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DRAG COEFFICIENTS OF VIBRATING
SYNTHETIC ROPE

by

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ABSTRACT

The drag, amplitude, frequency tension, diameter and length
of synthetic ropes vibrating because of vortex-induced forces, and
not vibrating at different tensions were measured. Photographs
were taken of the vortices. Drag coefficients were calculated
and plotted against Reynolds Number. The measured frequency is
compared with data from other sources. The measured diameter is
compared with that calculated from conservation of volume.

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CHAPTER I

INTRODUCTION

With the emphasis on the study of the deep ocean in the past decade and the next, more sophisticated ocean data acquisition systems are being built and used. One of the most challenging systems to build is the unmanned, moored, instrumented buoy system. This system may be moored in the deep ocean with either the whole system being submerged, Fig. 1, or the main floatation being on the surface, Fig. 2. As can be seen from these figures obtained from the W.H.O.I. Buoy Engineering Group, these systems are complicated and they must operate unattended in the ocean for months at a time.

One of the important factors in the design of the buoy system is the drag of the cable and rope used in the mooring. Computer programs have been generated to solve the mooring line configuration under the influence of the forces imposed on the cable by the current at the particular site. These programs depend upon the drag coefficient C_d to predict one of the forces, the pressure drag force, exerted on the cable. The pressure drag coefficient is determined by testing and plotting the results against the Reynolds number. Having C_d one may use:

$$R = 1/2 \rho C_d d V^2$$

R = pressure drag (pounds)

ρ = fluid density (slugs/ft³)

d = diameter of cable (feet)

V = velocity of fluid relative
and normal to cable (feet/sec)

So far C_d has been obtained mainly for smooth cylinders but has been used in cable and rope calculations. Another factor affecting C_d

*TYPICAL W. H. O. I.
INTERMEDIATE
MOORING*

Figure 1
Subsurface Mooring

PURPOSE OF TEST — EVALUATION OF MOORING CONFIGURATION AS SHOWN OVER
A TWO MONTH PERIOD — MEASUREMENT OF MOORING TENSION STRECH 13%
PROCEDURE — LAUNCH BOOY, PAY OUT MOORING LINE, ATTACH
BALLS, LAUNCH ANCHOR, CHECK ANCHORING,
RETRIEVE NEXT CRUISE
EQUIPMENT — AS SHOWN

Figure 2
Surface Mooring

is the cable's vibration which may change the drag coefficient as much as 35% (12). These vibrations are caused by the shedding of vortices from the sides of the cable which induces lateral periodic side forces on the cable. These side forces cause the cable to vibrate laterally in a direction perpendicular to the direction of fluid flow. The frequency of these vibrations can be obtained from the Strouhal number. This is an empirical dimensionless number based on the frequency of vibration, diameter of the cylinder or rope, and the component of fluid velocity normal to the cylinder.

$$S_t = \frac{fd}{u_n}$$

f= frequency (cps)

d= diameter (feet)

u_n = fluid velocity normal to the cylinder (feet/sec)

The Strouhal number is plotted against Reynolds number as seen in references 3, 5, 22, and 23. The Reynolds number range of 10^3 to 10^5 is the one the report will be concerned with. In this range the Strouhal number remains fairly constant at 0.2 for a cylinder. The frequency of vibration for a cylinder is given by the expression below:

$$f = \frac{0.2 u_n}{d}$$

Using the Strouhal number for a cylinder, we can estimate the frequency of vibration of rope. In order to see what type of wave will form we must use the theory of vibrating strings. As presented in Den Hartog (13), a vibrating string vibrates in a sinusoidal manner. The natural frequency of vibration depends on the length and mass of the string. It also depends upon the tension the string is subjected to and

the number of 1/2 standing sine waves the vibrating string forms. These relations are presented in the expression below:

$$f = \frac{n}{2l} \sqrt{\frac{T}{\mu}}$$

f = frequency (cps)

n = number of 1/2 standing waves

l = length of the string (feet)

