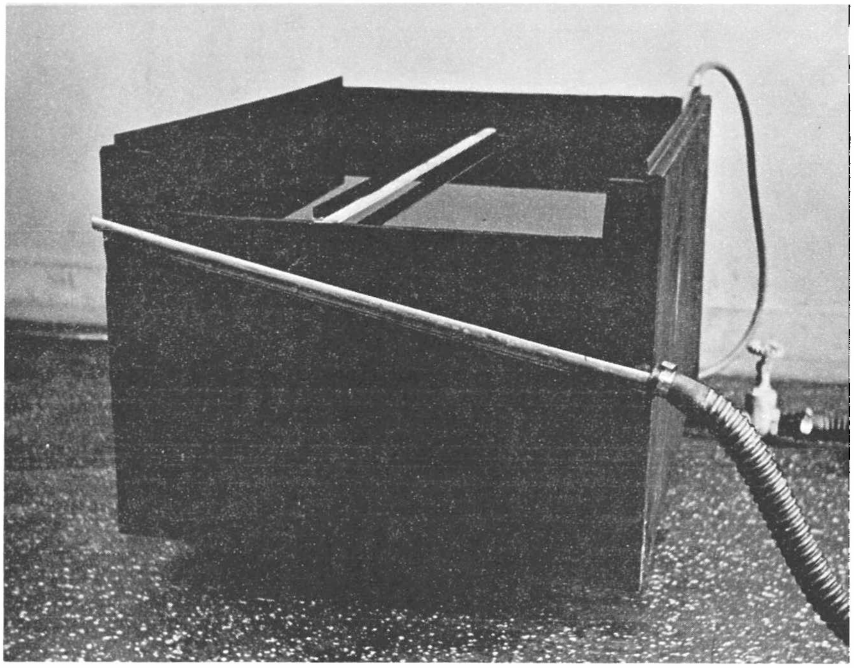


Figure 3. Water Tank

Mechanical Drive

The mechanical drive can be seen in Figure 4. In order to convert a rotary motion into a reciprocating motion, a Scotch yoke was built. As the crank rotates about its center, a sliding shoe oscillates in the yoke and a reciprocating motion of the system results. This motion is a pure simple-harmonic motion. The amplitude of the motion could be varied continuously from 0 to 6 inches by altering the position of the crank which was held by a special nut in a milled slot. The crankshaft was belt-driven from a DC variable speed electromotor with a power of 1/4 hp. The pulleys used were producing an rpm reduction between the motor and the crank-shaft of 6 to 1. The motor could be driven at any speed between 90 rpm and 2250 rpm with help of a variable-speed motor control.

The crank mechanism support and the electromotor support were welded and bolted respectively on a heavy steel plate. This base plate was supported by three setting-screws which permitted the crankshaft to be aligned perfectly to the yoke. Small hard rubber plates were placed between the floor and the setting-screws to absorb vibrations. In order to maintain the vibration level of the model at a minimum, the mechanical drive unit was comletely separated from the other parts of the apparatus. The only connection was the crank shoe sliding in the yoke and transmitting the driving force from the crank to the oscillating frame (see Figure 5).

Special care was given to the design of this sliding

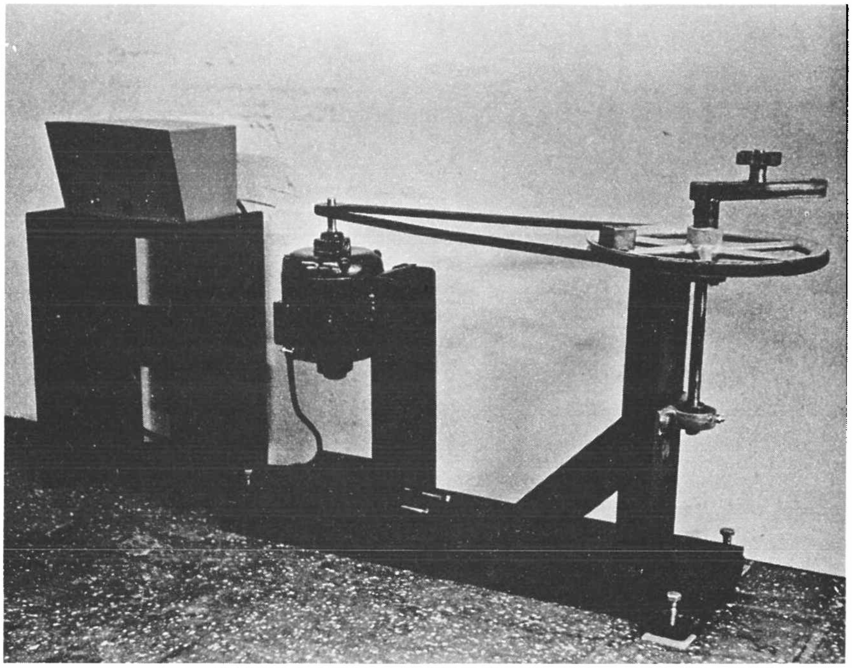


Figure 4. Mechanical Drive

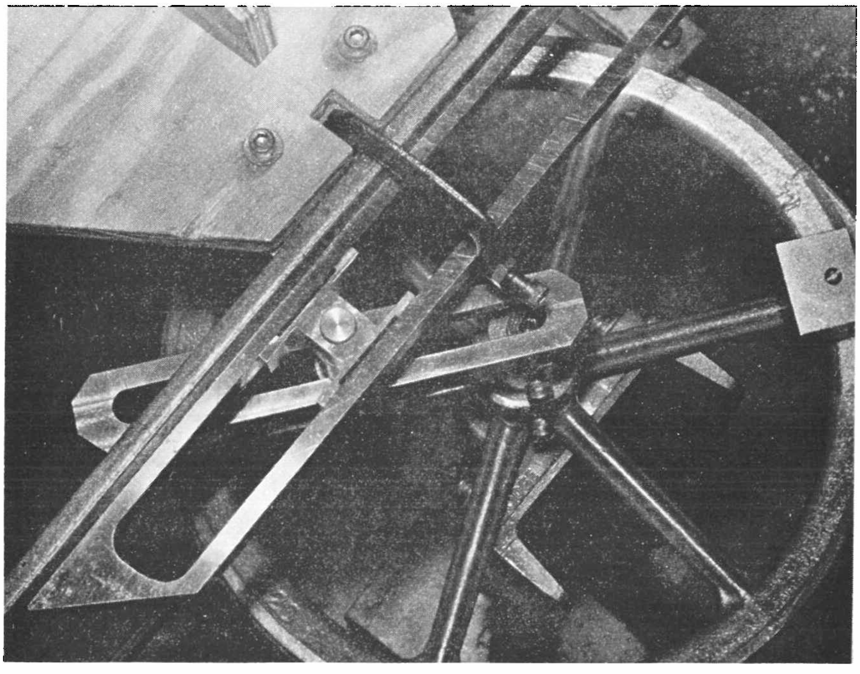


Figure 5. Scotch Yoke

crank shoe in order to avoid shocks on the oscillating frame at the points of inversion of the oscillatory motion. For this reason, the shoe which was made of bronze was spring loaded slightly in order to maintain contact at any time with both sides of the guiding slot milled in the yoke. In this manner the passage through the middle of the yoke occured smoothly.

Oscillating Frame and Support

The oscillating frame and its support can be seen in Figure 6. This frame was composed of two parallel 1 inch diameter by 3 feet long polished steel tubes which were held rigidly together at one end by a steel bar which was part of the yoke. The oscillating frame was attached to the assembly by means of four bronze bearings which guided the oscillatory motion. These bearings were held with the help of six setting-screws each, inside four short cylinders welded on top of a very rigid frame made of Unistrut tubes. The setting-screws were used to align perfectly the four bearings with the sliding tubes. Again this frame had no contact with the water tank or the mechanical drive.

Bolted at three points on the oscillating frame was a triangular frame supporting the model and the camera. In order to damp vibrations, this triangular frame was made of wood and openings were cut out to reduce the mass of the oscillating parts. The triangular form of the wooden frame was chosen in order to reinforce the sliding frame formed of the two tubes and the yoke. The central part of this wooden frame also connected the yoke directly to the camera. This allowed the driving force to be transmitted directly from its point of application to the point of the greatest moving mass. Thus, the whole oscillating frame slid smoothly even when the driving force acted at a point as much as 1 foot out of center.

The camera was mounted directly above the model and was therefore moving with the model. Five camera positions were possible allowing the distance between the water surface and the camera lens to be varied from 9 to 15 inches (see Figure 7).

<u>General Comments</u>

The combination of the mechanical drive with the oscillating frame worked smoothly at most speeds. At frequencies below 15 cycles per minute, vibrations were present which disturbed the flow pattern around the model. Different factors were responsible for this behavior, the main reason being the fluctuation in rpm of the electromotor at very low speeds. The rpm fluctuation was produced by the uneven friction of the brushes on the collector of the motor. A very slight shock could be felt at the end of each stroke. The shock could have been generated by the inversion of the friction force on the sliding tubes at that point. The shock was, however, small enough to remain undetected at the model on the water surface.

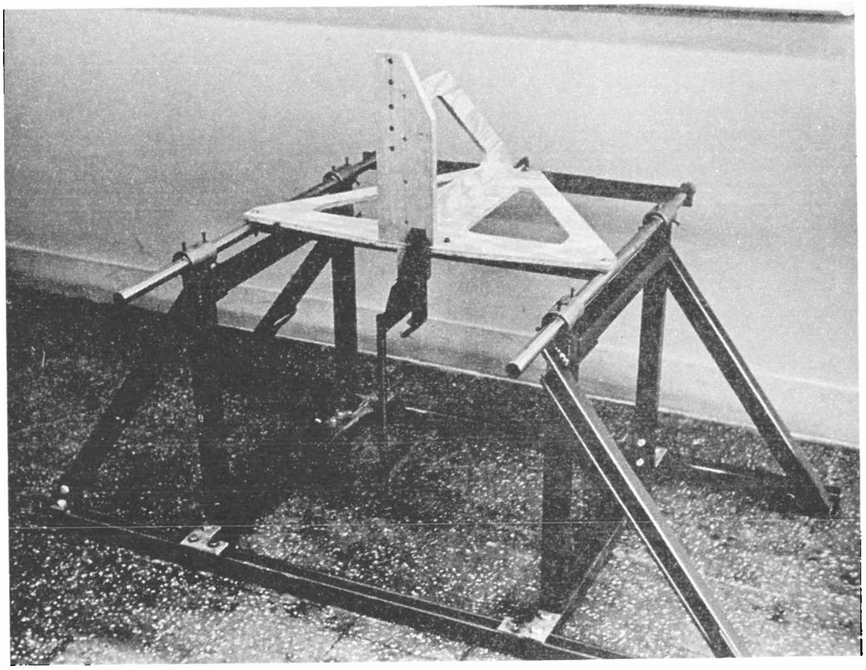


Figure 6. Oscillating Frame

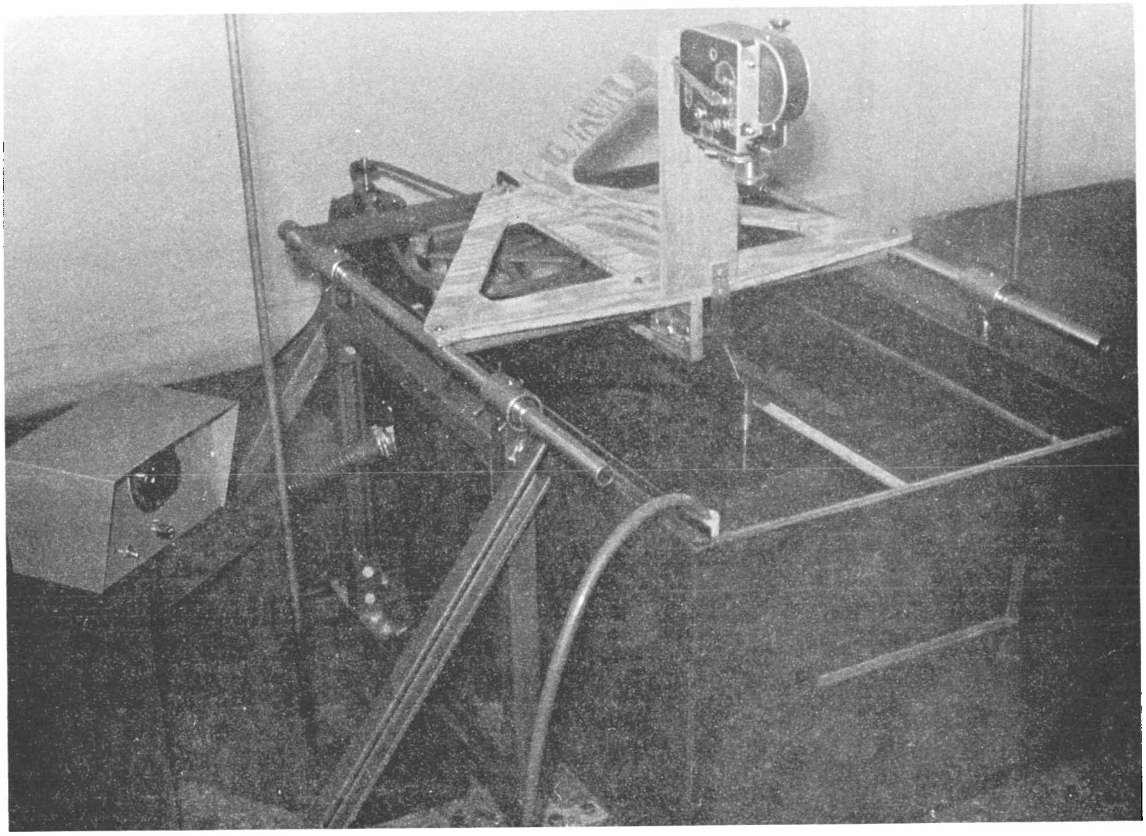


Figure 7. Overall View

CHAPTER III

FLOW VISUALIZATION

Tracer Elements

In order to render the two-dimensional flow pattern around a circular cylinder visible, tracer elements had to be used. Thus, the paths of the individual tracer elements described the flow field about the model. The tracers employed in the flow visualization had to have following characteristics: They had to be highly reflective in order to show up well under lighting, they had to give a good contrast with the water, and they had to be small enough to stay on the water surface and give a true indication of the actual physical flow phenomena. Aluminum powder was found to satisfy the above requirements when sprinkled on the water surface. Several brands of aluminum powder were evaluated and the powder which was found to be most successful was "Alcoa Aluminum Standard Unpolished Powder No 606", which is a fine flaked powder. This particular brand, unlike most aluminum powders, is manufactured with only a small amount of aluminum stereate. The stereate, which is added to most powders, acts as a lubricant and polisher and was found to contaminate the water surface. Care had to be taken that no capillary effect came into play. This requirement meant keeping the surface of the water meticulously clean. Even the dipping of a hand or a few hours of contact with the atmosphere makes the surface useless for the purpose of flow visualization. To be certain that the condition of the surface was satisfactory, the following test was used: Sprinkle some aluminum powder on the water surface and then blow vertically down on it with the mouth. This spreads the aluminum particles in all directions and clears a circular area of the surface. If, after the blowing, the aluminum particles remain where they are, the surface is clean. If, however, the circle closes by itself, the surface is contaminated and has to be renewed. In order to obtain a clean surface, an overflow was used to remove the contaminated surface. Given a clean surface, the aluminum particles were found to indicate the flow pattern very satisfactorily.

To prevent the aluminum particles from running away from the model under the influence of the capillary angle between the water surface and the model, it was helpful to coat the latter with a thin layer of paraffin. By means of this procedure, it was possible to prevent the capillary action so that the fluid surface remained completely horizontal at the model. It was even possible to create a negative capillary angle by lowering the model somewhat or rising the water surface, which may be useful for showing the history of the boundary layer particles. Under the influence of a negative capillary angle, the aluminum particles were crowded around the model, and after a short time of motion it was seen clearly where these boundary layer particles had moved.

A serious disadvantage of observing the flow pattern at the surface of the fluid was that at relatively small velocities capillary waves are formed in front of the model. For water this critical velocity was found to be about 10 inches per second. A circular cylinder moving through water with a certain velocity generates approximately twice this velocity at some local points in the water so that the model could not be moved at a speed greater than about 5 inches per second if capillary waves were to be avoided. If greater velocities are desired it would be necessary to photograph the motion on a plane parallel to and beneath the surface of the water, the tracer elements being in suspension in the water and illuminated by a thin sheet of light.

Photographic Technique

Observation of the flow pattern around a moving cylinder was best achieved by a filmed history, since a photographic record of a flow will disclose many facts which cannot be obtained by visual observation. Still photography was not suitable since the flow was unsteady and therefore only a sequence of pictures could disclose the flow behavior during one or more cycles. Motion pictures were taken allowing the different sequences to be projected repeatedly on a screen, making their evaluation easier.

A 16 mm camera was used with Kodak Double-X film having an ASA rating of 200 Tungsten. Certain difficulties arose from the fact that the model was not moving at constant speed but was accelerated repeatedly from rest to its maximum speed and decelerated again to rest. Better photographic results were obtained at lower rather than at higher shutter speeds. Aperture openings and shutter speeds ranged from f 8 to f 22 and from 12 to 32 frames per second respectively depending on the frequency and amplitude of the oscillatory motion.

In order to obtain sharp contrast between the water surface and the aluminum particles, it was necessary to illuminate artificially the surface. The lighting was provided by three photospots with a power of 150 watts each, illuminating the water surface at an angle of 45 degrees. All photographs were enlarged and printed on Luminos Bromide Contrast 2 paper.

CHAPTER IV

EXPERIMENTAL INVESTIGATION

Range of Investigation

The range of the oscillations of interest to this investigation was as follows: Amplitudes ranging from 0.4 to 4.8 cylinder diameters and frequencies smaller than 60 cycles per minute.

Two polished brass cylinders of 5/8 inch and 1 inch diameter respectively were used as models. These two cylinder diameters were chosen for the following reasons: Cylinders smaller than 1/2 inch in diameter did not produce a well defined wake due to the size and repartition of the tracer particles on the water surface. On the other hand, cylinders greater than 1 inch in diameter would have required a wider water tank in order to minimize wall effects. Both cylinders extended 13 inches beneath the water surface.

Different combinations of cylinder diameter, amplitude, and frequency were investigated as can be seen in Figure 8. Several physical factors were found to limit the possible range of this investigation. The upper limit of the range of investigation was fixed by a definite combination of amplitude and frequency of oscillation producing a maximum velocity of the model of more than 5 inches per second, and thus, giving rise to capillary waves in front of the model. The lower limit of the range of investigation was set by the occurrence of small vibrations of the oscillating frame at

Cylinder Diameter, 5/8 inch

A inches	Frequency in cycles/minute 15	20	30	40	50	60	A/D
0.25				x	x	x	0.4
0.5		x	x	x	x (1)	x	0.8
0.75		x	x	x	x	x	1.2
1	x	x	x	x	x		1.6
1.5	x (7)	x	x	x			2.4
2		x (8)	x				3.2
3		x (9)					4.8

Cylinder Diameter, 1 inch

A inches	Frequency in cycles/minute 15	20	30	40	50	60	A/D
0.5		x	x	x	x	x	0.5
1	x (2)	x (3)	x	x	x (4)		1
1.5	x	x	x (5)	x			1.5
2		x (6)	x				2
3		x					3

Figure 8. Combinations of Frequencies and Amplitudes of Oscillation Investigated. (The numbers correspond to the sequences presented).

frequencies of 15 cycles per minute or less.

