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VORTEX-INDUCED VIBRATION STUDIES

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RESEARCH AND DEVELOPMENT REPORT

July 1958

Report 1190

VORTEX-INDUCED VIBRATION STUDIES

by

Morris S. Macovsky

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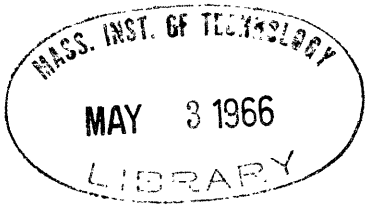

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ABSTRACT

The progress at the David Taylor Model Basin of basic studies concerning the mechanism of vortex-induced vibration of a circular cylinder is reviewed. Techniques for measuring lift and drag forces and for analyzing wake structure are presented. Measurements of the maximum alternating lift force coefficients in the Reynolds range $10^4 < R < 10^5$ are given. It is shown that these values are comparable to the drag coefficients at the low end of this Reynolds range, but diminish rapidly near 10^5. Breakdown of the two-dimensionality of the flow is presumed to be the explanation, judging from earlier flow studies.

INTRODUCTION

The phenomena of periodic vortex-shedding from a body immersed in a moving stream has been investigated at the David Taylor Model Basin for some time. Early studies[1] of the problem at TMB were undertaken just before World War II. During and after the war the problem of improving periscope performance[2, 3] by eliminating vortex-induced vibration revived interest in the subject. Subsequent interest in designing vibration-free submarine radar masts, submarine radio antennae, and other strut appendages subject to these unsteady hydrodynamic forces stimulated research in this field. Especially lacking from the point of view of the designer was a method for predicting the magnitude of the periodic vortex-induced forces, as well as an understanding of the mechanism of shedding in order to design optimum fairing shapes that could minimize the adverse vortex interaction effects.

With these motivating factors, TMB was authorized to design and construct a miniature model basin, and to assemble necessary equipment for investigating the mechanism of vortex shedding. This report summarizes the progress made to date. The equipment assembled, the techniques developed, and the results obtained are described.

THE PROGRAM

The program outlined at the start of this project consisted of both experimental and theoretical investigations of the vortex wake behind bodies that vibrate as a result of their interactions with the wake. The ultimate aim was to achieve a complete understanding of the mechanics of vortex-excited vibrations and of the effect of forced vibrations on the resultant geometry of the wake. Later phases of the project were to include a study of methods for suppressing vortex formation.

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[1]References are listed on page 14.

Before theoretical analyses could be undertaken, it was obvious that some experimental results were essential to guide the thinking. The initial phase of the program, therefore, was to investigate the two-dimensional flow about smooth circular cylinders. This study was to consist of the measurement of the magnitude and the time variation of the forces induced on the cylinders by the vortex wake at low Reynolds numbers. From photographs of the vortex formation in the wake made concurrent with force measurements, it was desired to correlate the phase and strength of the vortices formed with the time variation of the lift and drag forces. The study would then be extended to correlate imposed lateral vibrations with the resulting forces on the cylinders and the vortex patterns in the wake. The amplitude of vibration would be varied in convenient steps and the range of forced frequencies would include the frequency of vortex formation and would extend over an adequate range on each side of resonance. In each case, instantaneous velocity measurements made in the wake could permit the determination of the strength and geometric configuration of the vortices shed from the smooth cylinder, and the determination of the correlation of these measured vortex strengths with the instantaneous magnitude and phase of the wake-induced forces.

INSTRUMENTATION

MINIATURE MODEL BASIN

In accordance with the above-mentioned authorizations and test propram, the miniature model basin shown in Figure 1 was constructed. The tank, which has an overall length of 57 feet and a 2-foot square cross section, floats on cork padding in the supporting framework. This method of support provides some isolation against possible transmission of vibrations from the floor. As seen in the photograph, the 10-foot test section is glass-paneled for both viewing and photographing flow configurations. A similar panel is installed on the tank bottom to permit lighting the test section. The upstream end (left end of the photograph) is provided with a "dry dock." A plate inserted in a grooved section of the tank, 3 feet from the end, permits emptying this portion for the mounting of models and the calibrating of dynamometers. The access port is visible in the photograph.

CARRIAGE

The carriage shown in Figures 1 and 2 is driven by an endless cable, as seen in Figure 1. The carriage is supported by 3 wheels with side guide wheels which limit side motion of the order of 0.003 inch. Potentiometer control of the drive motor permits continuous variation of the carriage speed, without load, from 0.5 to 9.0 feet per second. The drive system is equipped with an electromagnetic brake activated by a trip switch mounted on the rails. Should this brake fail to operate, the carriage motion would be arrested at the far end of the basin by a pneumatic bumper that strikes a stop plate, shown in Figure 2.