T = tension in the string (pounds)

μ = mass of the string per unit length (slugs/foot)

If the mass of the rope per unit length, the tension in the rope, the length of the rope, and the velocity of the fluid normal to the rope are known, then the frequency and wave form may be calculated using the following expressions:

$$f = \frac{0.2u_n}{d} \quad n = 2fl \sqrt{\frac{\mu}{T}}$$

Some measurements of drag have been made with vibrating rods, tubes, and smooth electrical cables. Since rods and tubes are stiff they can be suspended from their centers in a flow and the drag can be measured easily. They may also be mounted in a yoke shaped fixture and vibrated by external means. Bishop and Hassen (6) used this technique on a rigid cylinder in water and found the drag increased near the Strouhal frequency and decreased on both sides. Thus the drag follows a resonance curve with a peak at a frequency governed by the Strouhal number. They have also observed that the drag increases with an increase in amplitude of the vibrations and an increase in fluid velocity. The latter requires the vibrational frequency to increase for constant Strouhal number.

Koopman (16) has used this technique in a wind tunnel and found that the vortex aligns itself parallel to the rod when the rod vibrates

at the natural frequency and obliquely at different frequencies. Also the lateral spacing of the vortices on either side of the rod is reduced at the natural frequency.

Dale, Candless, and Holler (12) have towed smooth electrical cables in water for their study. They found that the curve of drag versus frequency exhibited maxima at those frequencies that satisfied the string formulas and Strouhal number presented earlier. The minimum values were approximated by the nonvibrating drag coefficients from curves such as those found in reference 15. It was also found that the drag coefficient decreased and the drag increased as the number of standing waves increased with velocity.

They also ran a test with two cables twisted together. The drag coefficient based on a cable two times the diameter of one of the cables twisted together was calculated. This was found to be significantly more than the twisted cable test data. This shows that the surface roughness of ropes may be a significant factor effecting drag.

Many investigators as well as the ones above have also noticed a lock in phenomena associated with vibrating cables. The vortex wake has the same natural frequencies even if the rod or cable is forced to vibrate somewhat away from the natural frequency. Koopman (16) has observed this locked in range to be about 25% of the natural frequency. As a rod or cable passes out of this range, the length of the regular vortex wake behind the rod shortens and finally disappears. The wake then becomes irregular until another natural frequency range is entered. Bishop and Hassan (6) among others, have also observed a hysteresis effect on the drag as a natural frequency is gone through and passed from the upper limit down and from the lower limit up.

Roshko (23) has observed the following about vortex shedding:

<u>Reynolds Number</u>	<u>Observation</u>
40 to 150	regular laminar vortex without turbulence
150 to 300	regular laminar and turbulent vortices
300 to 10000	fully turbulent vortices

Bearman (2) has observed turbulent vortices at Reynolds numbers up to 5.5×10^5 .

The peak to peak amplitude of these vibrations has been observed by Poffenberger (21) among others to be 2 diameters of the rope being tested.

There has been some measurement of drag coefficients of nonvibrating roughened cylinders. Hoerner (15) points out that around a Reynolds number of 2×10^5 there is a marked decrease in drag due to the formation of a turbulent boundary layer that retards separation of the flow around the cylinder. The rougher the cylinder, the lower is the Reynolds number where this may happen. It has been observed at a Reynolds number as low as 2×10^4 .

After searching the literature and consulting with the W.H.O.I. Buoy Engineering Group, I concluded no study of drag had been made on the synthetic rope used in W.H.O.I. moorings. Surface roughness seems to be an important factor in drag and the surface of a rope changes with tension. Since it is impossible to scale surface roughness, this thesis was directed toward measuring drag coefficients of rope, vibrating at 10 percent of rated breaking strength and not vibrating about 40 percent of rated breaking strength. The Reynolds number was $10^3 - 10^5$.