Test Procedure

The amplitude of the oscillation was set with help of the scale mounted on the water tank. Before each run the desired frequency of oscillation was set by means of the variable-speed motor control and checked over a lapse of time of one minute.

Before each run the water surface was reconditioned in the following manner: The old aluminum particles were skimmed away and the surface was made perfectly clean through the use of the overflow. After this the water surface was lowered to the desired level. The water was then left standing motionless for about 15 minutes in order to let all internal circulation die out. Shortly before a new run was made, the aluminum powder was blown on the surface of the water.

CHAPTER V

PHOTOGRAPHIC RESULTS

All the filmed sequences have been projected repeatedly on a screen for their evaluation. Several sequences representing the entire range investigated are reproduced here to show the flow pattern in the wake of an oscillating cylinder. The sequences are presented in order of increasing relative amplitude of oscillation A/D (where A is the amplitude of oscillation defined as one half of the distance between the extreme positions of the oscillating cylinder and D is the diameter of the cylinder). The parameter A/D provides the means of relating the wakes of oscillating cylinders of different diameter to each other.

Most of the sequences presented here show the first cycle of oscillation of the cylinder; one sequence shows the first cycle and a half and another sequence shows the first two cycles of oscillation. For every sequence, the number of the run, the number of cycles shown, the relative amplitude A/D, the cylinder diameter D, the frequency of oscillation f, and the speed at which the sequence has been filmed are indicated.

The number beneath each picture refers to the number of the frame in the corresponding filmed sequence. The metallic tongue seen on the lower right hand side corner of every picture moves with the model and indicates the cylinder position. The double line on the scale indicates the point about which the cylinder oscillates, that is, the point where the velocity of the cylinder is at a maximum during every stroke of the Scotch yoke.

Sequence 1 shows the flow field around the 5/8 inch cylinder oscillating with a relative amplitude A/D of 0.8 and a frequency of 50 cycles/minute. Sequences 2, 3 and 4 show the 1 inch cylinder oscillating at different frequencies but with the same relative amplitude of 1.0. Sequences 2 through 4 can be compared in order to determine the effect of the frequency of oscillation on the flow pattern in the wake of the cylinder. Sequences 5 and 6 show the 1 inch cylinder oscillating at frequencies of 30 and 20 cycles/minute respectively and with relative amplitudes of 1.5 and 2.0 respectively. Sequences 7, 8 and 9 show the 5/8 inch cylinder oscillating at frequencies of 15, 20 and 20 cycles/minute respectively and with relative amplitudes of 2.4, 3.2 and 4.8 respectively. The following pairs of sequences, 1 and 4, 3, 6, 8 and 9, and 2 and 7, can be compared to determine the effect on the wake of the oscillating cylinder of varying the relative amplitude at constant frequency.

For very small relative amplitudes of oscillation, separation and subsequent vortex formation do not take place in the wake of the cylinder. Still pictures do not, therefore, show satisfactorily the flow pattern about the oscillating cylinder. For this reason, no sequence corresponding to this range of amplitude of oscillation has been included in this presentation.

SEQUENCE NUMBER 1

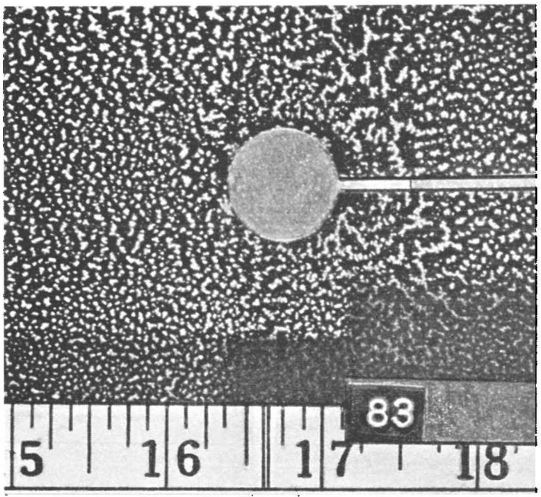
Run 83 --- 2 cycles

A/D = 0.8

D = 5/8 inch

f = 50 cycles/minute

Camera speed = 24 frames/second



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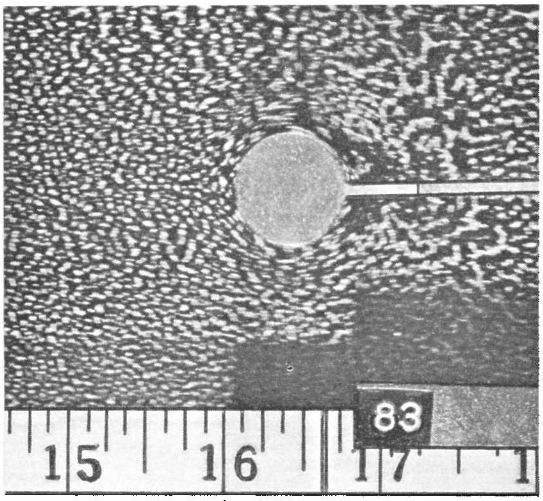

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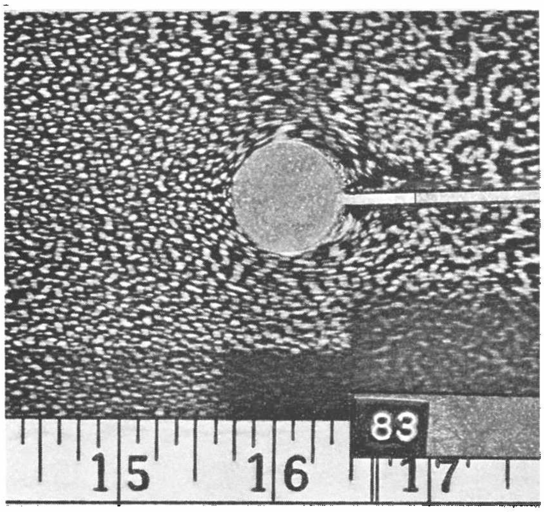

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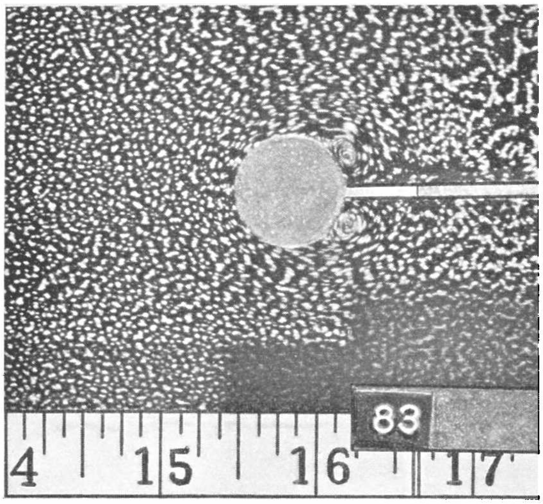

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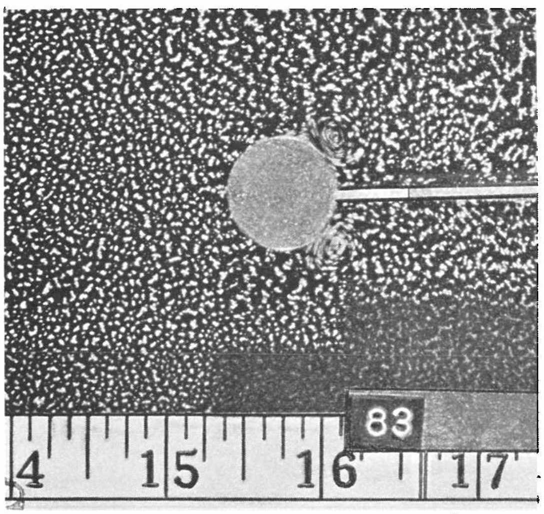

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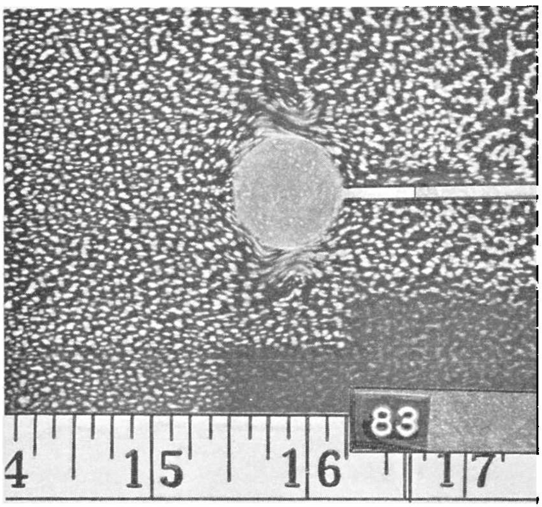

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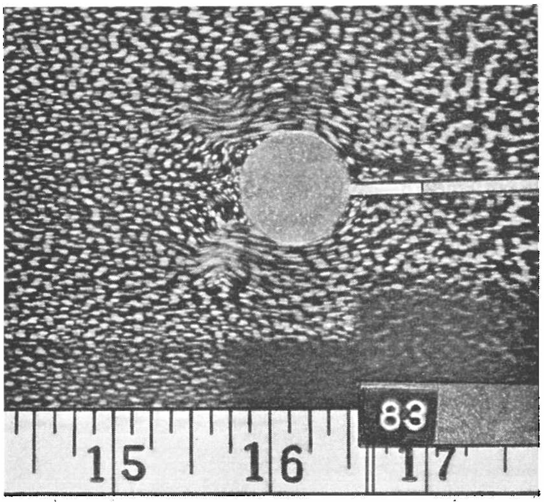

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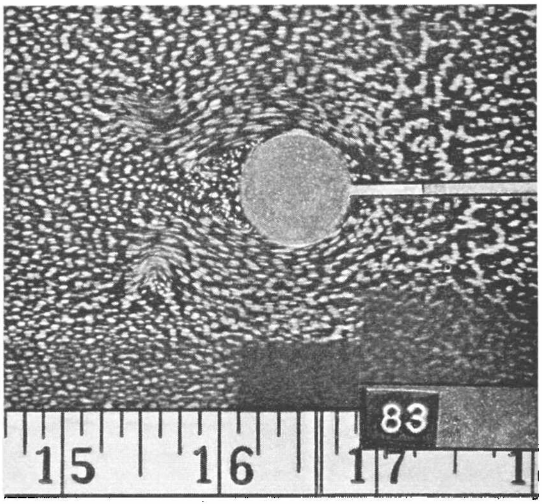

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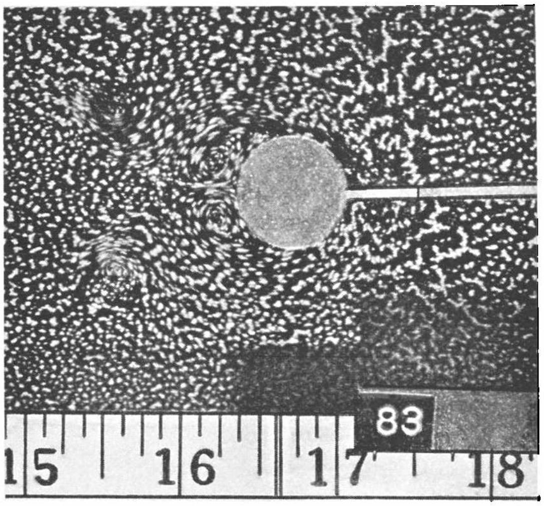

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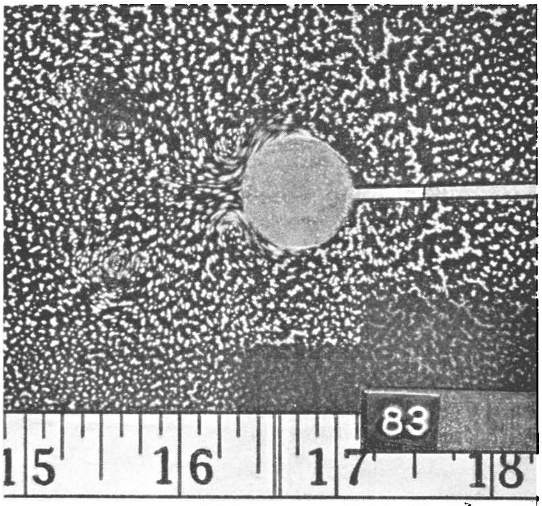

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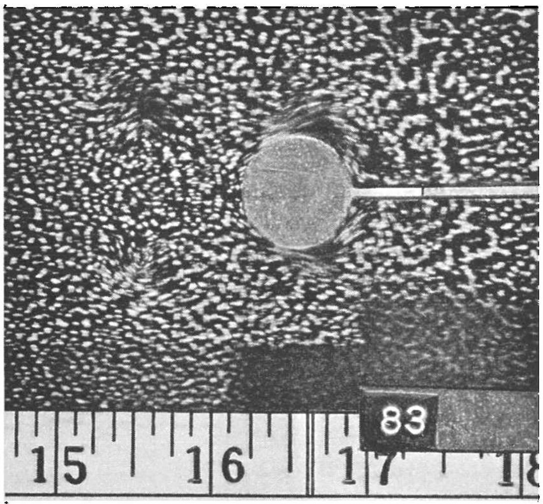

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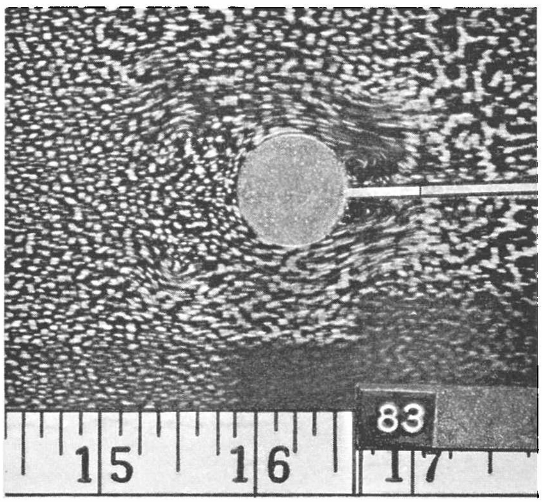

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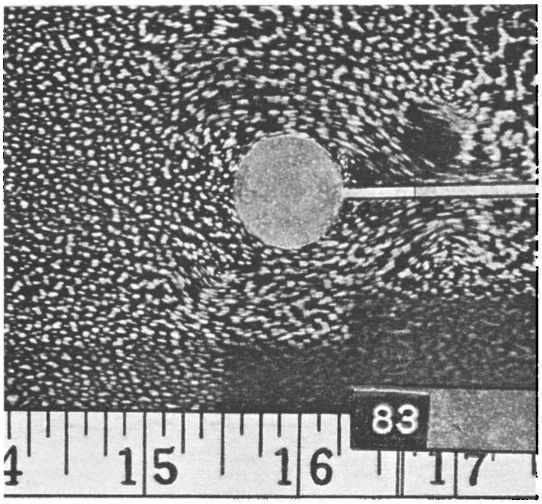

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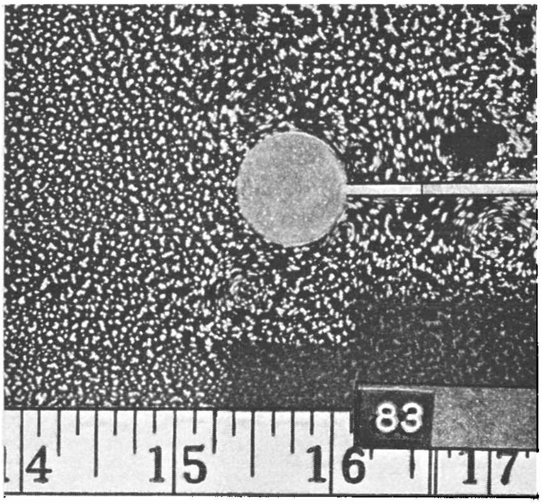

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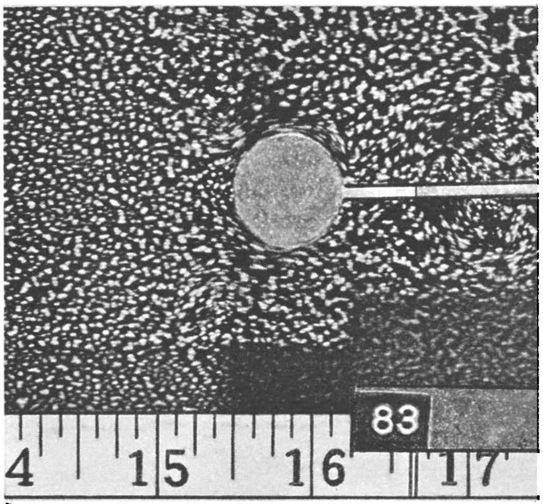

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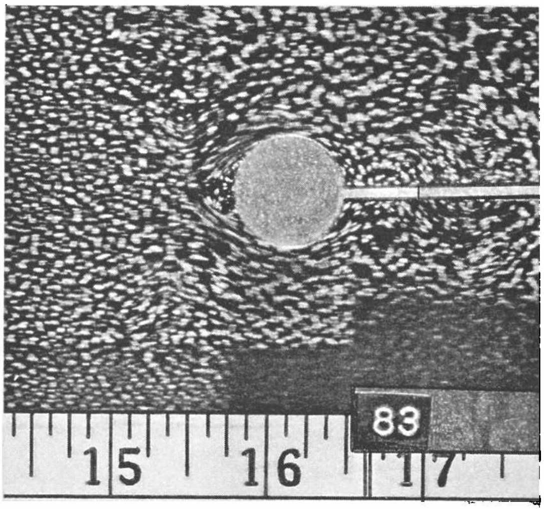

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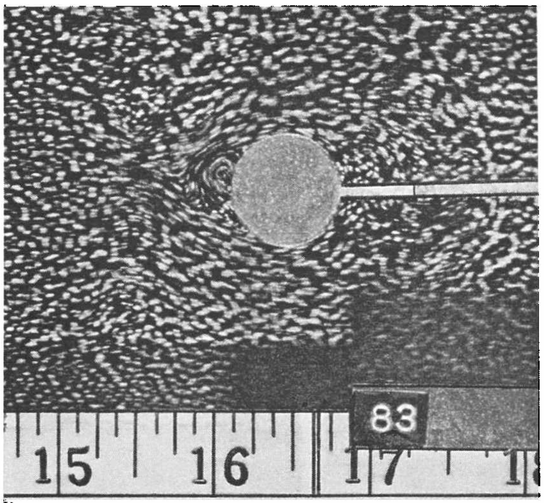