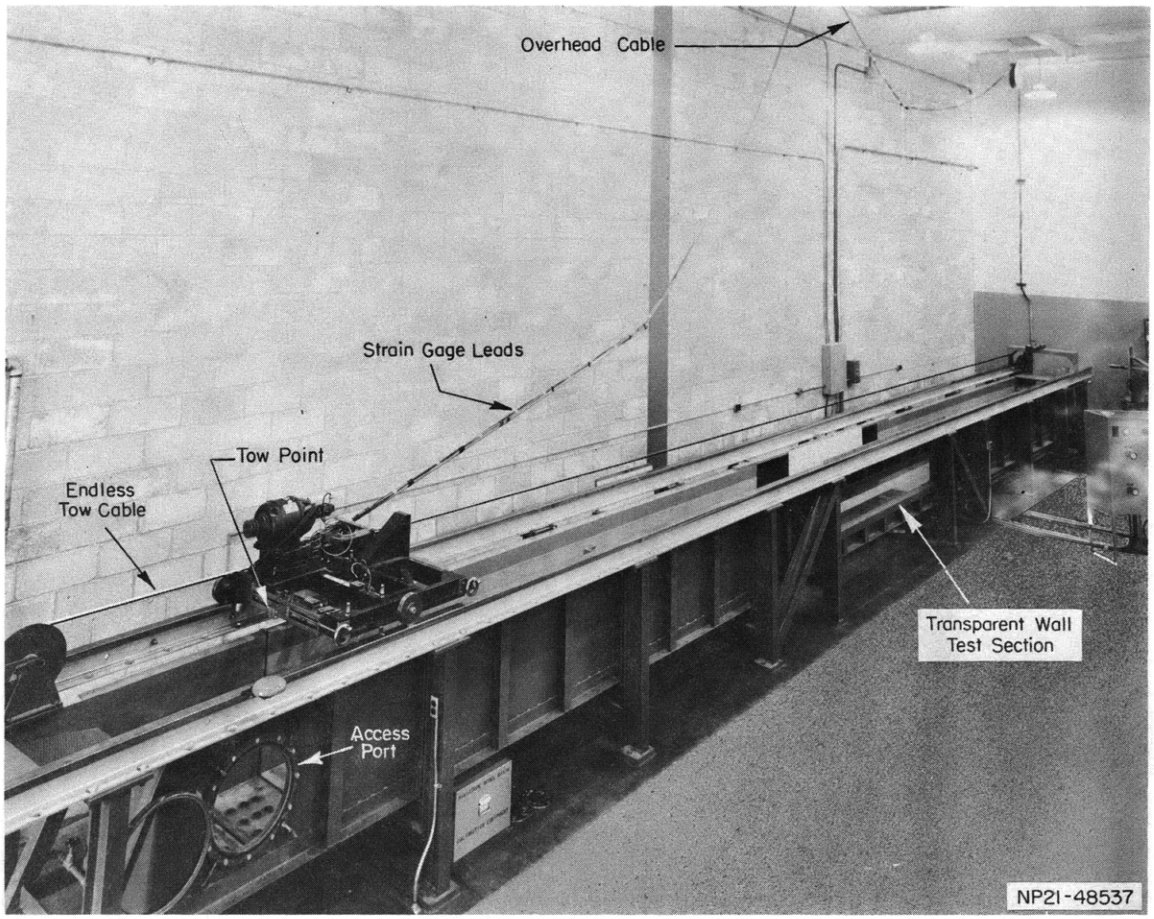

Figure 1 – Miniature Model Basin and Carriage

Also as shown in Figure 2, the carriage is equipped with a mechanical oscillator for driving a model in the vertical plane; i. e., normal to the direction of motion. Power for the oscillator motion is delivered by the overhead cable visible in Figure 1. The oscillator half-amplitude can be varied continuously from 0 to 2 inches by proper positioning of the eccentric driving arm. The frequency, which of course is governed by the drive motor rpm, is variable through a continuous range from 0 to 20 cps, the full range being restricted to amplitudes such that vertical acceleration does not exceed 5 g's.

Also visible in Figure 1 is a tow point which can be varied in position in a direction normal to the tank centerline. A similar tow point on the forward end of the carriage is shown (Figure 2) without the lead screw in place.

The dynamometer assembly is mounted on the oscillator beam as shown in Figure 3. This dynamometer consists of four ring-type flexures: two for measuring lift, and two for drag. Deflections are detected by wire strain gages pasted on the flexures. The sensitivity of the dynamometer system may be changed by substituting flexures of different thicknesses. The maximum design loads for the dynamometer are 60 pounds drag and 250 pounds lift.

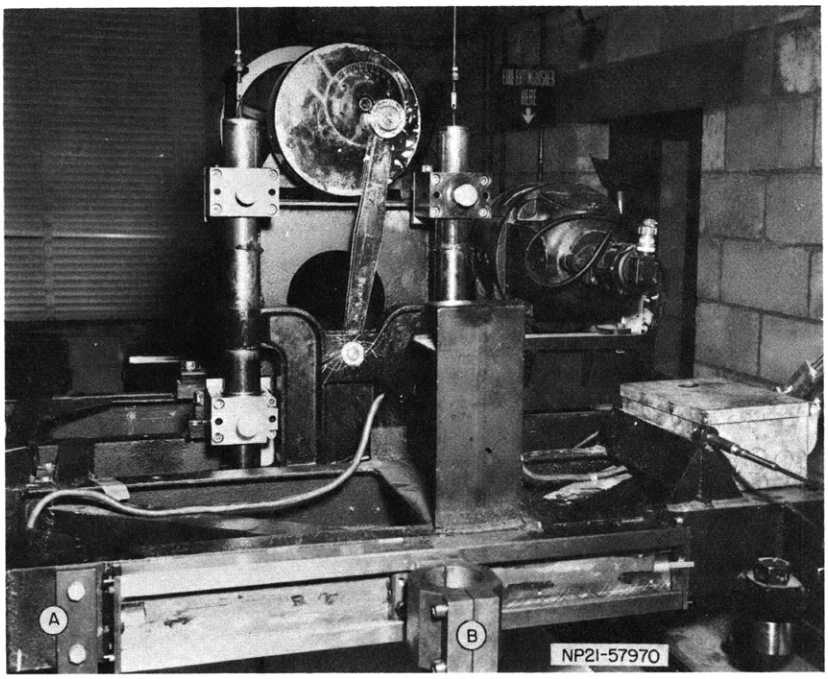

Figure 2 – Close-Up View of Carriage Showing Oscillator

A. Stop Plate
B. Forward Tow Bracket

Signals from the strain gages are transmitted to Sanborn strain gage amplifiers and a Sanborn model 67, 4-channel recorder. The overhead strain-gage leads are shown in Figure 1.