CHAPTER II

APPARATUS

Since the lines used in the oceanographic moorings of W.H.O.I. may be over a mile long and be subjected to tensions up to 5000 pounds, it is desirable that the rope exhibit good torque balance characteristics. Plaited and braided rope have this characteristic and are used at W.H.O.I. Since the moorings are left in the water for as long as three months, the material must be resistant to rotting. Since the stress in the rope depends on its weight and size, a material with as high a strength to weight ratio as possible is desirable. Thus, nylon and dacron rope are used.

The ropes tested with their size, breaking strength, material, and construction are listed below and shown in Figure 3.

<u>Size (inches)</u>	<u>Material</u>	<u>Construction</u>	<u>Breaking Strength (lbs)</u>
9/16	nylon	Columbian Ply-Moor 8 strand plaited	8,300
5/8	nylon	Columbian Ply-Moor 8 strand plaited	10,500
3/4	nylon	Columbian Ply-Moor 8 strand plaited	14,000
3/8	dacron	Samson single braided	3,520

Because it was desired to test the rope under actual working tensions, some type of heavy tensioning frame had to be built. This frame had to be fairly massive to support such stress. Such a frame would have also created undesirable end conditions if it had been immersed with the rope which ruled out the use of a towing tank. It was decided that the best way to conduct the experiment was to use the Variable Pressure Water Tunnel at the Massachusetts Institute of Technology (Fig. 4) for the test.

Figure 3. Ropes Tested

VARIABLE PRESSURE WATER TUNNEL

Figure 4

The heavy tensioning frame could be located outside the tunnel and the rope could pass through the test section. The rope could be allowed to move freely by sealing the tank with flexible rubber bellows at the points where the rope entered and left the test section.

Nylon stretches as much as 20 percent of its length for a load of 30 percent of its maximum breaking strength. Thus, a strong, simple design that would allow for a good deal of travel was desired. Also as long a span of rope as possible was desired to avoid end constraints on the rope. The design chosen, shown in Fig. 5, was a bucksaw type arrangement with the rope replacing the sawblade and a chainfall replacing the usual turnbuckle. A minimum safety factor of two was used in the design of this frame. Because of the dimensions of the room in which the water tunnel is located, the center member of the frame was eleven feet long, pin to pin. It was made from a three-inch water pipe with a safety factor of four in buckling according to AISC (Ref. 1) standards. Using beam theory in Timoshenko and Young (Ref. 26) two 5 $\times$ 9 channels were chosen for each arm of the frame. These were bolted together using four one-inch diameter steel spacers. Holes were drilled in the channel and pipe to accommodate one-inch diameter steel rods that were used as pivots. Collars were welded onto the central pipe and the channel to insure the safety factor of two in compression of the pin and bearing surface. Washers and cotter pins held the pivot pins in place.

At the ends of the arms two types of fixtures were used. At the lower end a 3/4-inch safety chain shackle was used to attach the hook of a two-ton chainfall. The upper end was a bit weldment, made from 1/2-inch steel plate and two-inch water pipe. The 1/2-inch plate was

Figure 5
Apparatus

welded to a one-inch pipe through which one of the pivot pins past. The rope was passed figure eight fashion around the bit and snubbed with a rolling hitch as shown in Figure 6.

Since the tensioning frame was to be raised and lowered as more or less tension was applied, a frame constructed of 4 x 4 and 2 x 4 was built with a jack screw in each corner (Fig. 5). The center pipe was placed in notches in the frame and fastened down with U-bolts.

In order to measure the drag on the rope, a U-shaped frame was constructed from 3 x 2 steel tubing. Bearing surfaces and all mating surfaces as seen in Figure 7 were machined to insure the bearing surfaces were parallel to each other and perpendicular to the dynamometer on top of the tunnel. The frame is shown in place in Figure 8. As seen in Figure 7 a delrin block with a V-notch machined in its upper surface was used to transmit the force on the rope to the bearing surface and then through the frame to the dynamometer. The dynamometer fixture was a plate suspended by steel flexures from a frame bolted to the upper window of the Water Tunnel. Incorporated into the flexures were removable load cells. The fixture is designed to measure forces on the suspended plate with 6 degrees of freedom. The bearing frame was bolted to this plate. Since only the downstream component of the force was desired, the load cell in the flexure designed to sense this component was the only cell read. The aluminum stock and steel tubing were used in the frame to insure the proper stiffness while still being light enough as not to put an undue strain on the dynamometer.