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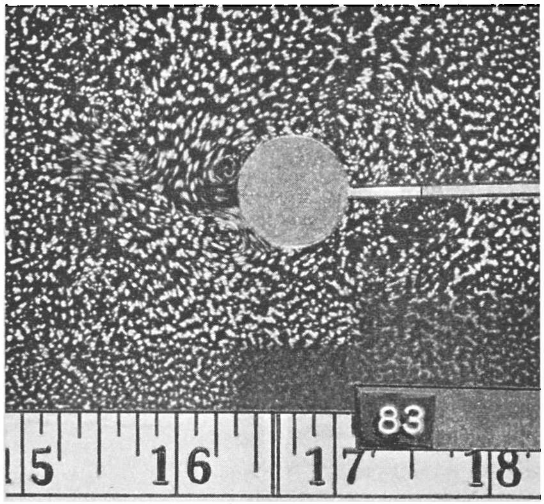


55

SEQUENCE NUMBER 2

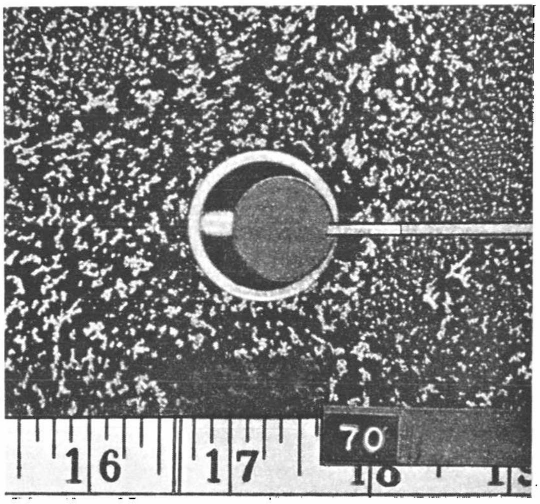
Run 70 --- 1 cycle

$A/D = 1$

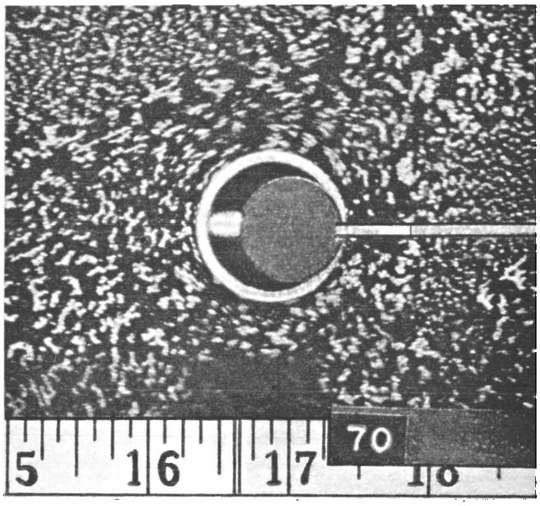
$D = 1$ inch

$f = 15$ cycles/minute

Camera speed = 12 frames/second



1



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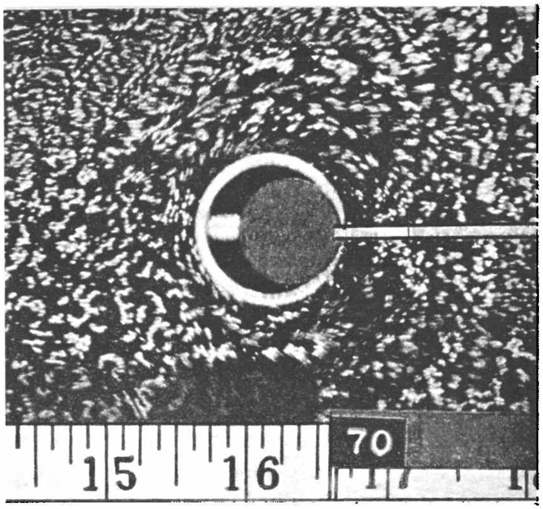

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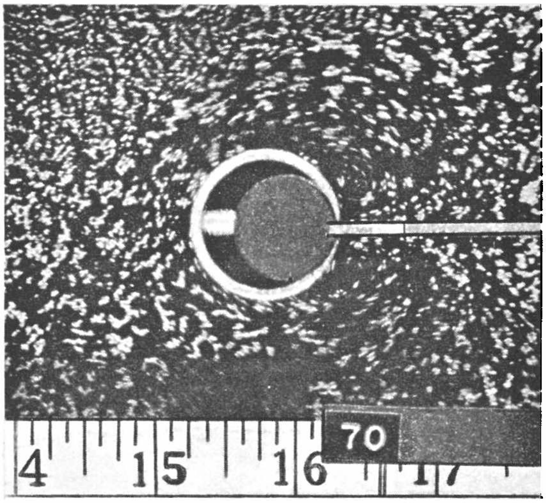

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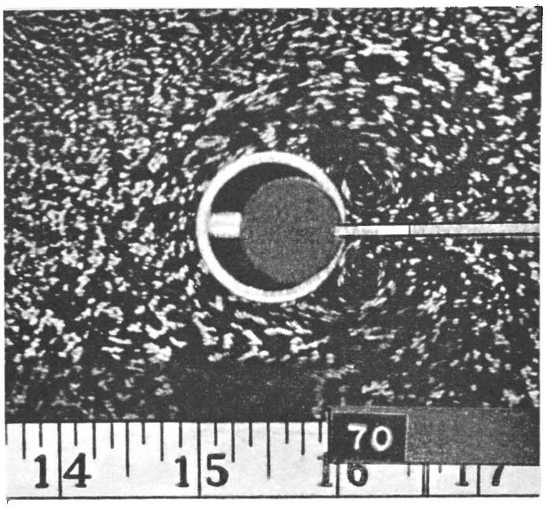

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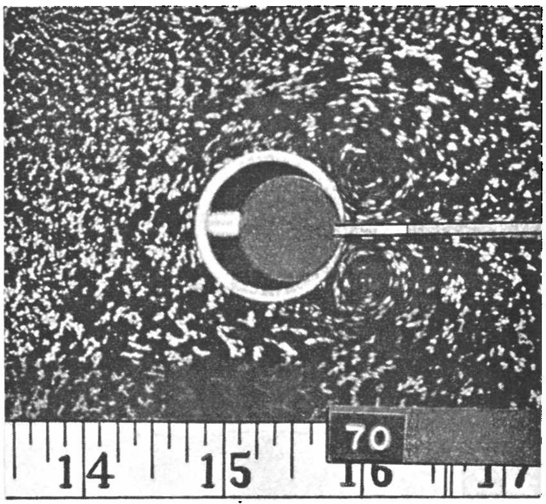

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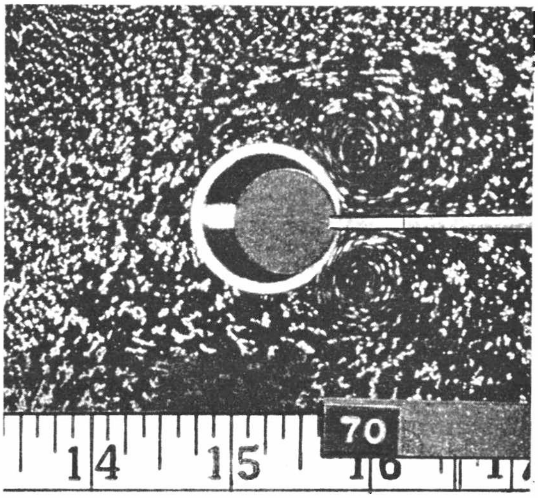

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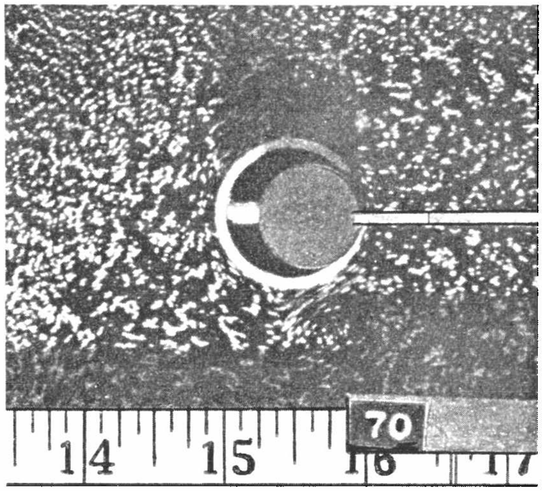

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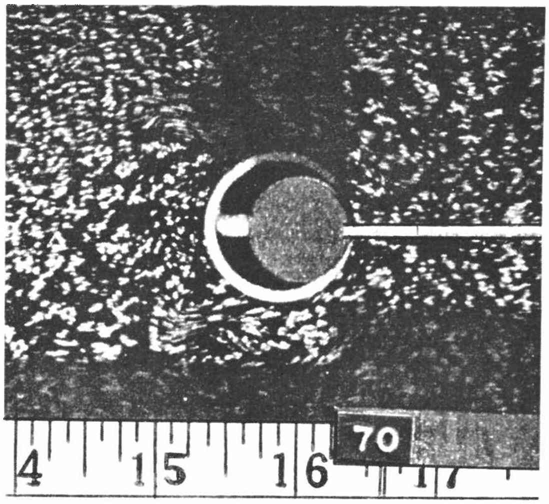

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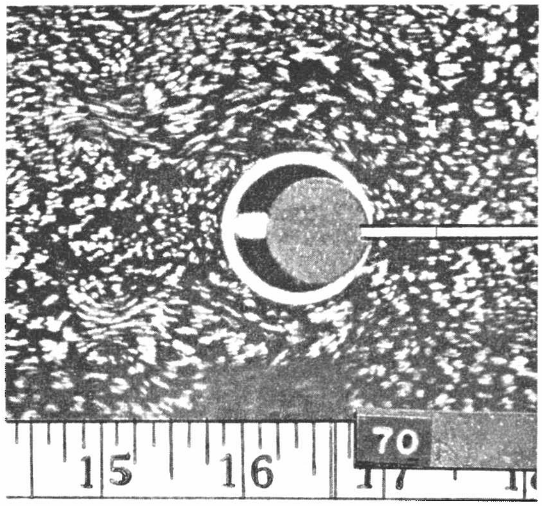

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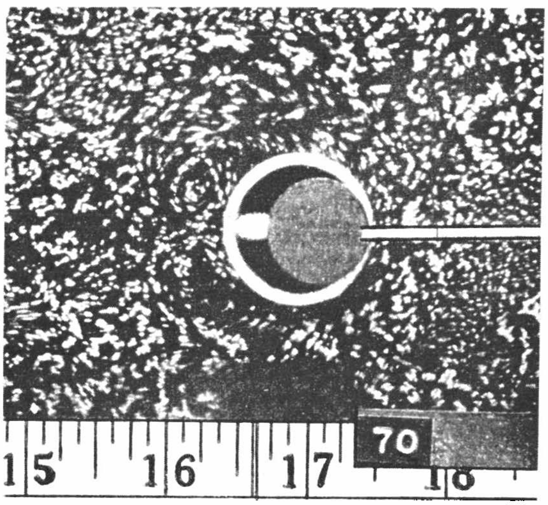

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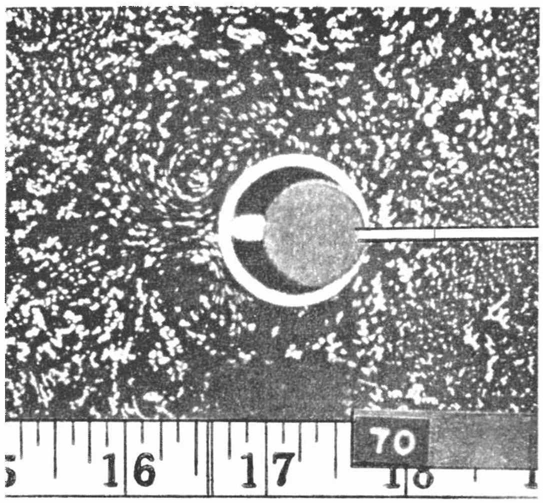