Dynamometer calibration is conducted by the application of known loads to a dummy model, in the directions of the hydrodynamic forces. By adding weights to pans appropriately placed on the calibration equipment, the system can be calibrated in any oscillator position, the oscillator beam being locked in any desired position. At the time of calibration, the carriage position is fixed to the rail by dowel pins.

To measure and record carriage speed, a 30-foot brass speed bar has been mounted on the rails. This bar, centered on the test section, has been equipped with insulator plugs inserted in holes placed at 6.000-inch ±0.005-inch intervals. A point contactor mounted conveniently on the carriage completes an electrical circuit when in contact with the brass bar. Interruptions of the current, by passage of the contactor over an insulator plug, are recorded on a two-channel Sanborn recorder having a calibrated paper speed. By this method, average carriage speeds over a 0.5-foot interval can be measured to an accuracy of ±0.001 foot/second.

OPTICAL EQUIPMENT

Since one of the objectives of this research program is to correlate vortex-wake structure with the induced lift, it was necessary to devise a method for visualizing the wake,

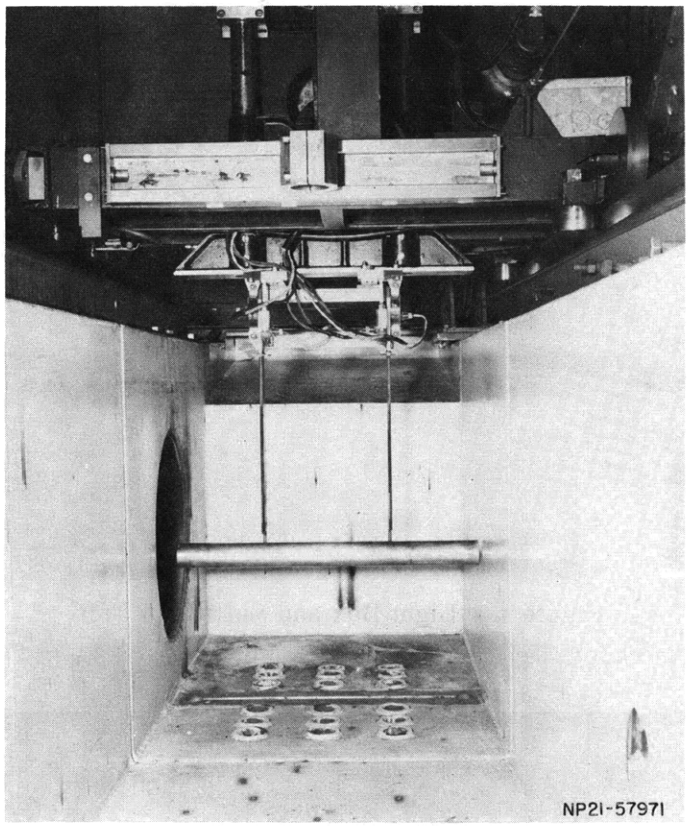

Figure 3 – Dynamometer, Struts, and Test Cylinder as Mounted on Oscillator Beam

and at the same time for measuring the vorticity. Of the methods considered, the most promising was that of the neutrally-buoyant oil-droplet technique, which consists of mixing carbon tetrachloride and mineral oil in proper proportions (approximately one part CCl_4 to three parts mineral oil). The mixture, when broken up into small spherical globules in water suspension, has the property of reflecting maximum light at approximately 90 deg to the source of illumination. Hence to employ this property, a light box (shown in Figure 4) was constructed. It contains an FT 23 GE type multiflash bulb 54 inches long. Light emitted from the bulb is passed through a cylindrical collimating lens over which is a variable-width aperture. By placing the bulb at approximately the focal line of the lens, a narrow plane of light can be transmitted through the bottom test section window, to illuminate the oil-drop suspension. This bulb, a multiflash type, is powered by a unit (also shown in Figure 4) which was constructed specifically for this project. The power unit consists of three banks of condensers that are discharged consecutively through the bulb by means of triggering circuits. The interval between flashes can be varied in steps of 0.001 second from 0.001 second to 0.010 second. By this technique, therefore, it is possible to record three successive positions of an illuminated droplet as it is placed into motion by the flow over the model. Such motion is then recorded on a photographic plate that is triple-exposed.