Figure 6 also shows the bellows arrangement that sealed in water and allowed the rope free movement. A 3.5-inch diameter hole was bored in the two side windows of the tunnel. Six blind holes were then drilled

Figure 6
Rope Attachment

Figure 7

Seal and Drag Pickup

Figure 8
Overall View of Apparatus

in each of the plexiglass windows and tapped for helicoils. An aluminum ring, also drilled, was placed over the flange of the bellows and bolted down. To seal against leakage between the rope and the bellows, silicon grease was smeared on the part of the rope that would be in the bellows. The bellows were then slid over this part of greased rope. Electrical tape was wrapped around the bellows for its protection. A hose clamp was then put over the tape and tightened. Though this seal seems quite makeshift it worked quite well, even with five feet of head on the tunnel.

To measure the drag on the rope, a Lebow model no. 3108-10 strain gauge sensor was used in the dynamometer on top of the tunnel shown in Figure 7. The cell had a capacity of ten pounds and a linearity of .1%. To display the output, a Lebow Model 66 Digital Strain Gauge Reader was used. The calibrate resistor was 60K and the counter range was 1000. The zero was set at 100 with a span of 799 on either side of zero. This gave a calibration factor of .01 pounds per counter unit. The six counters used with the tunnel are seen in Figure 7 to the left of the tensioning frame. In the experiment we used the upper right hand one.

For measuring velocity of the water, the tunnel has been calibrated with manometers at certain taps in the tunnel. Taps number seven over four with a Meriam No. D8325 open tube manometer using an indication fluid with a specific gravity of 1.75 were used in this experiment to measure velocity.

The tension in the rope was measured to plus or minus twenty-five pounds with a Martin Decker tensiometer. Its range was 0-5000 pounds. The sensing end was connected between the chainfall and one arm of the tensioning frame. The output dial can be seen on top of the propeller-impeller speed controller in Figure 7.

To measure the frequency of the rope vibrations, a General Radio Strobotac was used. It gave the frequency to three significant figures. It may be seen in Figure 7 to the left of the tensiometer.

The amplitude of the rope vibrations was measured by a Gaertner Scientific Co. transit shown to the left of the propeller-impeller speed control in Figure 7. It read to 0.1mm.

The vortices behind the rope were photographed with a Graflex view camera using Type 3000 Polaroid black and white film. Lighting and stop action was provided by the General Radio Strobotac.

To measure the diameter of the rope, a Starrett one-inch micrometer and two 1/4- x 1/2-inch parallels were used.

CHAPTER III

EXPERIMENTAL PROCEDURE

After the tensioning frame, wooden support stand, and bearing frame were set in place, the lower window of the water tunnel was removed. The side windows were already in place with the rubber bellows installed. A PVC pipe with a plexiglass center was inserted into the rubber bellows. The plexiglass insert was then removed, as shown in Figure 9., and the rope inserted in the bellows. After the rope was inserted in both bellows it was tied around the bits as previously shown.

The dynamometer was then calibrated in the following manner. After the zero and span were set on the strain gauge reader, a wheel with needle bearings was mounted in the tunnel. The wheel was placed in the middle of the tunnel with the top edge level with the rope. Weights were then hung from the middle of the rope over the wheel as shown in Figure 10. This was done for various weights and tensions. The calibration was done to check if the expected .01 pound per counter reading would be obtained. As seen in Figures 11-15 about .05 pounds per counter reading was obtained. This happened because at such low loads the flexures in the dynamometer were taking up part of the load. As the tension was applied to the rope, the ends of the tensioning frame also assumed part of the load. This can be seen as an increase in slope of the curves with tension as seen in Figures 12-15. As seen in Figure 11, the size of the rope used did not seem to effect the data to a great degree. Thus, not every rope was calibrated for all tensions, but since the 3/8 rope was of different construction from the rest, it was calibrated. Enough data was taken for the other ropes to make Figure 11 and the