56

SEQUENCE NUMBER 3

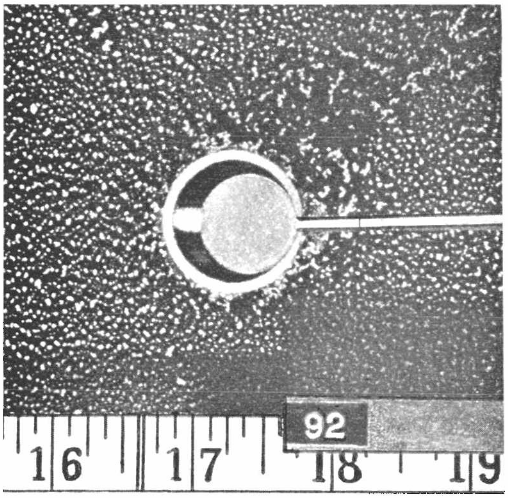
Run 92 --- 1.5 cycles

A/D = 1

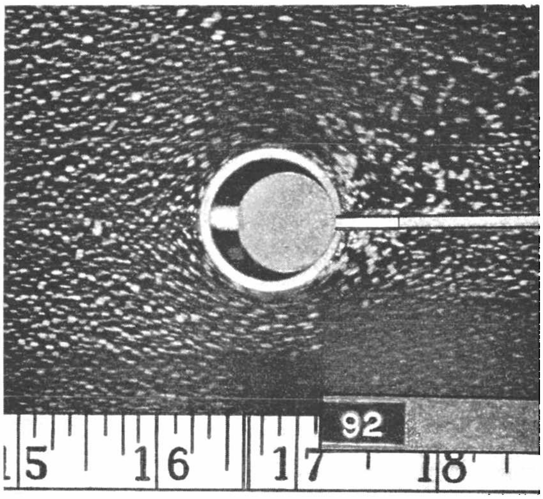
D = 1 inch

f = 20 cycles/minute

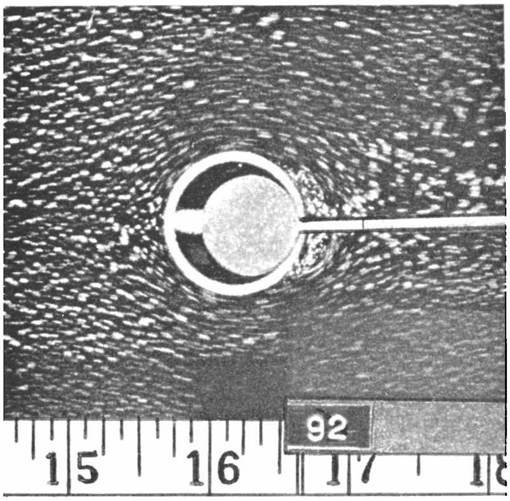
Camera speed = 12 frames/second


92
16 17 18 19

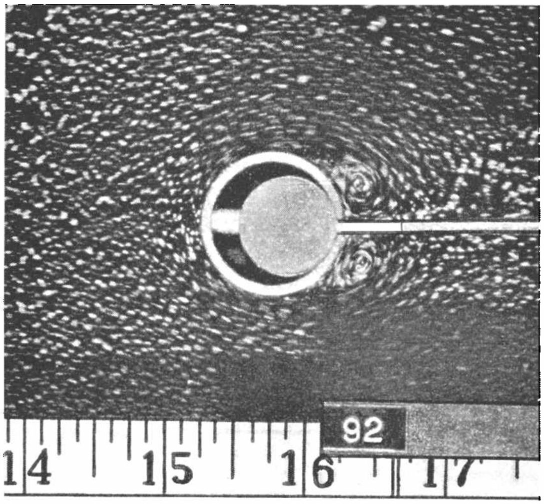
1


92
15 16 17 18

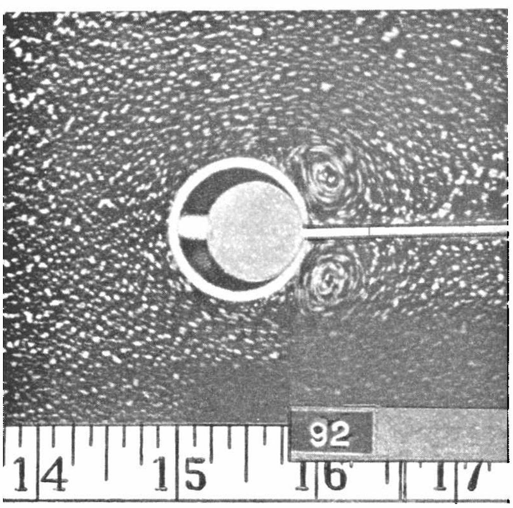
7


92
15 16 17

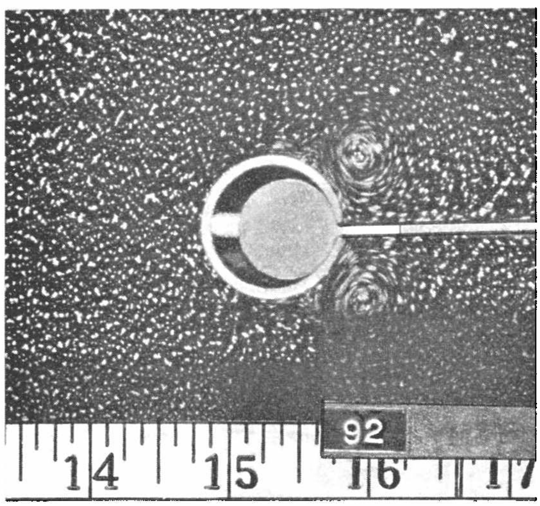
11


92
14 15 16 17

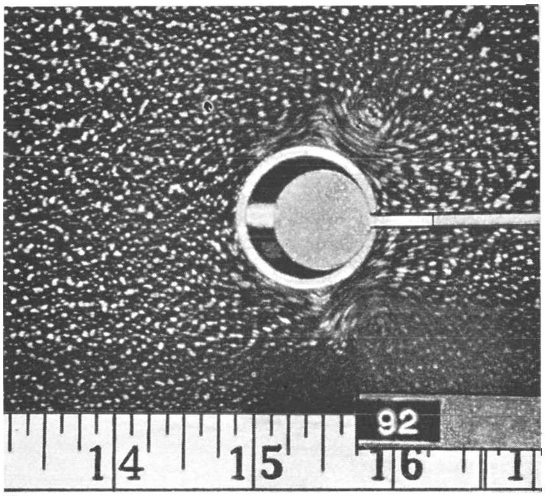
14


92
14 15 16 17

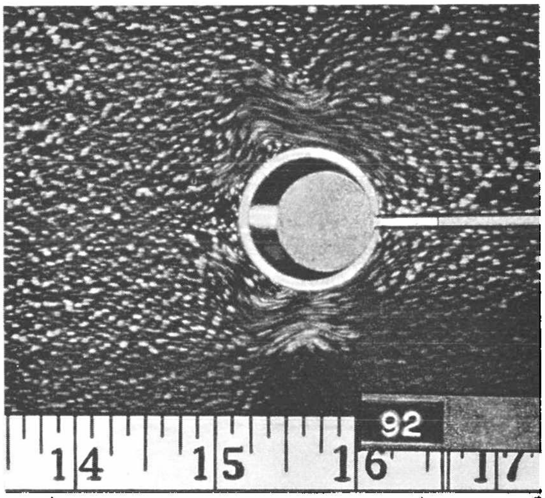
17


92
14 15 16 17

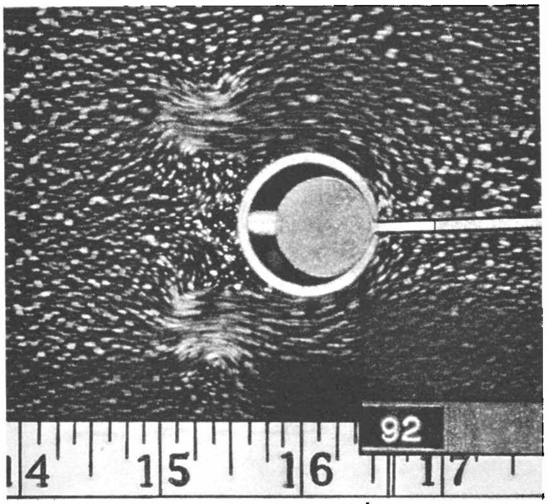
20



23



26



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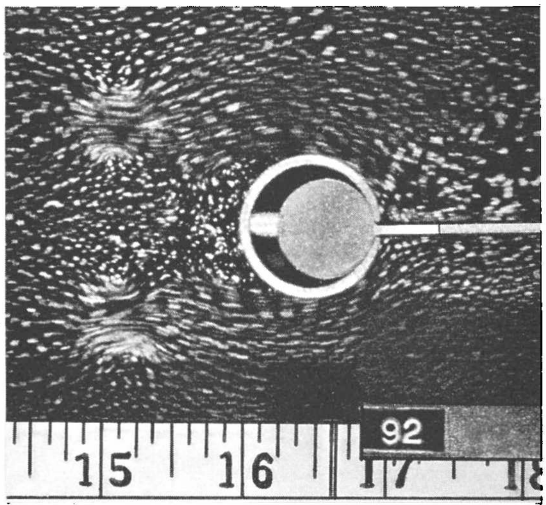
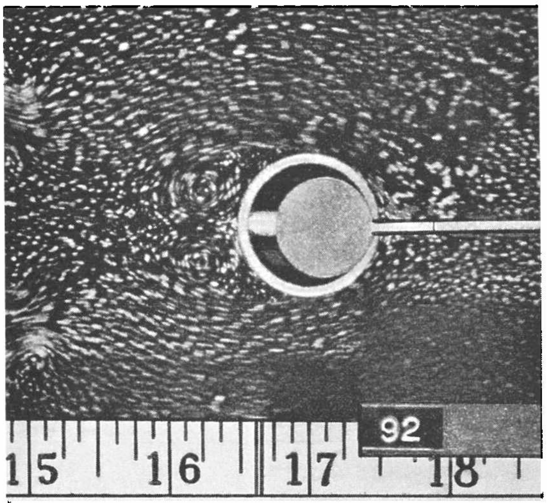


32



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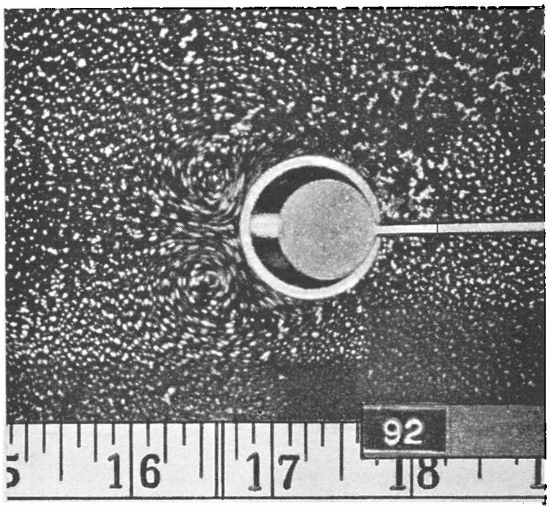

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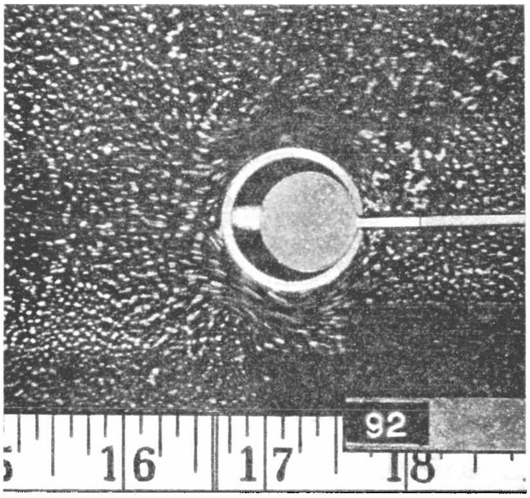

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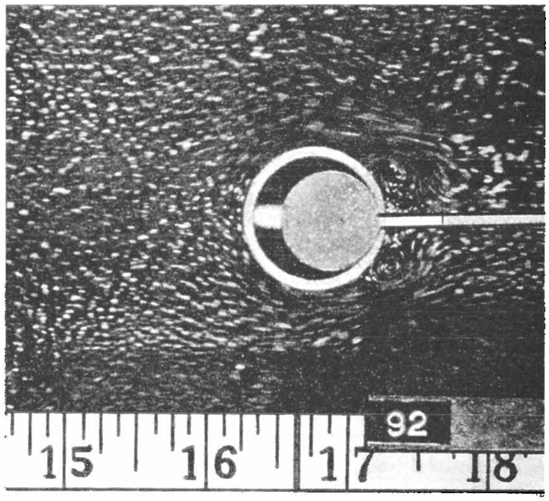

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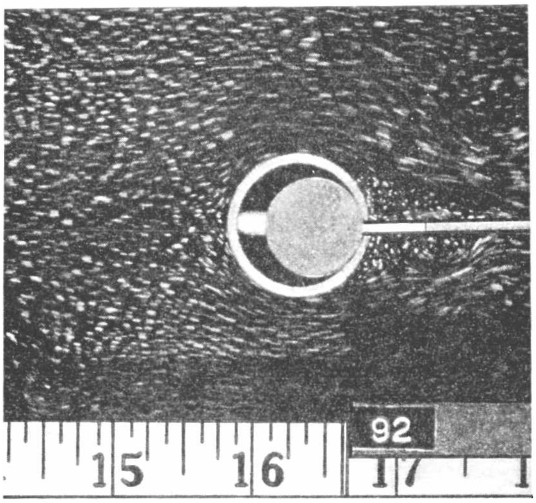

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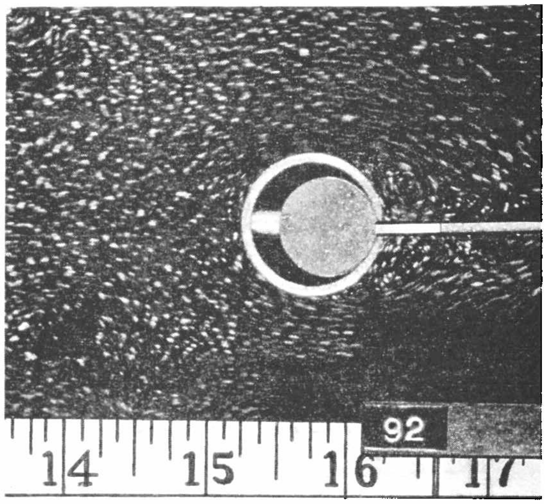

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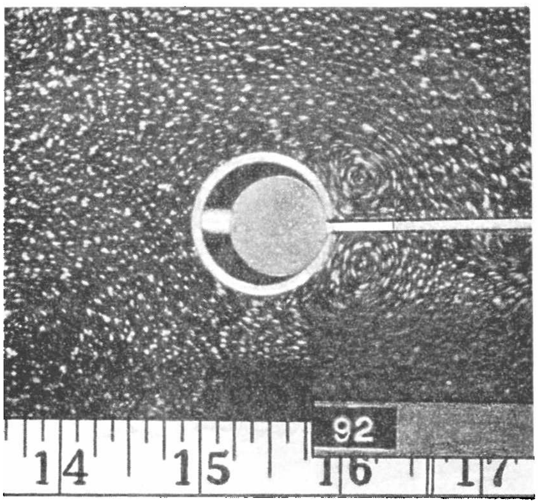
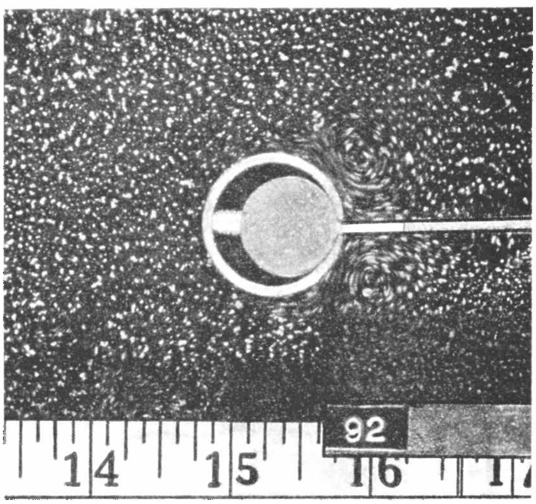


58



61

SEQUENCE NUMBER 4

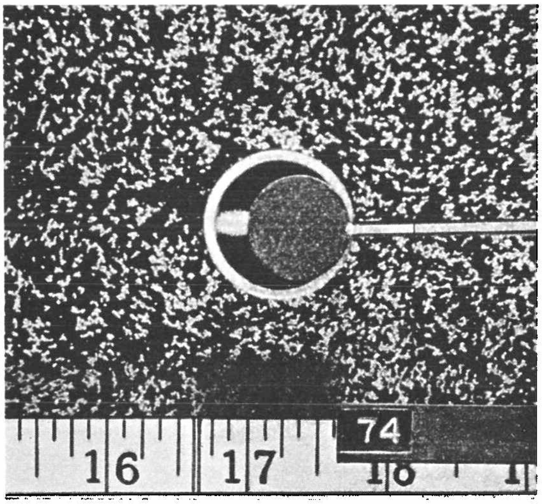
Run 74 --- 1 cycle

A/D = 1

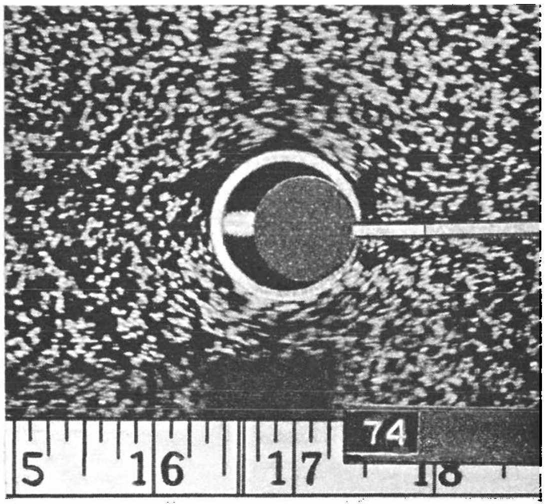
D = 1 inch

f = 50 cycles/minute

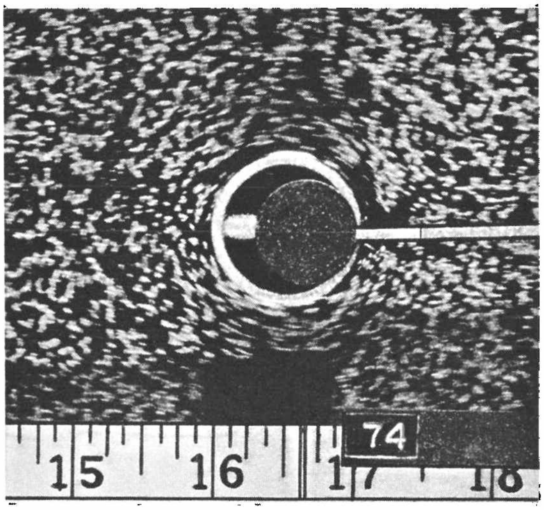
Camera speed = 32 frames/second



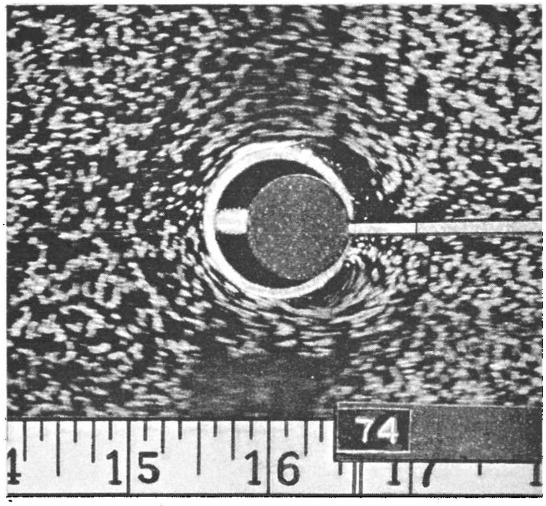
1



5



8



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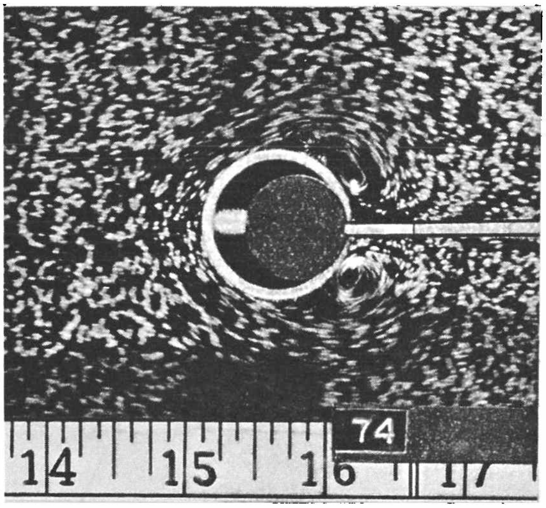

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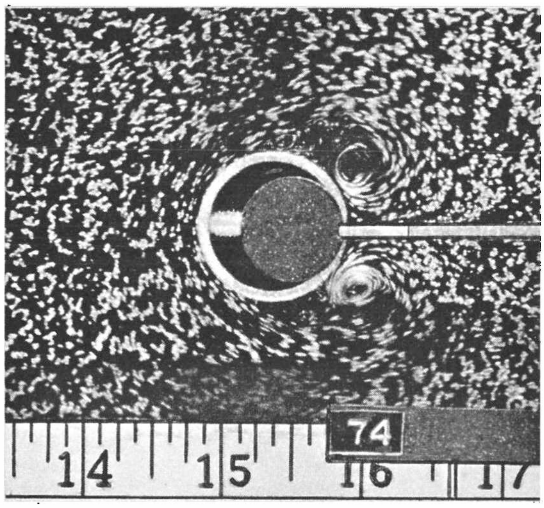

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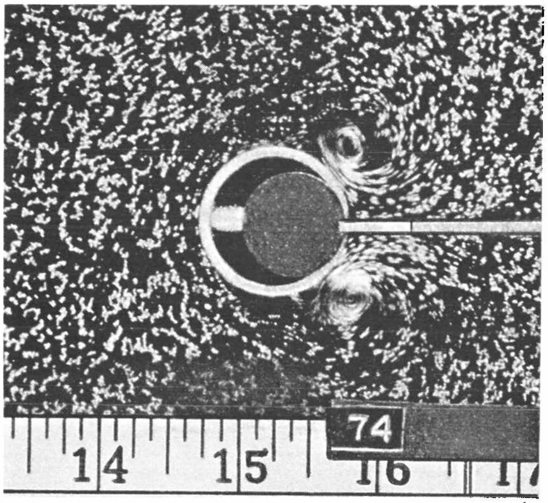

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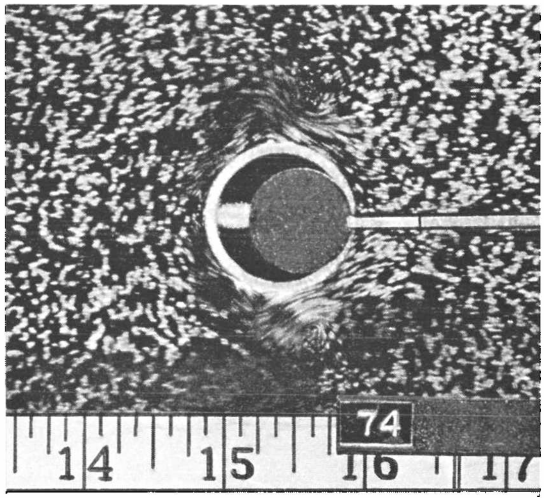

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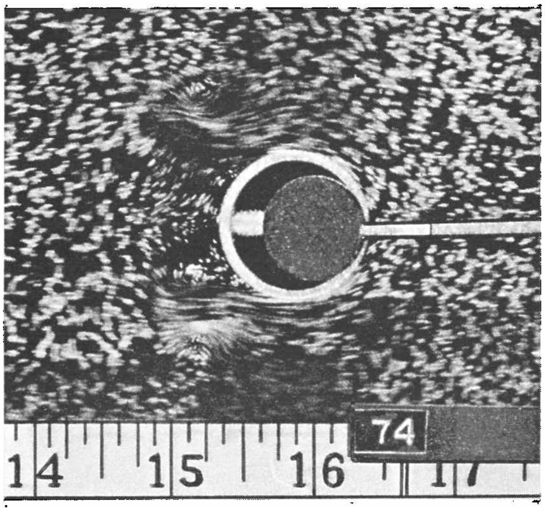
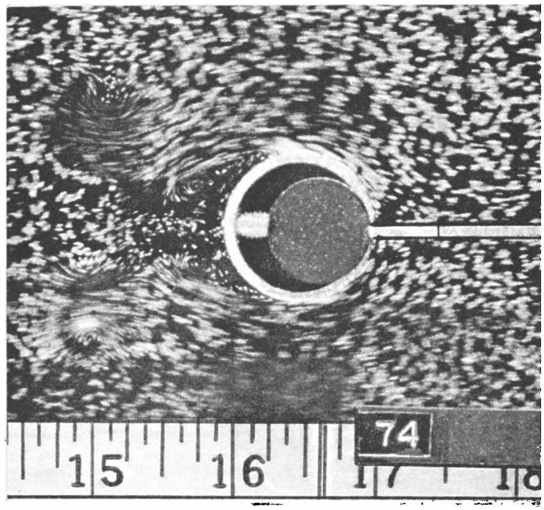