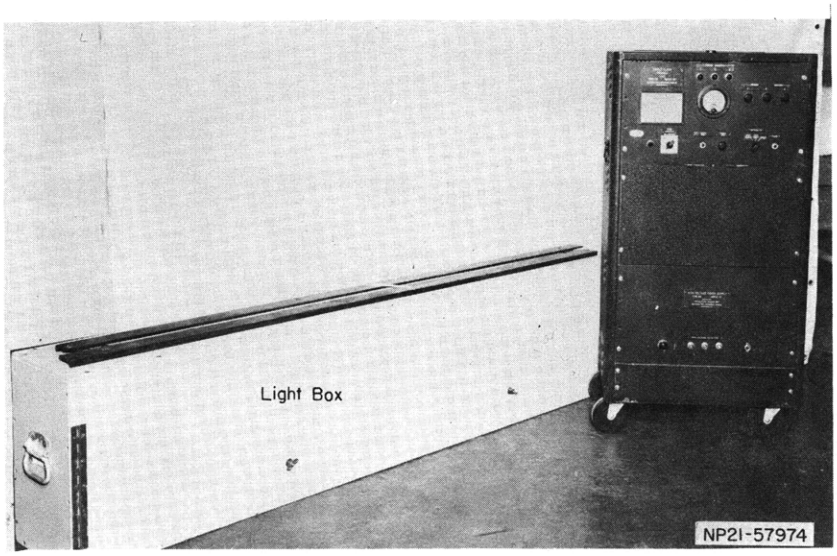

Figure 4 – Light Box and Multiflash Unit

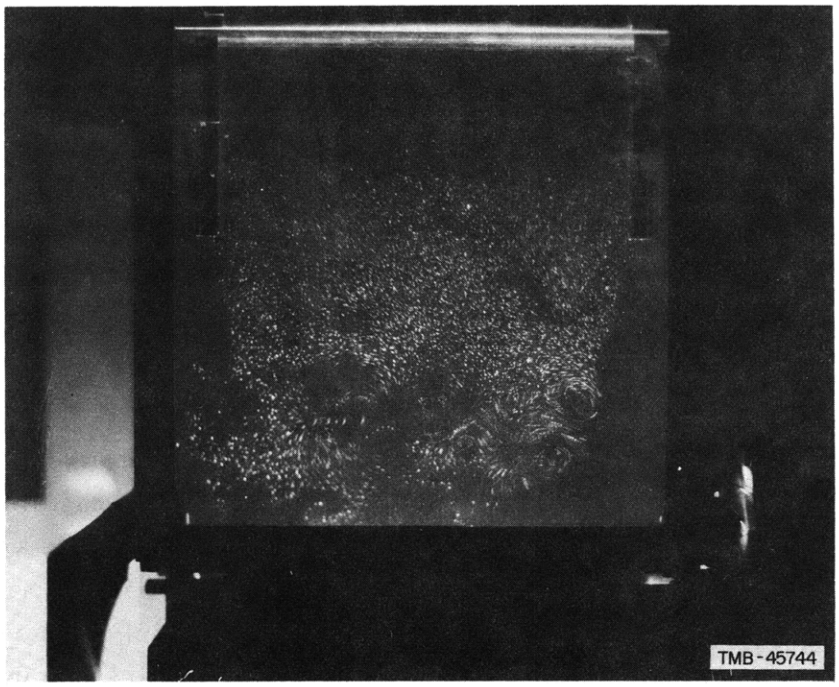

Figure 5 – Sample Multiflash Photograph of Neutrally Buoyant Oil-Drop Suspension in Wake of a Cylinder

This photograph was taken in a small brass tank having one glass side and glass bottom. Tests to perfect this photographic technique are conducted in this facility.

A microswitch, mounted appropriately on the rail, triggers the multiflash unit when the model, or any desired portion of the wake, is in the plane of view of the camera. The photographs,

of course, can be taken only with the room sufficiently darkened and with the camera shutter open during the entire interval of the test section portion of the run. A 4-inch by 5-inch Speed-Graphic camera having a Kodak Aero Ektar f:2.5 lens is used for the wake photography; a sample photograph is shown in Figure 5. By measuring the distance between successive positions of a droplet on the film, and knowing the time interval of exposure and distance calibration of the plane of view, it is possible to measure average droplet velocities. With a sufficient distribution of such droplets in the photograph, the vorticity in the wake can be determined by a line integration of the velocity over a properly chosen closed circuit.

BASIC ASSUMPTIONS AND CONSIDERATIONS

At the outset of this program, it was proposed that tests be conducted on circular cylinders for correlation with existing data on cylinder forces and wake pattern. Also, this shape would lend itself to theoretical treatment. Consequently, two aluminum cylinders were constructed, having lengths of approximately 24 inches (the width of the channel). It was intended that the model length be carefully adjusted so that a minimum of clearance to the channel walls be maintained in passage through the test section. As such, these models could be considered infinitely long if the end flows were thus eliminated. It was also assumed that at reasonably low Reynolds numbers,* say less than 10^4, the vortex filament being shed from the cylinder was two-dimensional, and consequently at any instant one could observe precisely the same wake pattern at any cross section of the wake. Based upon the assumption of two-dimensionality of the flow, it was considered sufficient to suspend oil droplets in any vertical plane which could most easily be illuminated. For the most part, this was approximately the centerline plane. The validity of this assumption is discussed later in this report.

After assuming that two-dimensional flow should exist, and that end flows should be insignificant in the test arrangement, it was further assumed that by attaching the dynamometer struts symmetrically to the cylinder (with respect to the centerline) the resulting hydrodynamic forces would be equally divided between the two drag and the two lift dynamometers. It was expected that the force records would consist of two periodic signals exactly in phase for the lift force, and perhaps, if sufficient sensitivity existed, two in-phase periodic signals for the drag force. The total force, in each case, would then be the algebraic sum of the two signals of each force component.

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*Reynolds number $= \frac{Ud}{\nu}$, where U is the cylinder velocity, d is its diameter, and ν is the kinematic viscosity of water.