Figure 9

Rope Insertion

FIGURE 10

Figure 11. Calibration of Dynamometer with Ropes at 3000 lbs. Tension

Figure 12. Calibration of Dynamometer with 3/8 in. Rope

Figure 13. Calibration of Dynamometer with 3/8 in. Rope

Figure 14. Calibration of Dynamometer with 3/4 in. Rope

Figure 15. Calibration of Dynamometer with No Rope and 9/16 in. Rope

calibration curves, Figures 12 through 15. If these curves of the same range but different rope construction are superimposed, they still agree quite well. The load used for calibration was a point load while under actual test conditions the load was distributed. Weights were hung directly from only one arm of the bearing frame to see if the load distribution was significant. As seen in Figure 14 the difference between the no rope curve and the 50 pound curve was about .05 pounds per counter reading. Thus choosing an accuracy of .05 pounds in converting counter reading to drag would take care of this error.

After the calibration was finished the bottom window was replaced and the tunnel was filled with water. The test was then run at various water velocities, vibration frequencies, and tensions. After the test was over, the process was repeated for each rope, calibrating as much as was necessary. When the results looked fairly consistent with increasing steps of tension, the run was terminated. At strain gauge readings over five pounds, the run was stopped as soon as possible. This procedure is a result of experience of the Water Tunnel personnel. They have found that when load cells are run up to their rated values they may not return to the original zero. This was felt to be caused by plastic deformation in the cell from dynamic loadings higher than the average reading on the counter. The cell was rated for ten pounds. Since we were only getting an average reading on the counter, a rule of thumb was applied that the dynamic loading could be as much as twice the reading and cause the cell to be damaged. This was chosen as a safe limit.

During the runs a certain segment of rope was marked off at fifty pounds' tension and measured at each tension step. The diameter of the rope was also measured at each tension step.

Throughout the experiment the bellows were held in the same shape by decreasing the pressure in the tunnel until the bellows assumed their natural shape. This shape was one the bellows assumed when there was no water in the tunnel and the dynamometer cell was being calibrated.

To photograph the vortices, it was thought that a shadowgraph technique might be used. This involves projecting a light through the water and then onto a piece of frosted glass. The principle involved is that the vortices might change the optical density of the water enough to leave a pattern on the frosted glass. This method was tried and it failed. Probably the vortices did not change the optical density of the water to the degree required for this technique.

However, it was noticed that when the 3/8 rope was put in the tunnel and the pressure lowered to keep the rubber bellows in their natural form bubbles rose from the rope. When the velocity of the water in the tunnel was increased and the pressure in the tunnel adjusted so the right amount of bubbles issued from the rope, the vortices could be seen with the stop-action aid of the strobotac. Pictures of this phenomenon were taken and these will be referred to later.

CHAPTER IV

RESULTS

Using the calibration curves presented previously, each of the counter readings was converted into pounds. Since the zero of the counter drifted, mainly due to slight creeping of the rope, the values of the zeros were recorded before and after each reading. This was done on both the calibrating and actual data runs. The zero for an actual data run was interpolated from the zero taken at the beginning of the run and at the end. For the run, the velocity was increased in approximately .1 foot per second intervals until the five-pound limit was reached on the load cell. From the calibration curves, it was decided that the accuracy of the force on the rope was $\pm .05$ pounds.

The velocities were calculated from height of indicating fluid using the data available at the propeller tunnel. This data is most accurate at a tunnel and room temperature of $80^{\circ}\text{F} \pm 2.5^{\circ}$. During the week and a half the tests were run, the room temperature varied between $78^{\circ} - 84^{\circ}\text{F}$ and the tunnel temperature varied between $82^{\circ} - 84^{\circ}\text{F}$. Because of temperature and reading errors, $\pm .05$ feet per second was chosen as the accuracy of the velocity values.