28



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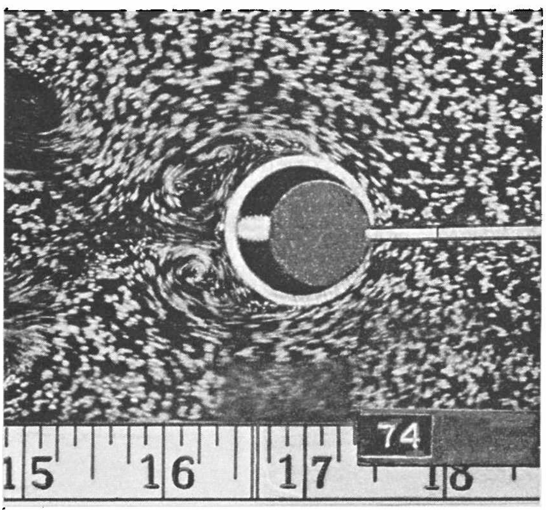

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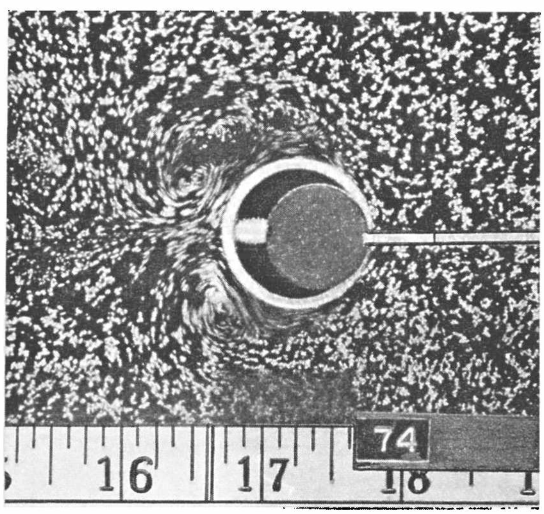


41

SEQUENCE NUMBER 5

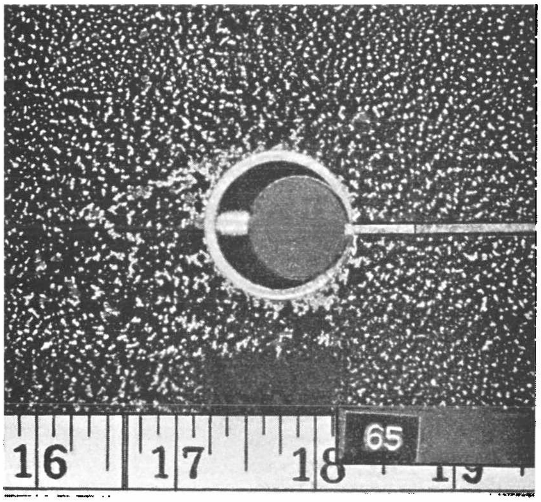
Run 65 --- 1 cycle

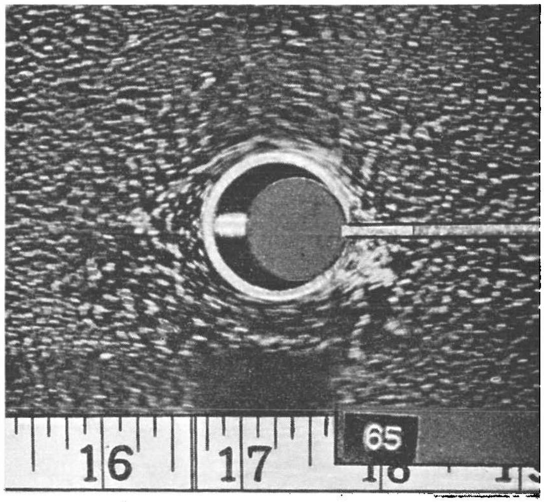
A/D = 1.5

D = 1 inch

f = 30 cycles/minute

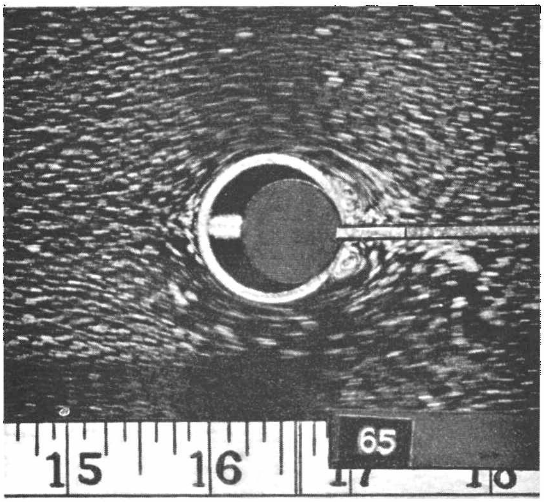
Camera speed = 20 frames/second

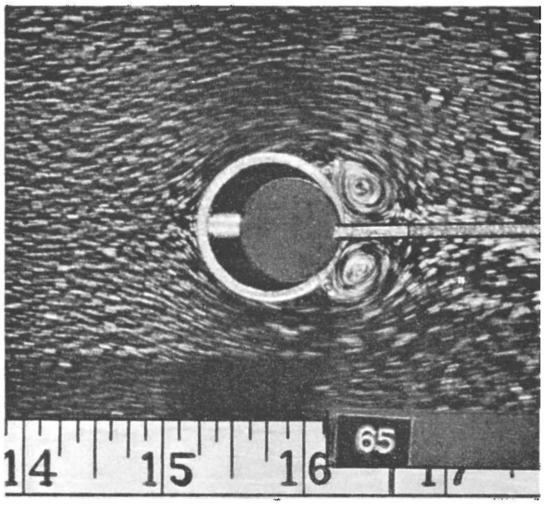




1

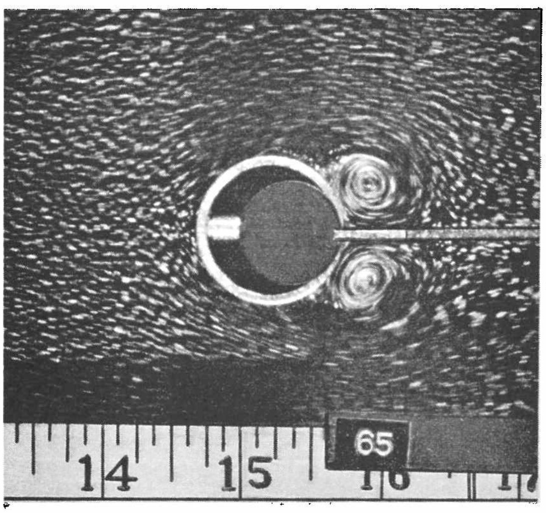
6

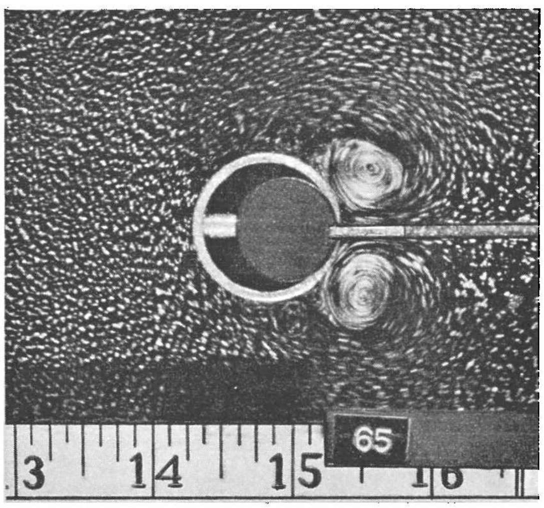




10

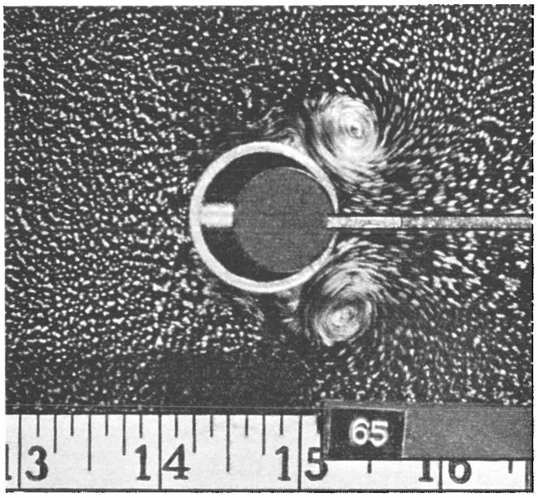
13





16

19



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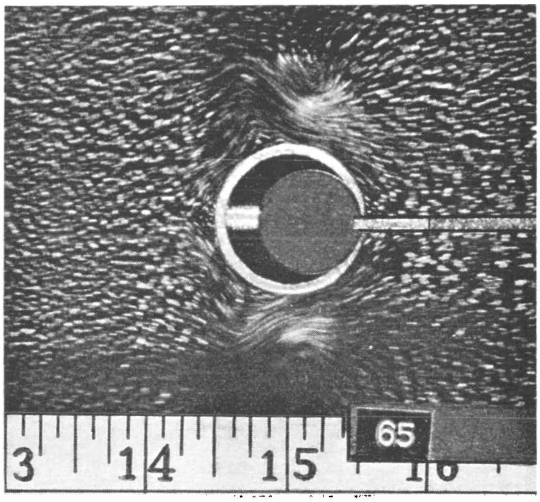

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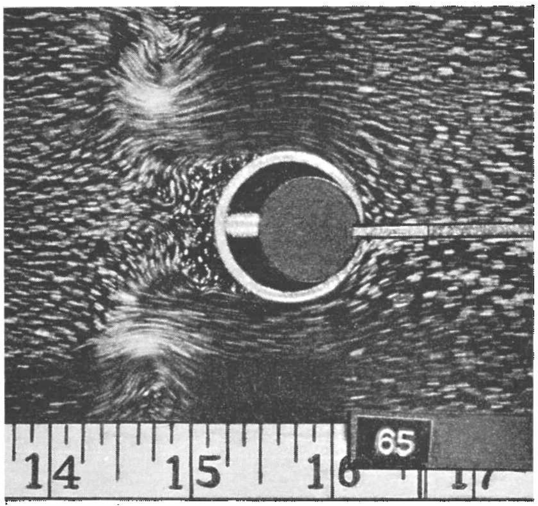

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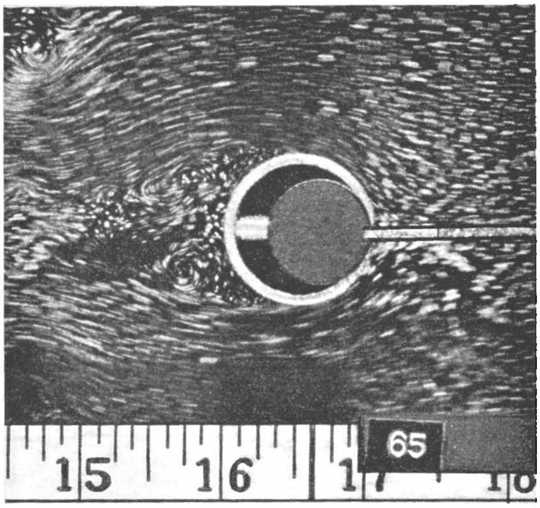

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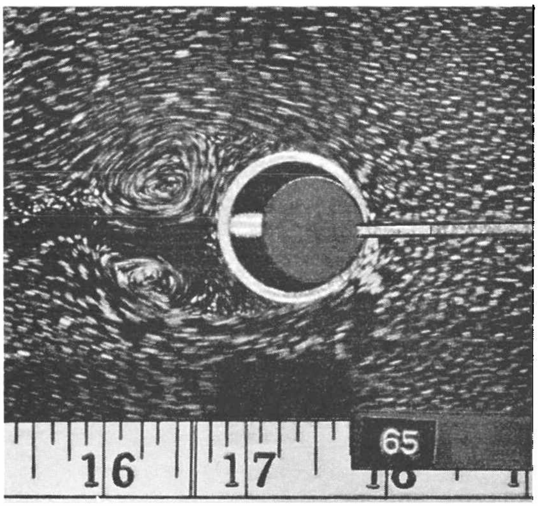
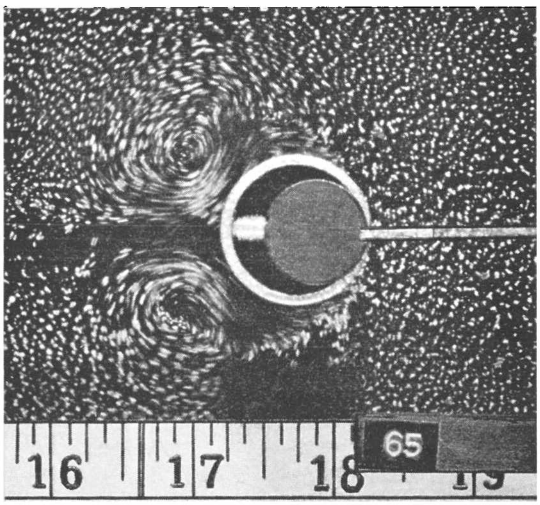


37



41

SEQUENCE NUMBER 6

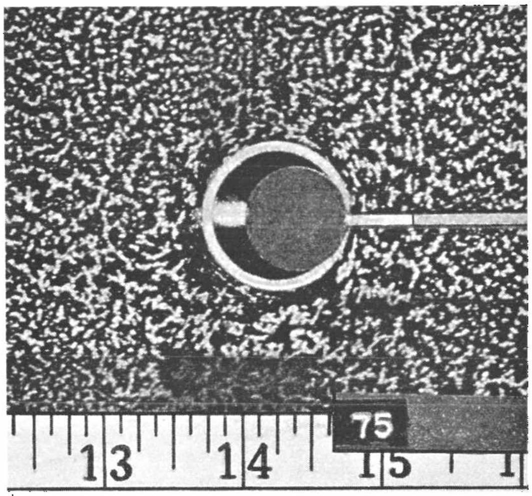
Run 75 --- 1 cycle

$A/D = 2$

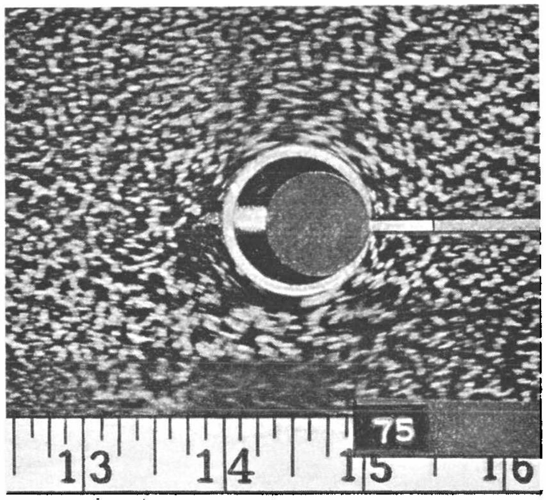
$D = 1$ inch

$f = 20$ cycles/minute

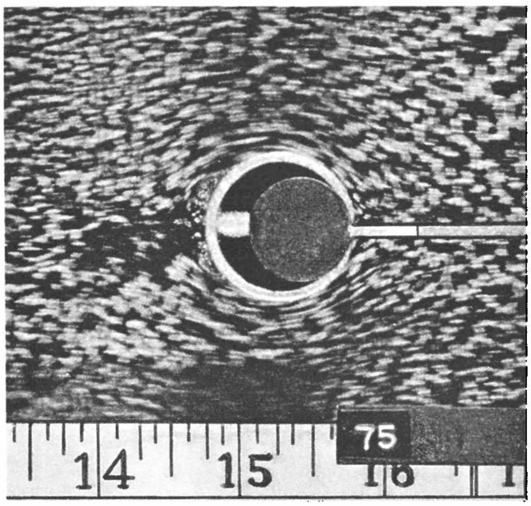
Camera speed = 16 frames/second



1



4



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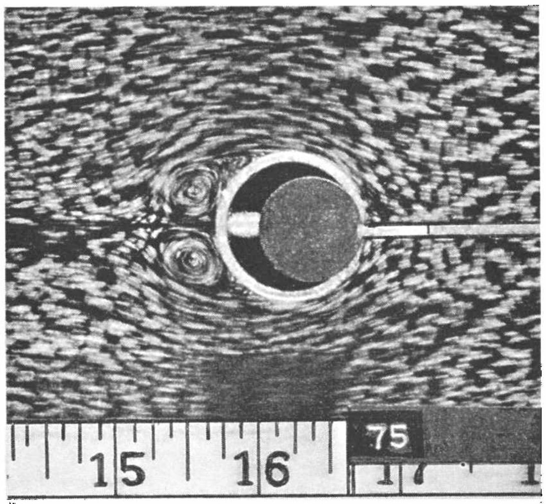
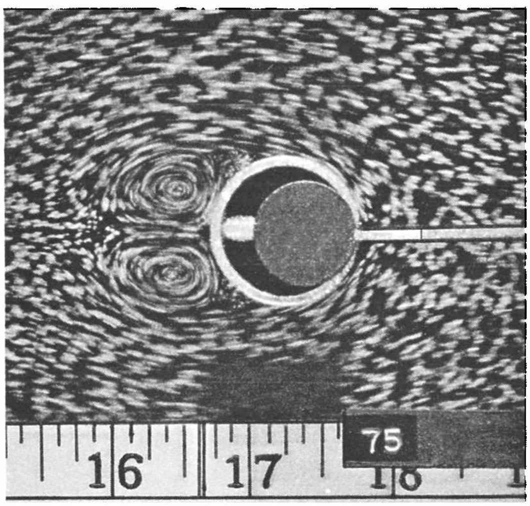


12



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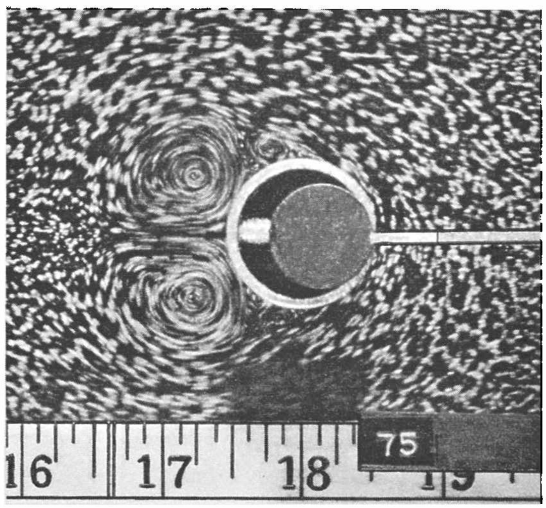

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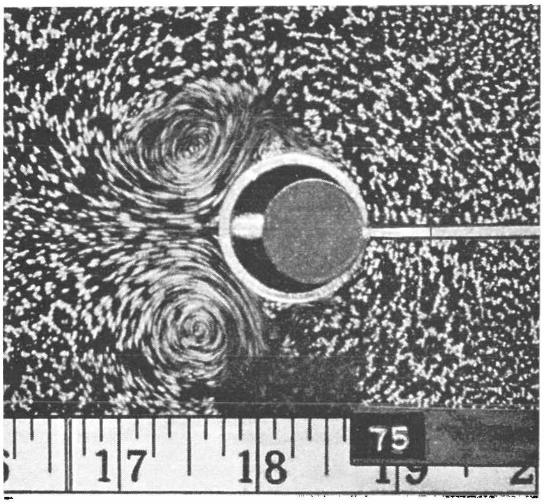