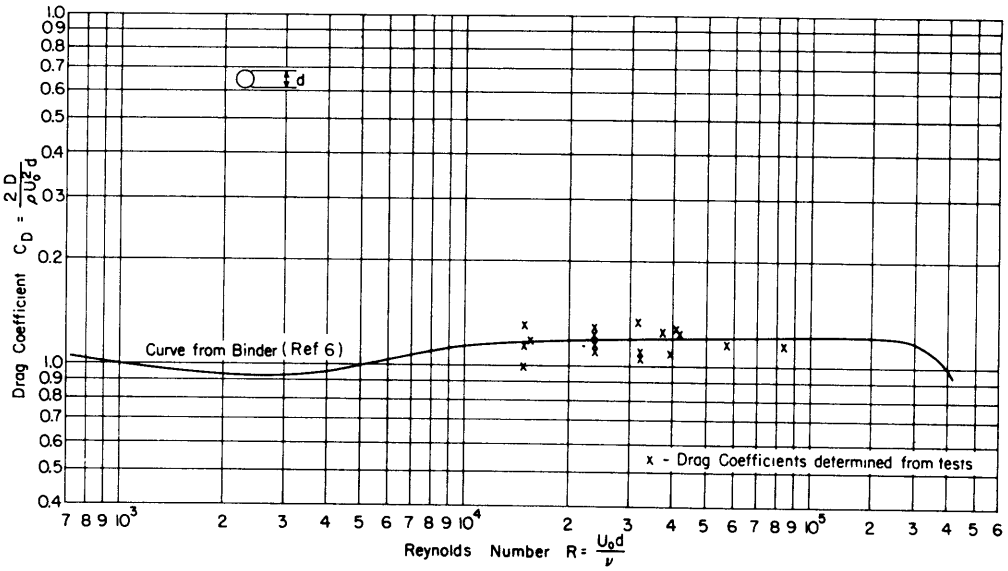

Figure 6 – Drag Coefficient versus Reynolds Number for Cylinder

PRELIMINARY EXPERIMENTS

FORCE MEASUREMENTS

As mentioned in the previous section, the first set of tests was performed with a circular cylinder for correlation of the results with existing data. Such correlation, in effect, serves as a means for checking the accuracy of the instrumentation and the validity of the interpretation of the recorded data.

The first set of tests was conducted on a cylinder 1 inch in diameter. The drag coefficients were determined and compared, with well established cylinder data (Figure 6). As shown, the drag coefficients agree reasonably well with existing data. Examination of the vortex-induced force records, however, uncovered a phenomenon which has altered the course of this project. Although the periodicity of the vortex-induced forces agreed well with the empirical Strouhal-Reynolds number relationship, neverless the two records of lift force were not always in phase, as had originally been assumed. Figure 7 is a photograph of a typical Sanborn recorder tape illustrating this phenomenon. The high-frequency traces are due to mechanically imposed "hash" arising from imperfect carriage wheels, rails, etc.

The first interpretation of the out-of-phase lift force records was that three-dimensional flow must have existed on the 1-inch cylinder as a result of the imperfections in the construction of the cylinder. Upon careful inspection, this test cylinder was observed to be pitted and bowed. Consequently, to determine the effects of these imperfections as well as to obtain higher Reynolds number data, a smooth and straight cylinder 2 inches in diameter was constructed and similarly tested. The results were comparable to those of the previous model. Further attempts to "clean up" the cylinder consisted of cutting away at the