The length of a marked section of rope was measured by a tape to within $1/16$ of an inch. The diameter was measured by a micrometer and machinists' parallels. The accuracy of the micrometer was .001 in. In measuring diameter, the largest diameter the rope presented was hoped to be obtained. Due to the rough texture of the rope, this did not happen. However, this data is presented to the nearest .001 inches.

Values of the density and kinematic viscosity were obtained to four places after the decimal from Saunders (25) corrected for tunnel temperature.

The Strouhal number of 0.2 was obtained for a Reynolds number range of $10^3 - 10^5$ from Roshko (22) and Capadona (7).

The length of rope exposed to the water flow was assumed to be twenty inches. This was the dimension of the tunnel test section.

Using the above values, the drag coefficients, Strouhal frequency, and Reynolds number based on both nominal and measured diameter were calculated.

The diameter of the rope based on conservation of volume and the first measured diameter at fifty pounds tension was also calculated.

The calculations were done by computer and the results are presented in Appendix A.

Some of the data not presented in the computer output concerned the measured frequency of vibration and amplitude of vibration. These are presented below in Table 1.

Table 1

Vibration Data

<u>Rope</u>	<u>Tension (lbs)</u>	<u>Reynolds Number (X10⁴)</u>	<u>Peak to Peak Amplitude (in.)</u>	<u>Frequency cpm</u>
9/16	50	2.05	.67	1440
		2.6	.902	1680
		3.1	.895	1960
		3.6	.842	2230
		4.15	.544	2930
	500			
5/8	50	2.25	.745	1180
		2.8	.938	1410
		3.35	1.13	1610
		3.85	1.095	1810
3/4	50	2.6	.98	1010
		3.25	1.54	1150
		3.85	1.37	1340
3/8	50	1.3	.382	1110
		1.65	.457	1365
		2.00	.434	1540
		2.3	.54	1810
		2.65	.465	1900

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Comparing Table 1 with the total amount of data obtained as listed in the computer program, it can be seen that the rope vibrated only at low tensions. This was due to the delrin blocks and the bearing surfaces. As seen in Figure 16, the rope vibrated in a sinusoidal manner with the nodes at the delrin block and a half wave length of thirty-eight inches. If the blocks were removed, the rope vibrated at all tensions in the form of a sinusoid with the nodes at the bits of the tensioning frame. When the delrin blocks were removed and the rope allowed to vibrate while rubbing on the aluminum bearing surface, the wave form still appeared between the bearing surfaces and only at low tensions. Originally a vibrator was to be attached to the delrin blocks to vibrate the rope at different amplitudes and frequencies. This idea was abandoned since it was thought that the natural induced vibrations of the shedding vortices would add to the mechanically induced vibrations and create unwanted wave forms. It was decided to try a dashpot arrangement attached to the delrin block to change frequency and amplitude at each velocity station. However, since the rope vibrated with nodes at the blocks, this idea had to be abandoned also. Thus, in the data presented there were no control over the frequency and amplitude of vibration. One way to overcome these problems would be to support the wooden frame on air bearings and eliminate the use of the bearing surfaces and dynamometer on top of the tunnel. If a load cell were attached to the now floating frame from a stationary point on the floor, readings could be obtained for drag while the rope vibrated at all tensions. This design would also eliminate the drifting zero problem due to creeping of the rope under

Figure 16

Rope Vibrating

tension. It can be seen from the calibration curves that the .01 pounds per counter reading was not achieved, probably due to the stiffness of the dynamometer flexures. With the air bearing design, the load cell would probably be capable of the .01 pounds per counter reading and thus more accurate data could be obtained. The amplitude of the vibrations did go to the expected two diameters peak to peak for the 3/4-inch rope. With the improved design, higher amplitudes may be measured. By placing weights at different places along the rope the wave form and thus the frequency could be changed for different fluid velocities in the tunnel.