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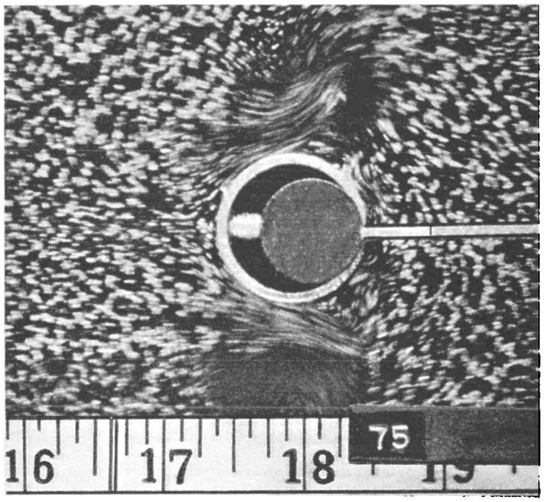

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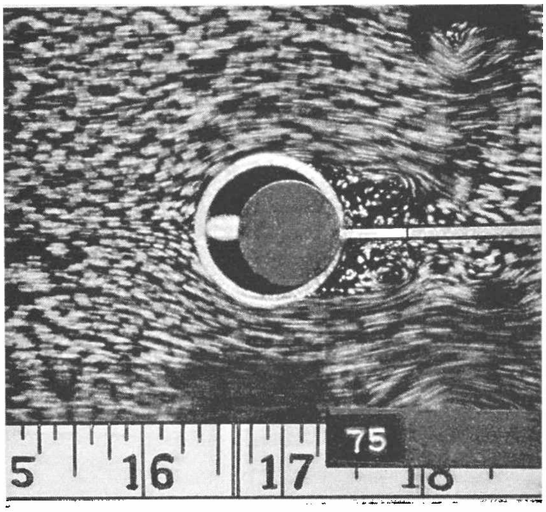

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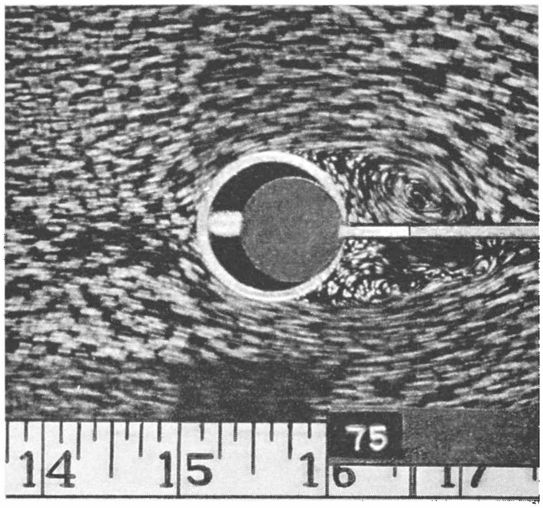

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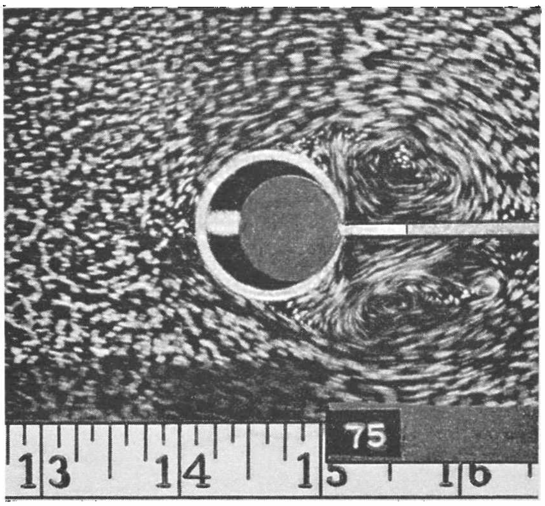

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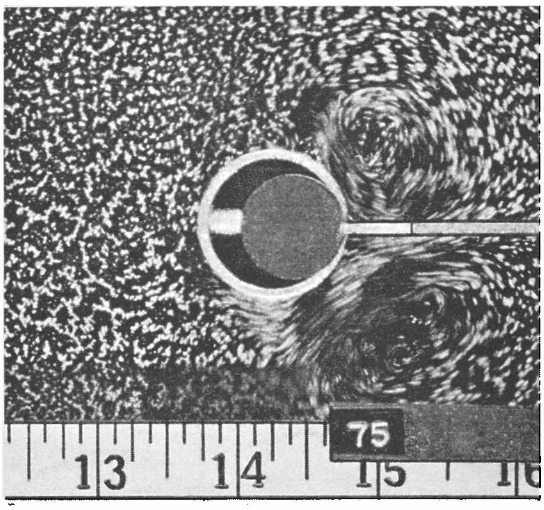

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SEQUENCE NUMBER 7

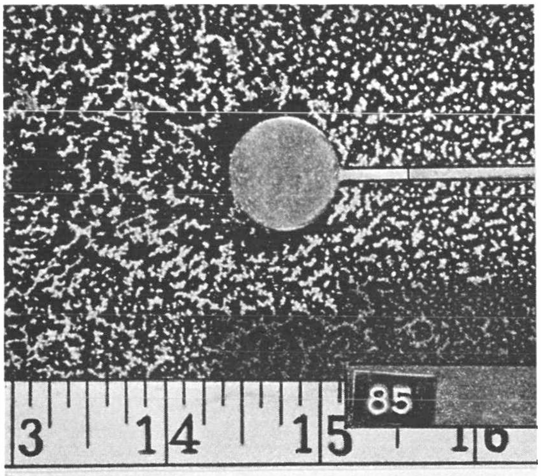
Run 85 --- 1 cycle

$A/D = 2.4$

$D = 5/8$ inch

$f = 15$ cycles/minute

Camera speed = 16 frames/second



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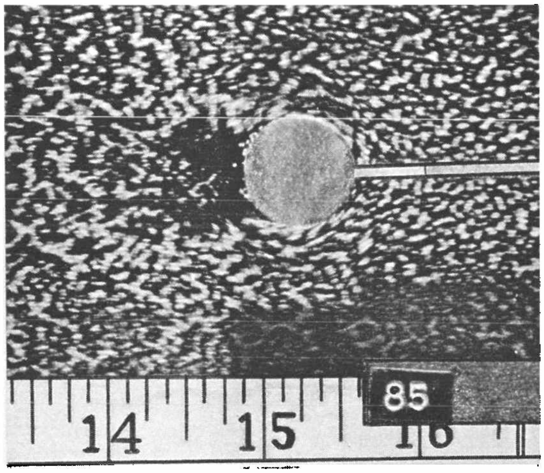

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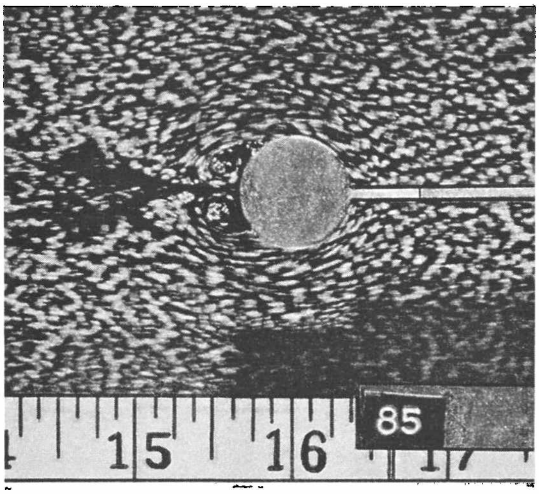

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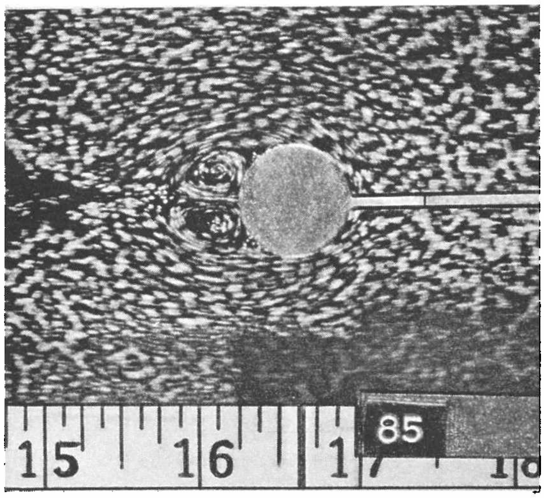

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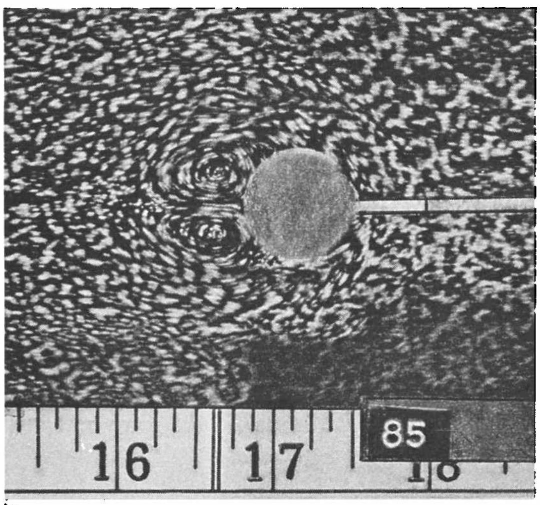

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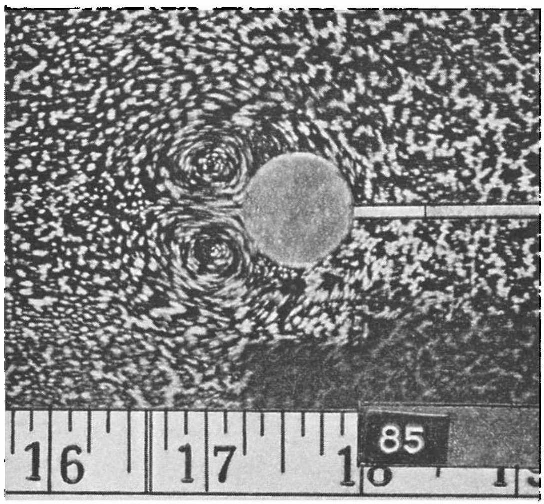

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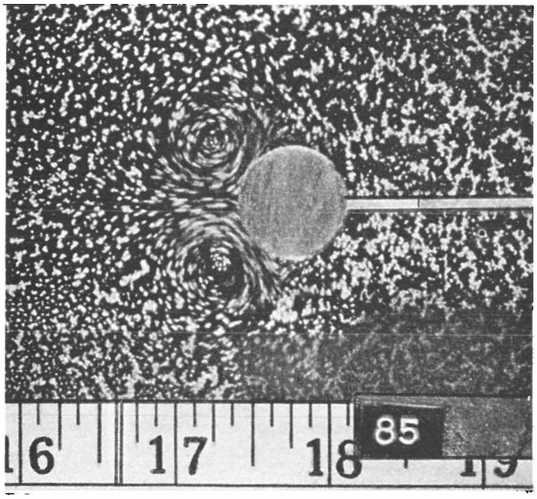

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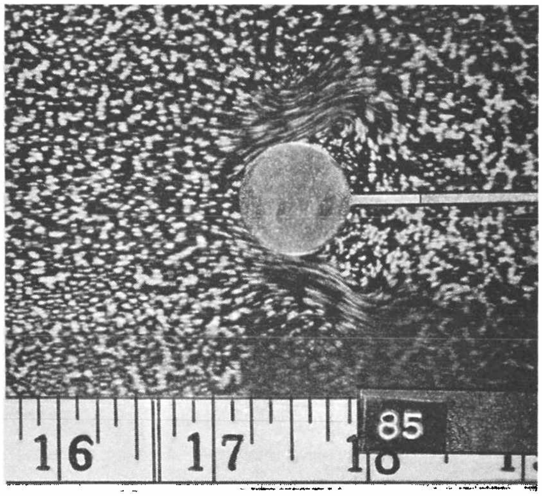

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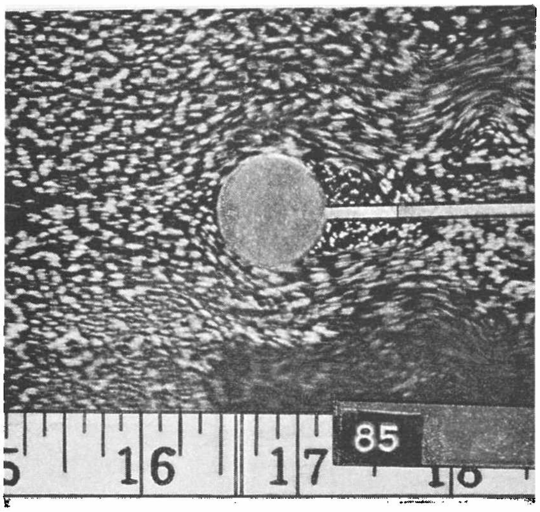

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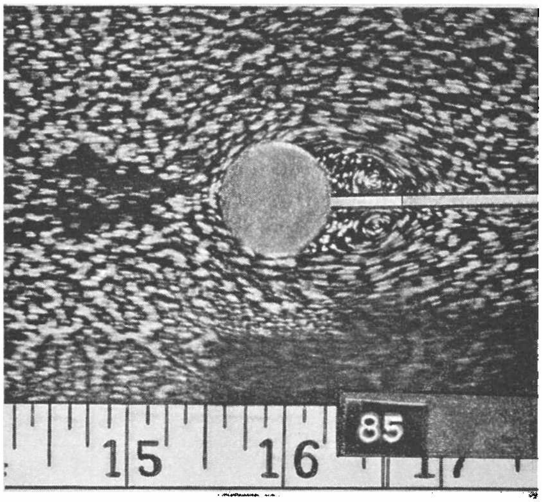

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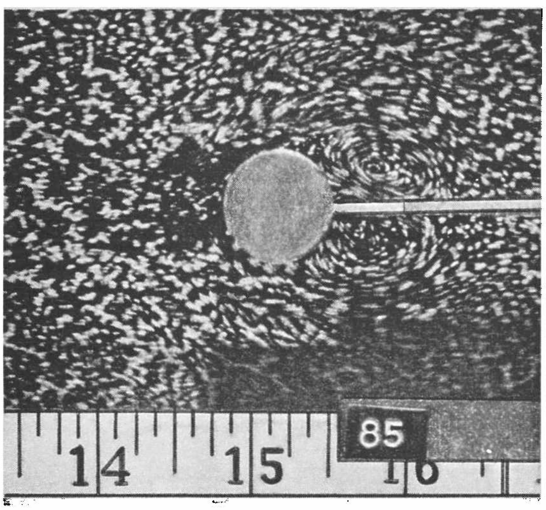

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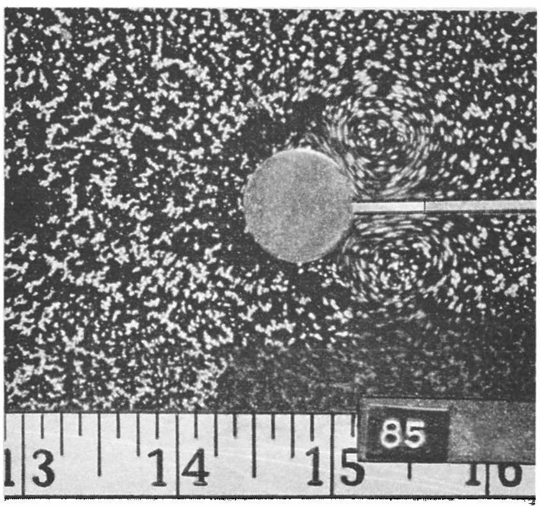

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SEQUENCE NUMBER 8

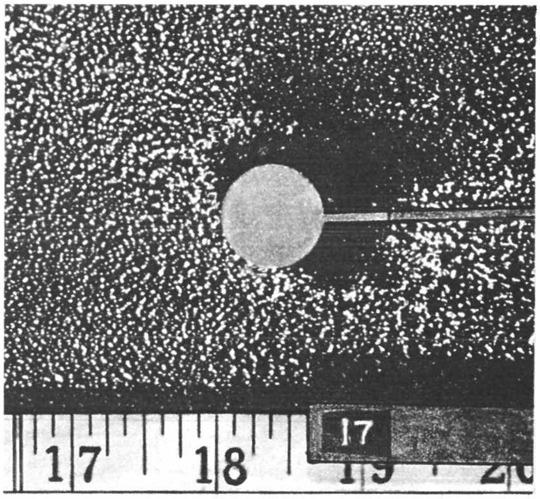
Run 17 --- 1 cycle

A/D = 3.2

D = 5/8 inch

f = 20 cycles/minute

Camera speed = 24 frames/second



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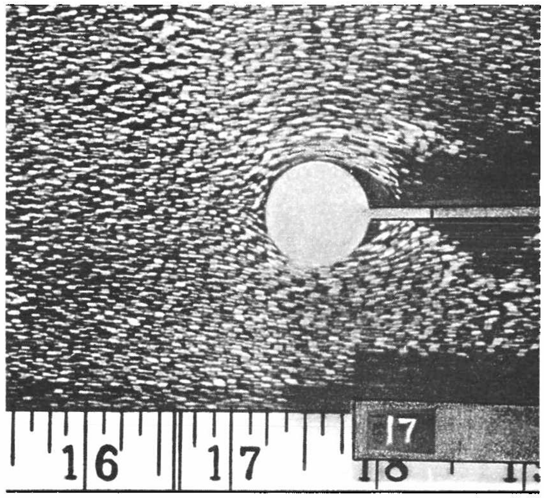

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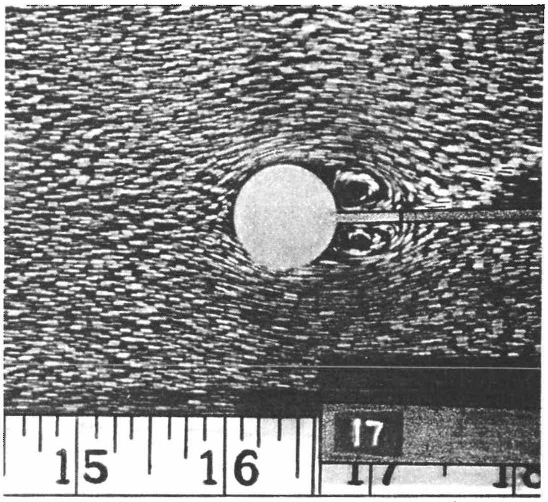