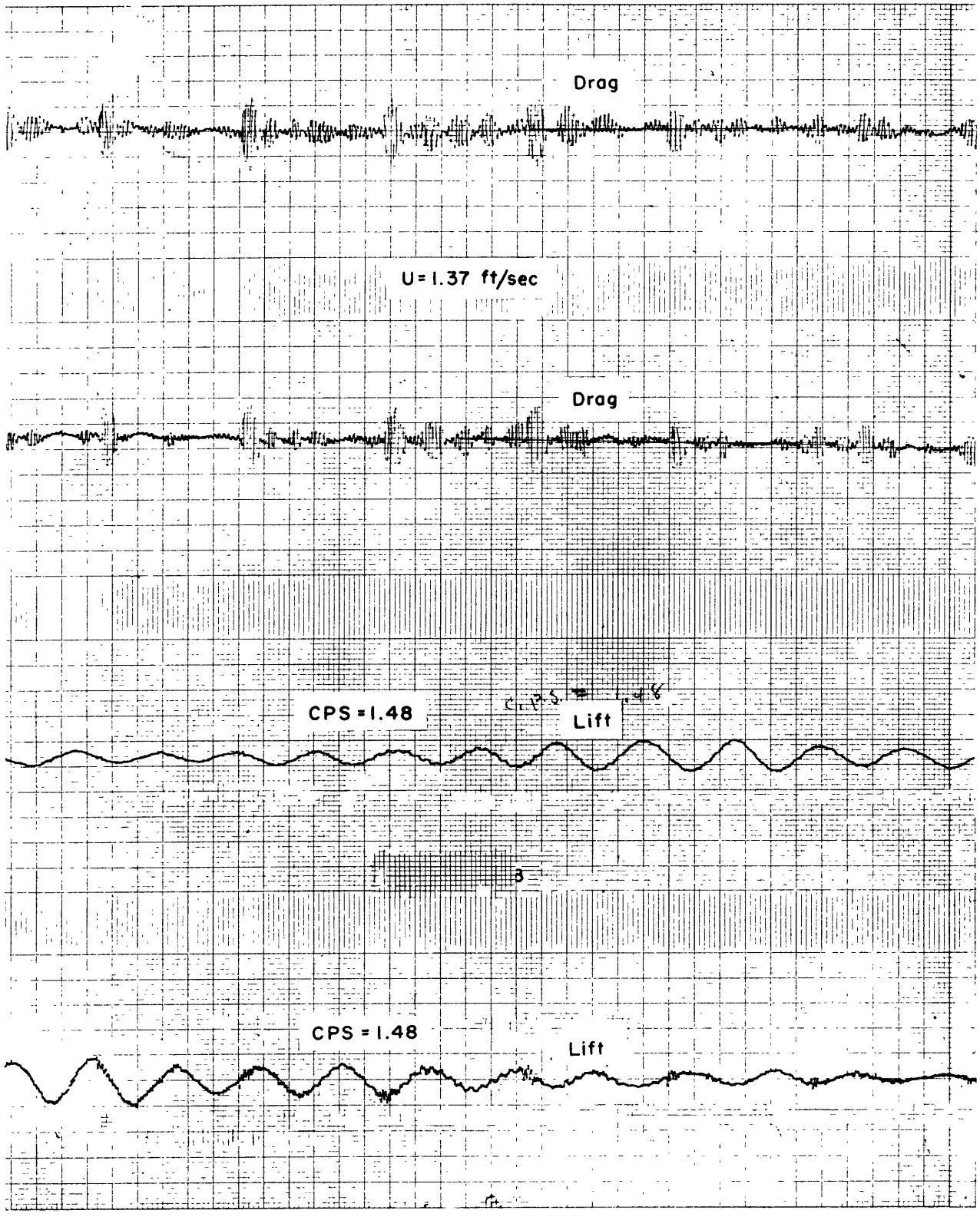

Figure 7 – Reproduction of Sample Oscillograph Record of Drag and Lift Measurements Showing Out-of-Phase Lift Records

strut-cylinder welds as much of the supporting struts as was feasible, in order to determine their influence on the two-dimensionality of the flow. A similar cylinder with struts attached to the ends of the cylinder was also tested. The results of these tests were again comparable to the others. Consequently, in order to observe the exact nature of the flow, it was decided to conduct flow visualization tests.

FLOW STUDIES

The 2-inch cylinder was first equipped with thread tufts attached to the trailing directrix. The test conditions (without recording the forces) previously run were repeated; visual and photographic observations of tuft configurations were made. From a series of tests of this type, both in the miniature model basin and in the circulating-water channel, it seemed quite obvious that the flow was definitely three-dimensional; i. e., the vortex sheet being shed was not homogeneous along the axis of the cylinder.

These tests were not considered conclusive, in view of the possibility that the inertia of the threads and their initial configurations might influence the resultant pattern of the set. Consequently, to remove any doubt regarding the true flow, the cylinder was equipped with jets placed 2.75 inches apart along the trailing direction. Emission of a purple dye (potassium permanganate which is neutralizable by sodium bisulphite) permitted photographic recording of the vortex wake at each of the injector stations. Care was taken, of course, to inject the dye with little or no initial velocity.

These dye injection tests proved quite convincingly what was previously suspected; namely, that the flow over the cylinder in the Reynolds range of $10^3 < R < 10^4$ was three-dimensional. Figure 8 consists of enlargements taken from the motion pictures which illustrate this phenomenon.

After these flow studies, the experiments by Roshko[4] were called to the attention of this writer. The above conclusions regarding the three-dimensionality of flow over the cylinder had also been observed by Roshko. Using hot wires and a wind tunnel as his test facility, he observed a spanwise periodic structure of the vortex street. Similar experiments using hot wires were conducted at TMB, both in the miniature model basin and in the low-turbulence wind tunnel. Very cursory observations were conducted merely to determine the feasibility of the techniques in the two facilities for future use.

TESTS ON A MODIFIED CYLINDER

As a result of the foregoing experiments, it was decided that the only possible successful approach to this problem lay in the redesign of the test cylinder. Instead of attempting to measure forces over a long cylinder and correlating them with observations of wake structure, it was decided to measure forces and wake on only a short segment* of

*This approach, determined independently, concurs with that proposed by Roshko (Reference 4). After the completion of this manuscript, the report by McGregor came to the attention of the author. See Reference 5.

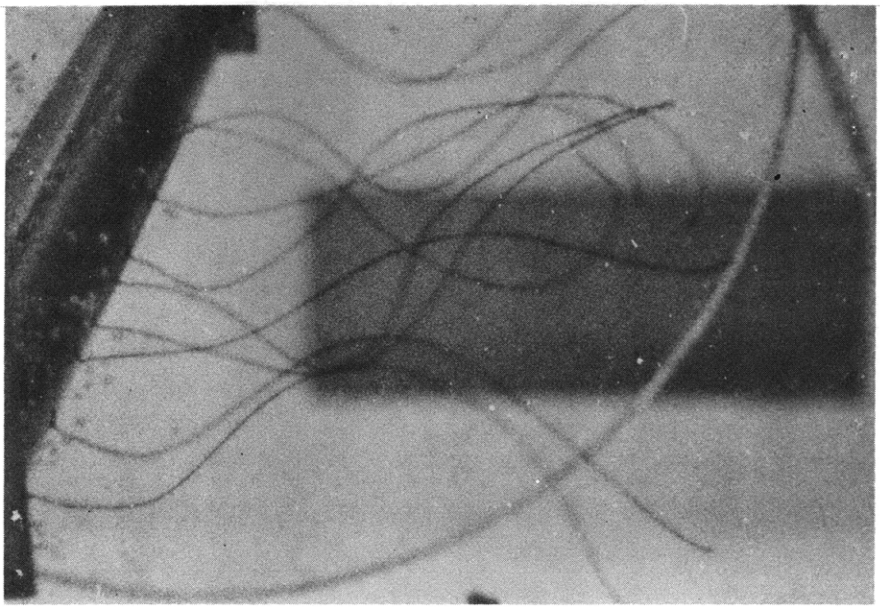

Figure 8a – Cotton Tufts
Note out-of-phase relationship across entire span.