In order to see the trends in the drag coefficients, plots of drag coefficients versus Reynolds number were made for Figures 17-20.

Since most readers will not have a relationship between tension in the rope and diameter of the rope, Figures 17-20 were based on the nominal diameter of the rope. As seen from the Figures, the drag coefficient was increased as much as 50 percent over the nonvibrating coefficients. When the rope was not vibrating, the drag coefficients remained fairly constant with tension. The line for the nonvibrating drag coefficients agrees quite well with standard texts such as Hoernor (15). In fact since we are near the critical Reynolds number for a cylinder, this may explain why the coefficients do remain fairly constant with tension. As the diameter is reduced with increased tension, the drag may remain fairly constant since the rope will become smoother. Thus the drag coefficient based on the nominal diameter will remain the same.

All of the Figures 17-20 look about the same except for the 3/8 rope. The drag coefficients are quite scattered compared with the rest of the graphs. This may be due to the construction of the rope or possibly the air bubbles emitted from the rope during the tests. In future tests this should be investigated.

There was a wide scatter of points in the first few data stations. This was probably due to the low values being measured. The air bearing design might possibly help obtain better data in this region.

Figure 17. 9/16 in. Rope Drag Coefficients

Figure 18. 5/8 in. Rope Drag Coefficients

Figure 19. 3/4 in. Rope Drag Coefficients

Figure 20. 3/8 in. Rope Drag Coefficients

Figure 21. Diameter of Rope Measured and Based on Conservation of Volume

Figure 22. Frequency of Vibrations

Shown in Figure 21 is a plot of calculated and measured diameters. The shapes of the curves of calculated and measured seem to be parallel except for the first two points. This may be caused by the elimination of air spaces during the first stages of stretching. Because of the rough weave in the ropes it was difficult at times to measure the largest diameter with parallels and a micrometer. In future tests, V-notched blocks may be more suitable for this measurement than flat parallels.

In Figure 22 the difference between the measured frequency and the calculated frequency based on the nominal diameter is depicted. The measured frequency was always higher than the calculated, except for the 3/8 rope. This seems to show the type of construction and material the rope is made of will effect the frequency of vibration. Also the emission of air bubbles from the rope may have been the cause. For all the ropes, the calculated frequency based on the measured diameter was higher when the measured diameter was smaller than the nominal. However, this increase was not sufficient to bring it up to the measured frequency. For the case of the 9/16 rope vibrating at an even higher frequency at 500 pounds tension than 50 pounds tension, more data in this area should be obtained in the future.

Since the plots of all the plaited rope come out about the same for the nonvibrating values and the 9/16 rope depicts the rope going through a natural frequency and coming out of it, a drag coefficient of 1.5 should be used with these ropes in this Reynolds number range. For the 3/8 rope since there is some question about the data because of the spread of points and because C_d reach a maximum in a somewhat lower Reynolds number range, a C_d of 1.5 should also be used.

The pictures taken of the vortices are presented in Figure 23. While using the strobotac for stop action, it was confirmed that the vortices are formed at the same frequency as the rope is vibrating. This agrees with the data of other investigators in the bibliography.

That the vortices become more turbulent at higher Reynolds' numbers is confirmed by the last picture of the vortices in a velocity of 8.1 feet per second. In this picture they cannot be seen.

When using this technique to photograph the vortices, the amount of bubbles issuing from this rope and the settings on the camera are important. This is shown by the series of pictures taken with the rope vibrating at a single velocity.

To my knowledge this was the first experiment of its kind to be run. The data collected gives a rough idea of the vibrating drag coefficients and frequencies in the Reynolds number range tested. Since the amplitude and frequency could not be controlled, this was about all that could be done. As seen in Figure 17, the curve of the drag coefficients as the maximum value is approached quite differently from the curve leading away from it as the maximum is passed. This seems to indicate that more than one parameter is at work, each changing differently with the Reynolds number. A possible combination of parameters may be the projected area of the vibrating rope and the frequency of the rope. With further testing and analysis of data, a means may be found to calculate the vibrating drag coefficient from the nonvibrating coefficient.