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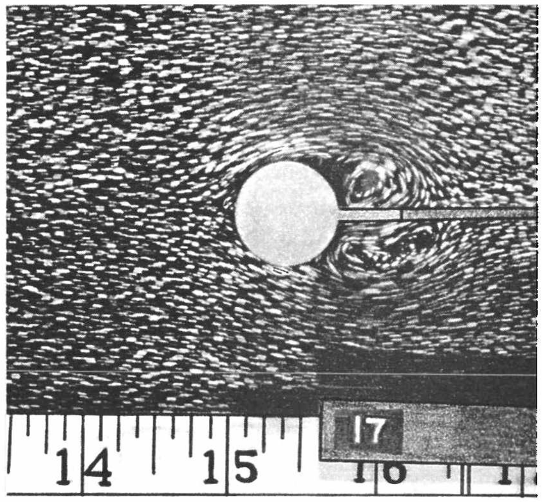

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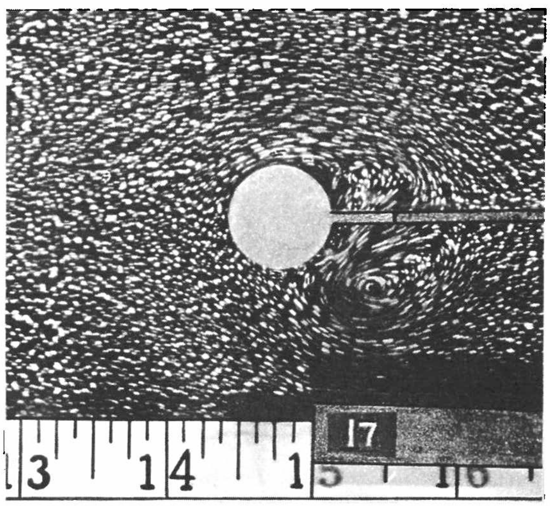

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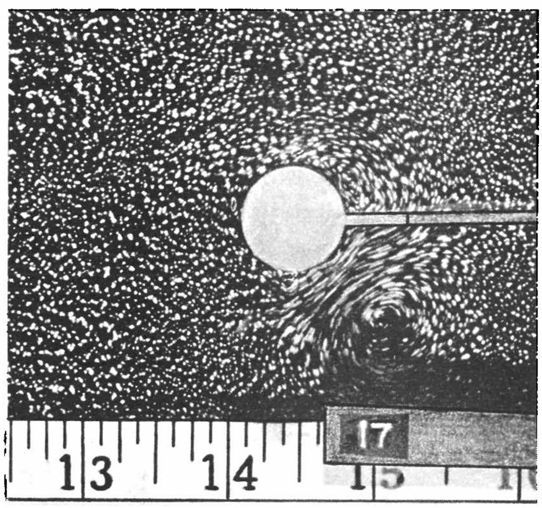

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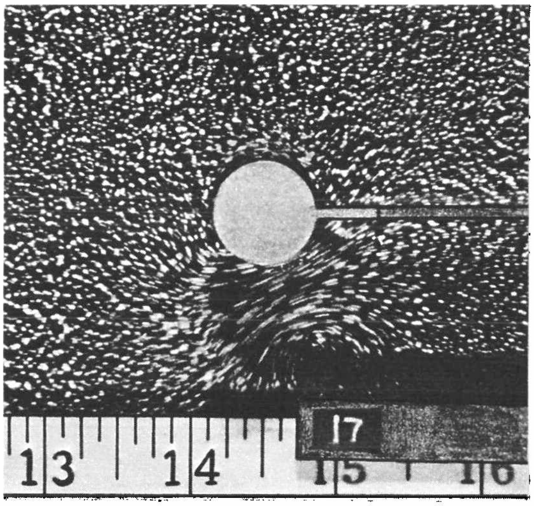

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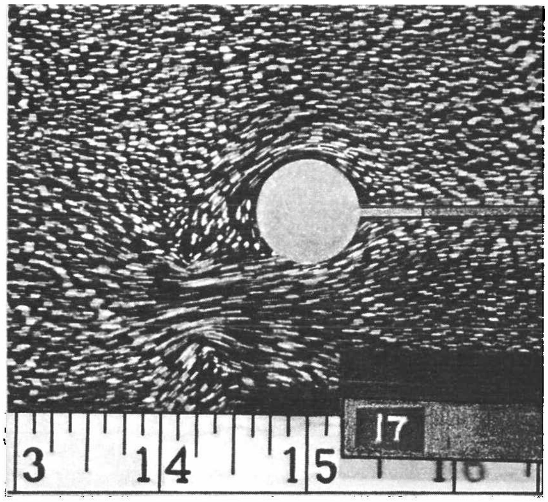

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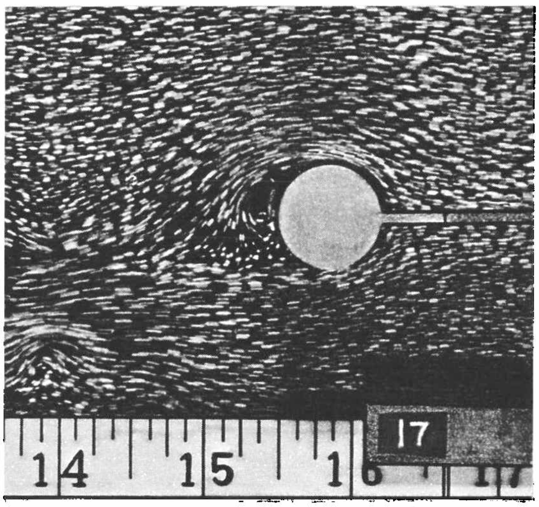

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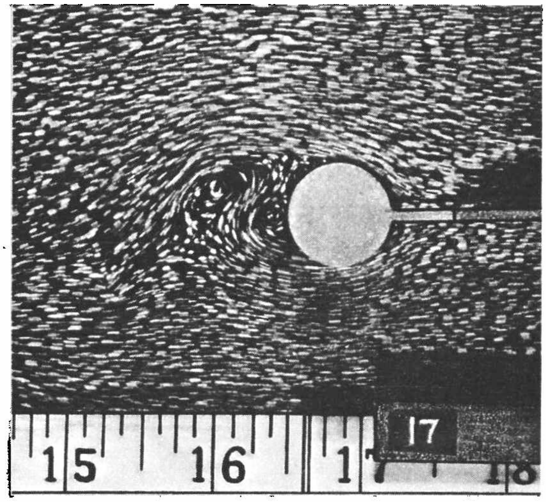

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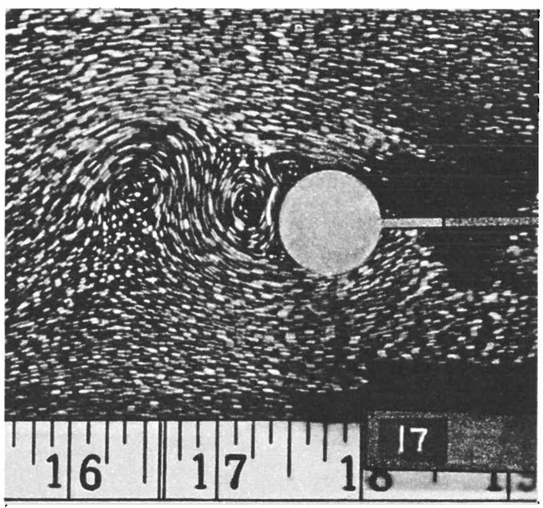

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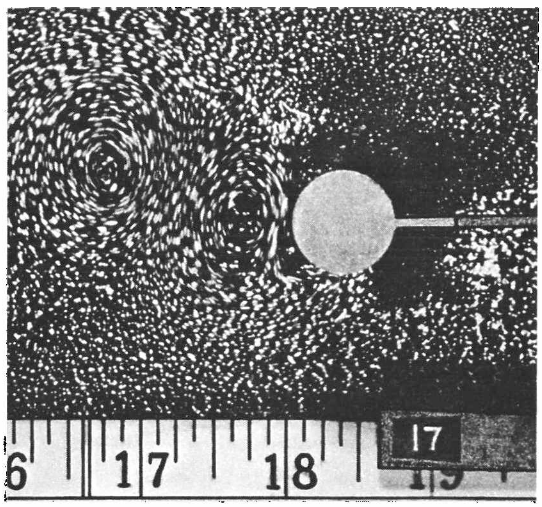

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SEQUENCE NUMBER 9

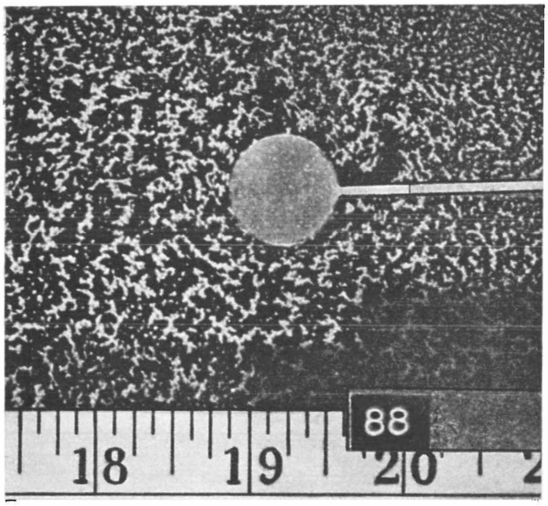
Run 88 --- 1 cycle

A/D = 4.8

D = 5/8 inch

f = 20 cycles/minute

Camera speed = 24 frames/second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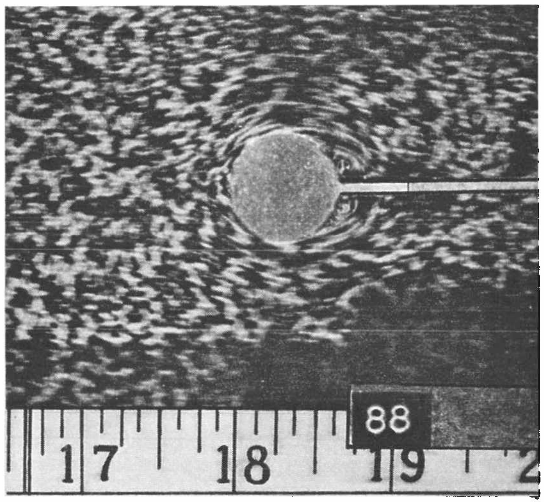
18
19
20

1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17
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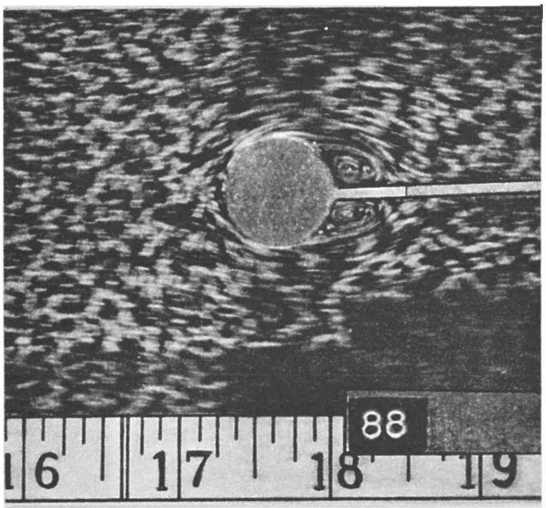
19

9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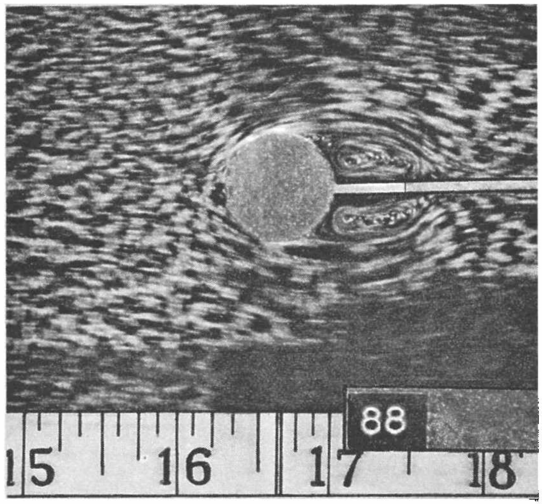
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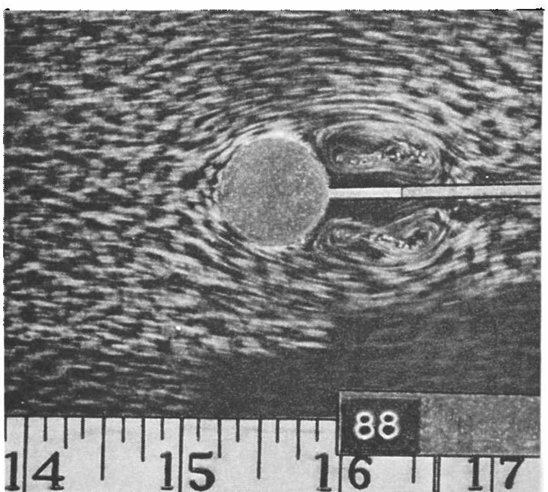
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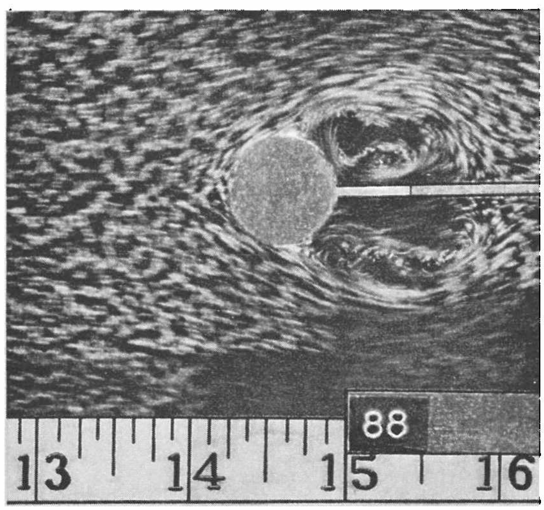
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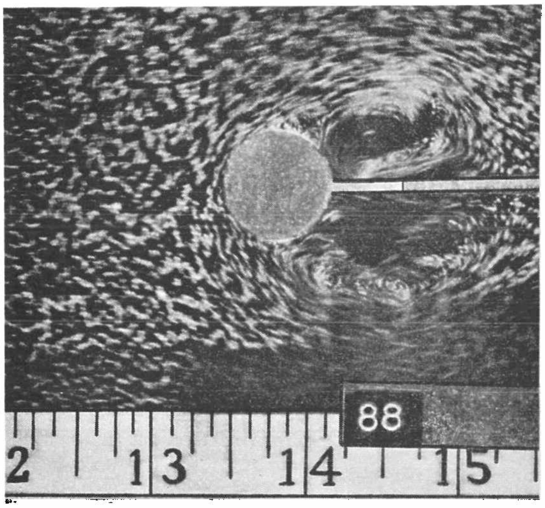

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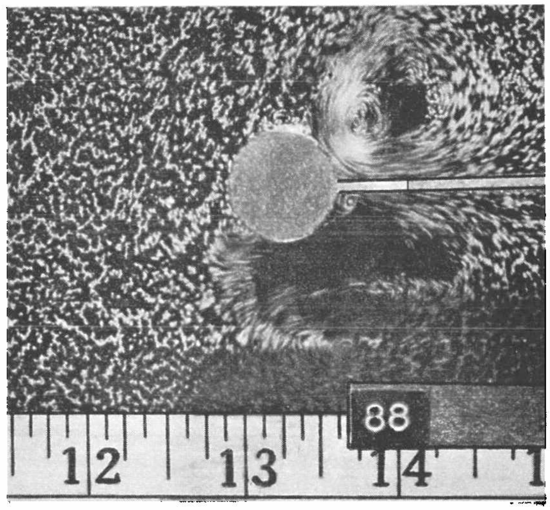

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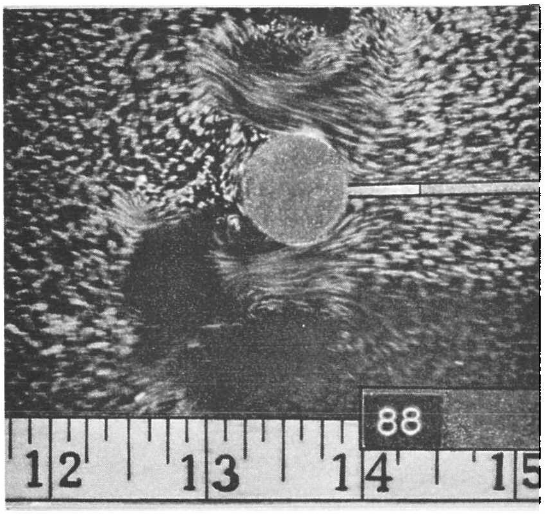

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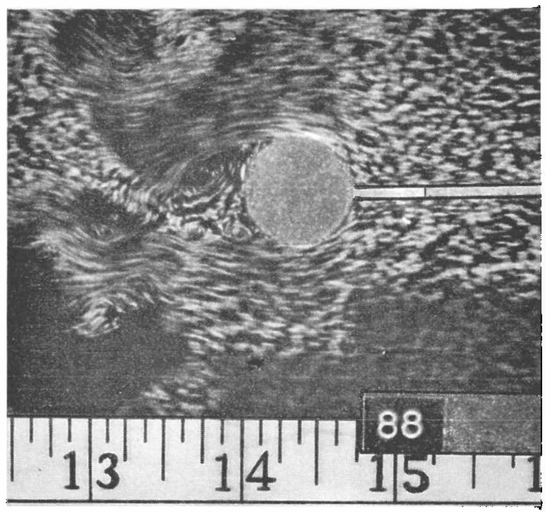

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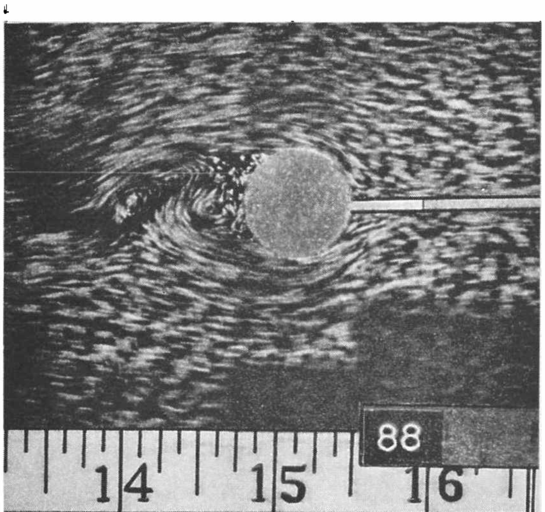