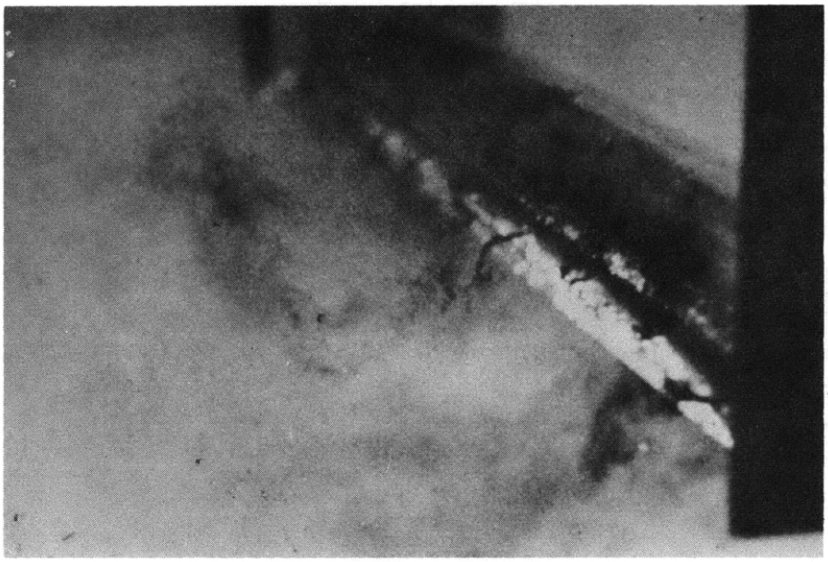

Figure 8b – Dye Emission
Note jets in foreground out-of-phase with those in rear.

Figure 8 – Enlarged Motion-Picture Frames Showing Three-Dimensionality of Flow over Test Cylinder

the cylinder. Figure 9 is a photograph of the new design. The central 4-inch segment of the cylinder is supported freely, independent of the remainder of the cylinder.

Force measurements on this segment have been conducted[6] in the Reynolds range $10^4 < R < 10^5$. The results are given in Figure 10. With the exception of the lowest Reynolds number data, where instrumentation sensitivity was inadequate, the drag coefficients agree reasonably well with the average drag curve for a smooth circular cylinder. The maximum

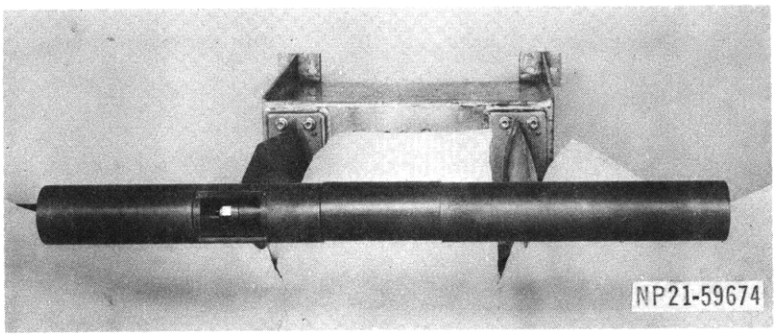

Figure 9 – Segmented Two-Inch Cylindrical Model

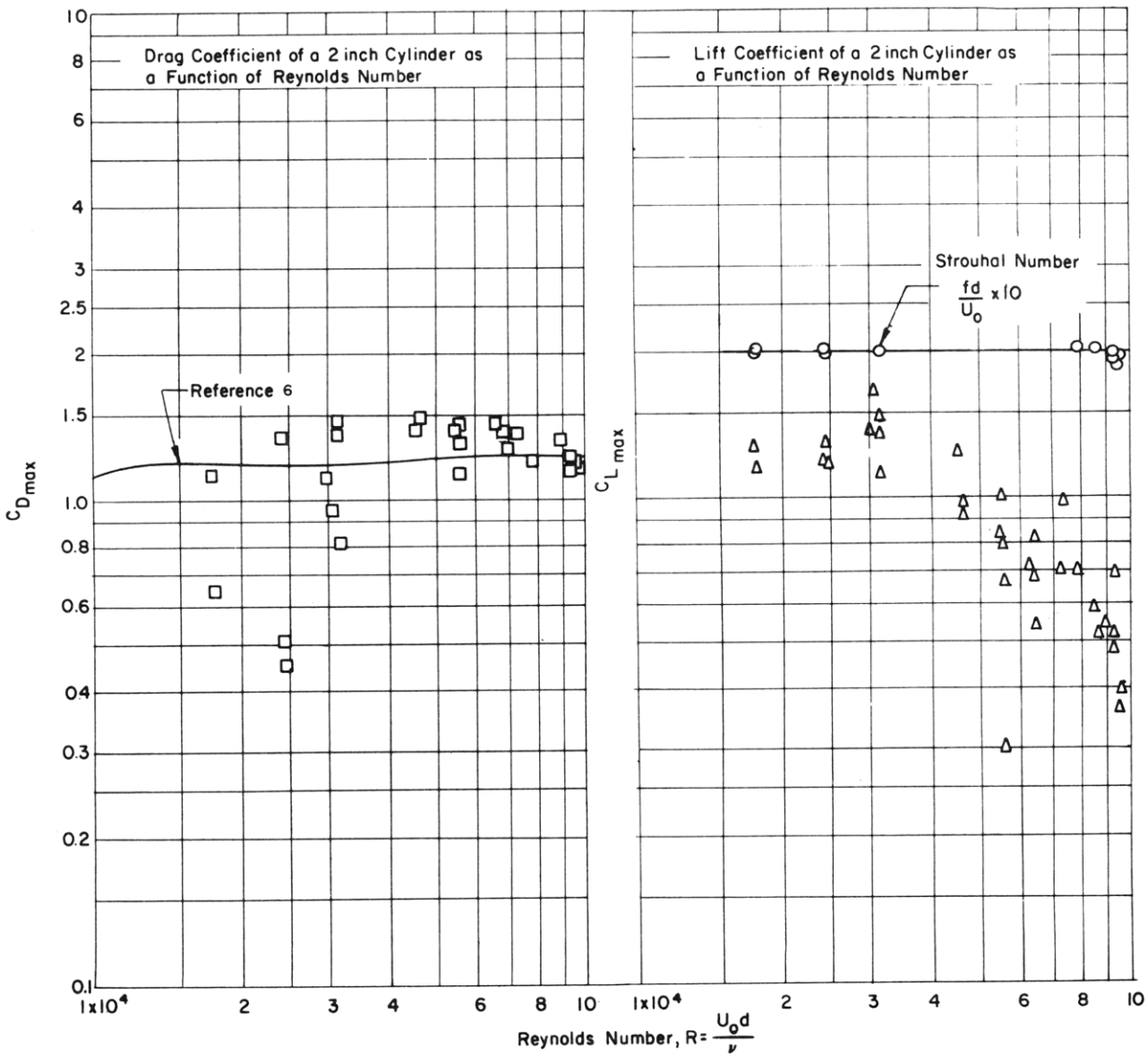

Figure 10 – Drag and Lift Coefficients as Function of Reynolds Number

lift coefficients are believed to be the first of their kind to be measured; consequently, no comparison with existing data can be made. These coefficients are defined as

$$C_{L_{max}} = \frac{|L|_{max}}{\frac{1}{2}\rho U_0^2 d}; \qquad C_{D_{max}} = \frac{|D|_{max}}{\frac{1}{2}\rho U_0^2 d}$$

where $|L|_{max}$ and $|D|_{max}$ are the absolute magnitude of the maximum half-amplitude values of alternating lift and drag forces per unit length, respectively.

ρ is the density of the fluid,

U_0 is the free-stream velocity, and

d is the diameter of the cylinder.

Since the test segment is not affected by three-dimensional end-flow effects, the coefficients essentially represent the value on a unit length of a cylinder of infinite length.

The diminishing values of the lift coefficient with increasing Reynolds number are consistent with the concept of the breakdown of the two-dimensional vortex sheet discussed earlier. As the speed increases, the wake of the cylinder becomes increasingly turbulent to the extent that the vortex pattern is three-dimensional. Consequently, the net alternating lift force, while exhibiting a predominant Strouhal frequency, diminishes in magnitude because of the canceling effects of the more or less randomly distributed vorticity. This concept applies to the rigid cylinder only. It is expected that a cylinder free to vibrate under the influence of the alternating lift force would tend to couple its motion with the wake being shed, to the extent that the two-dimensionality of the vortex sheet is preserved with increasing speed. Lift coefficients for this condition would largely depend upon the natural frequency of the cylinder suspension and the damping of the system.

CONCLUSIONS

In conclusion, the significant result obtained may be summarized as follows:

A circular cylinder, held rigidly in a fluid stream, is subjected to alternating lift forces having the same order of magnitude (for its maximum) as the steady drag force. Beyond the critical Reynolds number, the magnitude of this force diminishes rapidly as a result of the breakdown of the two-dimensionality of the flow.

RECOMMENDATION

The experiments conducted to date are merely the beginning. Measurement of wake structure using the neutrally buoyant oil droplets or some other convenient technique should be undertaken to confirm the hypothesized three-dimensional structure and correlated to the alternating forces. This will require span-wise vorticity correlation studies, as well as the correlation of vortex strength with instantaneous lift forces.

REFERENCES

1. Landweber, L., "Flow about a Pair of Adjacent, Parallel Cylinders Normal to a Stream; Theoretical Analysis," David Taylor Model Basin Report 485 (Jul 1942).

2. Grimminger, G., "The Effect of Rigid Guide Vanes on the Vibration and Drag of a Towed Circular Cylinder," David Taylor Model Basin Report 504 (Apr 1945).

3. Price, P. and Thompson, R. W., "Suppression of Fluid-Induced Vibration of Circular Cylinders," Thesis submitted to Stanford University, Department of Aeronautical Engineering (Dec 1953).

4. Roshko, Anatol, "On the Development of Turbulent Wakes from Vortex Streets," National Advisory Committee for Aeronautics TN 2913 (Mar 1953). (Superceded by National Advisory Committee for Aeronautics TR 1191; also in Document File.)

5. McGregor, D. M., "An Experimental Investigation of the Oscillating Pressures on a Circular Cylinder in a Fluid Stream," University of Toronto, Institute of Aerophysics, UTIA Technical Note 14 (Jun 1957).

6. Binder, R. C., "Fluid Mechanics," Prentice Hall, Inc., New York (1943), p. 136.

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The progress at the David Taylor Model Basin of basic studies concerning the mechanism of vortex-induced vibration of a circular cylinder is reviewed. Techniques for measuring lift and drag forces and for analyzing wake structure are presented. Measurements of the maximum alternating lift force coefficients in the Reynolds range $10^4 < R < 10^5$ are given. It is shown that these values are comparable to the drag coefficients at the low end of this Reynolds range, but diminish rapidly near 10^5. Breakdown of the two-dimensionality of the flow is presumed to be the explanation, judging from earlier flow studies.

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2. Circular cylinders – Vibration
3. Fluctuating flow – Analysis
4. Model basins – U.S. – David Taylor Model Basin
5. Vortices – Testing equipment

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