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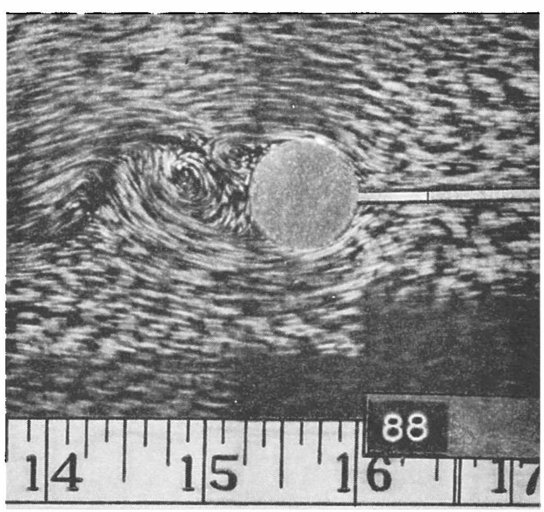

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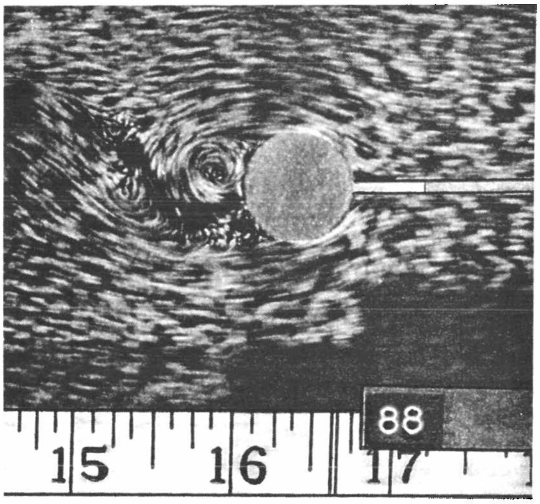

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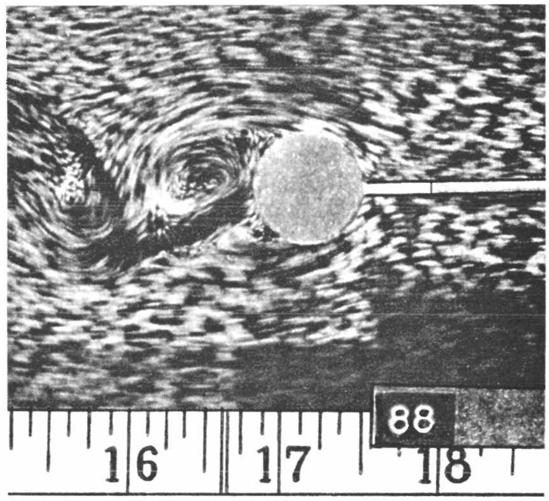

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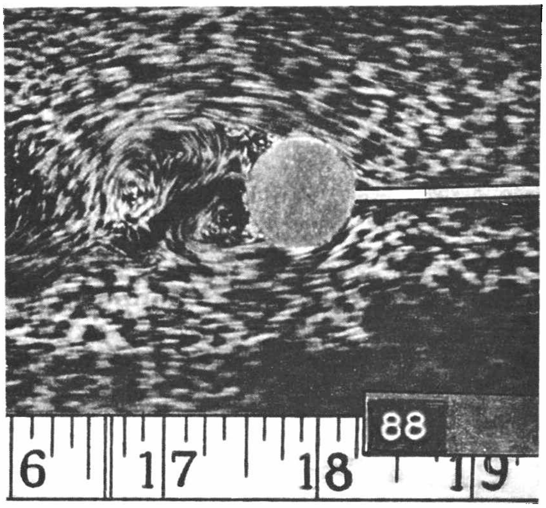

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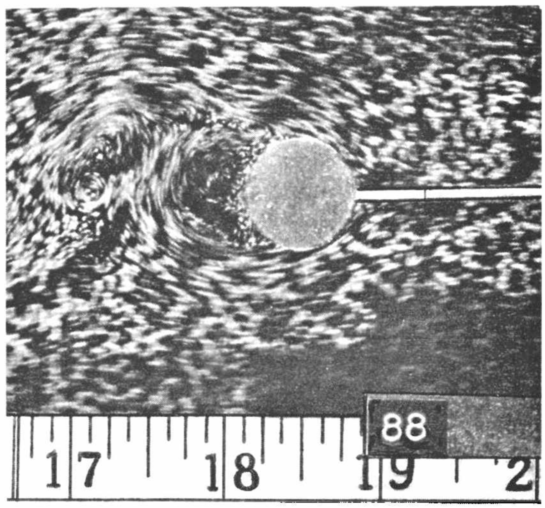

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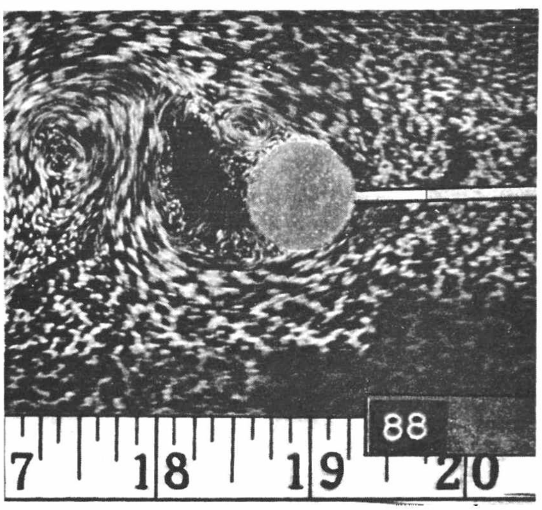

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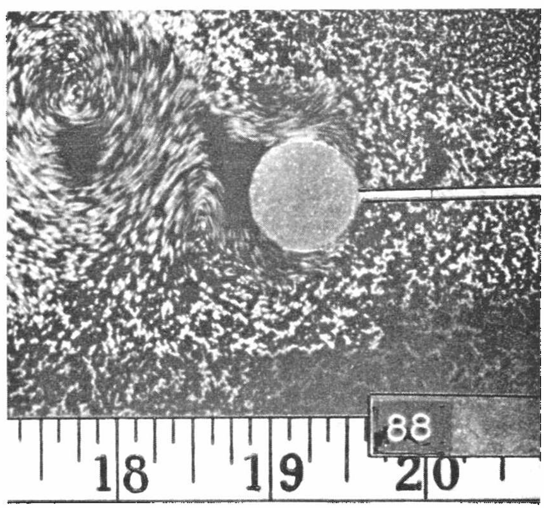

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CHAPTER VI

EVALUATION OF RESULTS

The most common flow pattern around an oscillating circular cylinder encountered in this investigation is seen in Sequence 5. This flow pattern occurs at a frequency of oscillation of 30 cycles/minute and at a relative amplitude A/D of 1.5 and corresponds to the middle of the range investigated.

As the cylinder is started from rest, the initial motion is practically irrotational. The initial thickness of the boundary layer is essentially zero, with what amounts to a vortex-sheet around the cylinder. The vorticity diffuses and the boundary layer grows in thickness. After a certain time separation of flow from the surface of the cylinder begins at the rear stagnation point.

This separation phenomenon takes place in the following manner: The motion of the thin stratum of fluid adjacent to the cylinder wall, and wholly inside the shear layer, is controlled by three factors. It is retarded by friction at the bounding wall, it is pulled forward by the stream above it through the action of viscosity, and it is retarded by the adverse pressure gradient due to the deceleration of the fluid on the downstream side of the cylinder. The energy and momentum of this thin stratum of fluid are therefore small and are insufficient for the stratum to continue to overcome the adverse pressure gradient. The stratum is then brought to rest and, farther on, next to the wall, a slow back-flow in the direction of the pressure gradient sets in. The forward stream then leaves the cylinder surface.

Two thin layers of vorticity, symmetrically situated about the rear stagnation point leave the surface of the cylindrical body and curl round on themselves. The vorticity becomes more and more concentrated in the rolled-up portion, giving rise to the familiar twin-vortices in the wake of the cylinder. The vortices thus formed gain in strength as more and more vorticity, shed from the surface, passes into them through the thin vortex-layer. As the strength of the vortices increases, they move slowly away from the cylinder.

As the cylinder moves through the point of maximum velocity during the first stroke, the twin-vortices are symmetrical and still relatively small. Meanwhile each vortex has produced a strong back-flow over the rear portion of the cylinder. This back-flow separates from the surface, with the formation of a small secondary vortex having an opposite rotation to the main vortex, with which it proceeds to coalesce (see Figure 9).

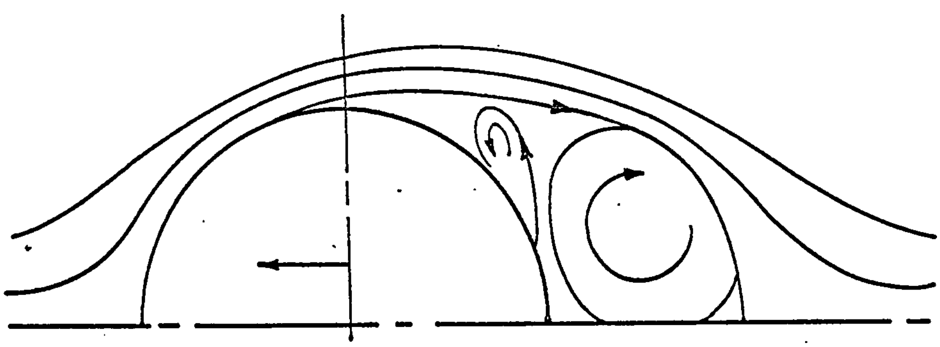

Figure 9. Formation of Secondary Vortex in Cylinder Wake

This little secondary vortex originates inside the triangle formed by the rear of the cylinder, the boundary of the main vortex and the separated shear layer feeding this vortex.

As the cylinder is decelerating, the twin-vortices continue to grow until shortly before the point of inversion of the oscillatory motion. At that point the model velocity is small enough so that the vortex-sheet does not separate from the surface any longer. The growth process of the twin-vortices is therefore interrupted, since the shear layer has stopped feeding them.

The fact that the twin-vortices are still undergoing a growing process even though the cylinder is decelerating can be explained in this way: As the cylinder is decelerating, the corresponding instantaneous Reynolds number is becoming smaller but is still much higher than the steady state Reynolds number corresponding to the twin-vortices of the same size. Therefore, given enough time, the vortices tend to approach the shape and size they would have at the same Reynolds number in steady flow.

Towards the end of the first stroke, at which time the growth of the vortices has ceased, the twin-vortices begin to flatten against the rear of the cylinder. As the cylinder is brought to rest and then starts its motion in the opposite direction, the secondary vortices and the twin-vortices are pushed out of the way by the cylinder and, as the cylinder passes in between them, they keep on moving due to their residual velocity.

Each secondary vortex stays close to the corresponding main vortex, forming two centers of vorticity with each containing two vortices with opposite rotation. These two centers of vorticity move slowly away from their shedding point and from each other and diffuse into the bulk of the liquid.

Meanwhile the cylinder is completing the second half of the first cycle, giving rise in its wake to the same flow pattern as just described. As the cylinder goes through successive cycles, more and more vortex-pairs are shed at both ends of the cylinder travel. This increase in vorticity in the bulk of the liquid causes asymmetry of the twin-vortices and even the shedding of these vortices. As the cylinder continues to oscillate back and forth, the field around it becomes completely disturbed and the flow pattern ceases to be periodical.

The movies of the flow pattern of the wake for every combination of cylinder diameter, frequency and amplitude of oscillation, as given in Figure 8, have been investigated frame by frame and some measurments of the vortex dimensions and positions have been made for the first cycle. Obviously, due to the unsteadiness of the motion and therefore to the lack of clarity of the flow pattern, and especially of the vortex boundaries, the dimensions given here should be taken as qualitative rather than quantitative evidence of the phenomena occuring.

For the relative amplitude A/D of 1.5 and a frequency of 30 cycles/minute (see Sequence 5), the length of the twin-vortices as the cylinder goes trough the point of maximum velocity is of the order of 0.2 D and the maximum length of these same vortices is about 0.6 D shortly before the beginning of the return portion of the first cycle. The twin-vortices remain symmetric during two strokes and asymmetry of the twin-vortices sets in shortly before their shedding at the end of the third stroke.

As the relative amplitude is reduced to 1.2, the same flow pattern as described before, but scaled down, takes place in the wake of the oscillating cylinder. The length of the twin-vortices at the point of maximum velocity is about 0.12 D and their maximum length during the first stroke is about 0.45 D. No sequence corresponding to this relative amplitude of oscillation has been included here.

If the wakes of a cylinder oscillating with a certain relative amplitude, but with different frequencies, are compared, very little difference can be detected. Separation of the vortex sheet from the cylinder occurs approximately at the same point. The size of the twin-vortices as the cylinder goes through the point of maximum velocity is about the same. The maximum size reached by the same twin-vortices is approximately equal and even the path followed by the vortex-pairs after shedding at the point of inversion is about the same. Only the number of cycles undergone by the cylinder until the twin-vortices become asymmetric and until the whole field is disturbed seems to be smaller at higher frequencies than at lower frequencies of oscillation. This can be seen in Sequences 2, 3 and 4 which correspond to a relative amplitude of 1.0 and frequencies of 15, 20 and 50 cycles/minute respectively. The length of the twin-vortices at the point of maximum velocity is about 0.1 D and the maximum length of the vortices is about 0.375 D. For the lower frequencies of oscillation, the wake remains symmetric for the first two cycles while at the frequency of 50 cycles/minute the wake becomes asymmetric after one and one half cycles.

As the cylinder oscillates with a relative amplitude of 0.8 (see Sequence 1), separation of the shear layer from the cylinder wall takes place approximately at the point of maximum velocity and the maximum length that the twin-vortices reach during the first half cycle is about 0.25 D. Again the frequency of oscillation seems to have very little effect on the wake of the cylinder. The wake remains symmetric for three or more cycles before the increasing vorticity in the bulk of the liquid causes the deformation of the twin-vortices. At this relative amplitude as well as in any oscillatory motion with a smaller relative amplitude, a streaming motion as described in Chapter 1 and illustrated in Figure 1 can be detected. This streaming motion is however very weak and can only be detected when the corresponding pictorial sequences are viewed as motion pictures.

As the cylinder oscillates with a relative amplitude equal to 0.5, separation occurs very late and the twin-vortices have just made their appearance when the direction of motion of the cylinder is reversed. As the cylinder moves in the opposite direction, the two vortices move along the cylinder walls and instead of leaving the cylinder when they reach the point of full cylinder breadth, they keep moving along the walls until they nearly reach the rear stagnation point before they detach and diffuse into the bulk of the liquid.

At a relative amplitude of 0.4, separation and subsequent vortex formation do not occur at all and the shear layer oscillates in a smooth regular fashion about the cylinder. The shear layer oscillations are in phase with the cylinder but the motion of the tracer particles just adjacent to this layer shows that the successive layers in the fluid oscillate with different phase shifts and that their amplitude of oscillation decreases outwards from the cylinder wall. At this relative amplitude, the frequency of oscillation has no visible effect on the flow field around the cylinder and the flow pattern remains periodically the same for an indefinite number of cycles. According to this investigation and for the range of frequency considered here, separation and vortex formation will take place in the wake of an oscillating cylinder only if the relative amplitude of oscillation is greater than about 0.45.

When, on the other hand, the relative amplitude is increased from 1.5 to 2.0 and 2.4, the general flow pattern in the wake of the oscillating cylinder is still as described before, but is magnified and asymmetry of the twin-vortices sets in after a smaller number of strokes. At a relative amplitude of 2.0 (see Sequence 6), the length of the twin-vortices at the point of maximum velocity is about 0.37 D, and the maximum length of these vortices during the first stroke is about 0.75 D. At A/D equal to 2.4, these two dimensions become 0.47 D and 0.8 D respectively. These values are found to be the same for all the frequencies of oscillation investigated at these relative amplitudes. During the second stroke, the twin-vortices in the wake of the cylinder become completely asymmetric but remain attached to the cylinder until the point of inversion where they leave the cylinder asymmetrically. Eventually, during the following strokes the vortices are shed alternately. Again the asymmetry of the twin-vortices is setting in earlier and is more pronounced at higher frequencies of oscillation than at lower frequencies. For the relative amplitude of 2.4 and a frequency of 15 cycles/minute (see Sequence 7), the twin-vortices are only slightly asymmetric at the end of the first cycle while for a frequency of oscillation of 30 or 40 cycles/minute the vortices are on the verge of being shed at the same point.

At a relative amplitude A/D of 3.2, the wake corresponding to the frequencies of 20 and 30 cycles/minute exhibit different characteristics. For both frequencies, the length of the twin-vortices at the point of maximum velocity is about 0.63 D and the maximum length of these vortices is about 1.0 D. At the frequency of 20 cycles/minute (see Sequence 8), after having reached their maximum size during the first stroke, the twin-vortices become asymmetric and at the point of inversion one of the vortices leaving the cylinder is much larger than the other. This causes the early asymmetry and then the alternate shedding of the twin-vortices during the second half and following cycles. At the frequency of 30 cycles/minute, after having reached their maximum size, the twin-vortices remain symmetric but become completely distorted and their boundary seems to disintegrate before the first point of inversion of the oscillatory motion. During the second and following strokes the vortices are shed alternately.

At the relative amplitude of 4.8 and a frequency of 20 cycles/minute (see Sequence 9), the length of the twin-vortices at the point of maximum velocity is about 1.0 D and the vortices keep growing until they reach a length of about 1.25 D. At this point the vortices become completely distorted but remain fairly symmetric and shedding seems to occur just before the first inversion point of the motion. As the cylinder is completing the second half of the first cycle, a regular Karman vortex-street appears in its wake.

It is not clear why, suddenly at a higher relative amplitude, the twin-vortices become completely distorted but remain symmetric at a point where at lower relative amplitude the asymmetry of the twin-vortices would occur. The thought that this phenomenon could take place above a critical acceleration of the model does not hold since several of the sequences investigated exhibit higher acceleration without giving rise to this phenomenon.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The flow pattern about a circular cylinder oscillating in a fluid has been investigated. The flow was considered to be two-dimensional; the fluid used for the investigation was water. Tracer elements were employed to gather photographic evidence of the physical phenomenon.

As shown by the evaluation of the results, the frequency of oscillation of an oscillating cylinder had little effect on the wake of the cylinder in the range of the frequencies investigated here. The frequency of oscillation has, however, a very definite influence on the wake of an oscillating cylinder since for any oscillatory motion producing an established wake at a given frequency, another lower frequency can be found at which no separation will occur, thus producing a completely different wake. The dimensions and characteristics of the vortices in the wake of an oscillating circular cylinder were, however, strongly dependent on the relative amplitude of the oscillation. The number of cycles required for the twin-vortices to become asymmetric and eventually to be shed during a stroke depended strongly on the relative amplitude of oscillation and only slightly on the frequency of the oscillatory motion. It was also seen that, independently of the number of cycles undergone, the relative amplitude of oscillation A/D had to be greater than about 2.0 if alternate shedding of the twin-vortices had to take place during a stroke some time after the start of the oscillatory motion.

Areas of further study should include mainly the investigation of lower frequencies of oscillation. Investigation of higher frequencies or higher amplitudes of oscillation would require the motion to be photographed on a plane parallel to but beneath the surface of the water.

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