Figure 23a

Photographs of Vortices Taken at the Same Water Velocity, but With Different Lighting Conditions and Camera Settings

Velocity = 5.7 ft/sec

Velocity = 5.7 ft/sec

Velocity = 5.7 ft/sec

Velocity = 5.7 ft/sec

Figure 23b

Photographs of Vortices Taken With the Same
Camera Settings and Lighting Conditions, but With
Water Velocity Changing

Velocity = 3.1 ft/sec

Velocity = 4.05 ft/sec

Velocity = 5.1 ft/sec

Velocity = 6.1 ft/sec

Velocity = 7.1 ft/sec

Velocity = 8.1 ft/sec

APPENDIX A

Measured and Calculated Variables

<u>Fortran Symbol</u>	<u>Meaning</u>	<u>Units</u>
T	tension	pounds
DIA1	nominal diameter	inches
DIA2	measured diameter	inches
DIA3	computed diameter	inches
RNEW	kinematic viscosity	ft ² per sec
RHO	density	slugs per ft ³
RLTH	length of rope segment used to calculate DIA3	inches
R	measured drag of rope	pounds
Vel	velocity of water	ft/sec
F1	Strouhal Frequency based on nominal diameter	cpm
F2	Strouhal Frequency based on measured diameter	cpm
CD1	drag coefficient based on nominal diameter	dimensionless
CD2	drag coefficient based on measured diameter	dimensionless

```

1: 3 READ(105,10) T,DIA1,DIA2,RNEW,RH0,RLTH,R,VEL
2: 10 FORMAT(8E10.4)
3: IF(20.0>T) GO TO 2
4: IF(T>100.0) GO TO 1
5: VRL=3.141593* DIA2**2/4.0*RLTH
6: 1 WRITE(108,20)
7: 20 FORMAT(//////,15X,1HT,17X,4HDIA1,16X,4HDIA2,16X,4HRNEW,17X,3HRH0,
8: 116X,4HRLTH,/)
9: WRITE(108,30)T,DIA1,DIA2,RNEW,RH0,RLTH
10: 30 FORMAT(4A19X,F10.4)
11: DIA3=SQRT(VRL/3.141593/RLTH*4.0)
12: WRITE(108,40) DIA3
13: 40 FORMAT(5X,6HDIA3=,1X,F10.4,/)
14: 2 F1=.2*VEL/DIA1*12.0*60.0
15: F2=.2*VEL/DIA2*12.0*60.0
16: RE1=VEL*DIA1/RNEW/12.0*1.E+05
17: RE2=VEL*DIA2/RNEW/12.0*1.E+05
18: CD1=2.0*R/(RH0*1.666666*DIA1/12.0*VEL**2)
19: CD2=2.0*R/(RH0*1.666666*DIA2/12.0*VEL**2)
20: WRITE(108,50) R,VEL
21: 50 FORMAT(5X,4HR = ,F10.4,5X,6HVEL = ,F10.4,/)
22: WRITE(108,60)
23: 60 FORMAT(14X,2HF1,18X,2HF2,17X,3HRE1,17X,3HRE2,17X,3HCD1,17X,
24: 13HCD2)
25: WRITE(108,70) F1,F2,RE1,RE2,CD1,CD2
26: 70 FORMAT(2(10X,F10.4),2(10X,E10.4),2(10X,F10.4),/)
27: GO TO 3
28: END

```

- RUN

T	DIA1	DIA2	RNEW	RHD	RLTH
DIA3	50.0000	.5630	.9075	1.9330	19.8750
	.5600				
R	.0500	VEL = 1.0000			
F1	255.7726	RE1	RE2	CD1	CD2
		.5170E 04	.5142E 04	.6616	.6651
F2	257.1426				
R	.2500	VEL = 2.0000			
F1	511.5452	RE1	RE2	CD1	CD2
		.1034E 05	.1028E 05	.8270	.8314
F2	514.2854				
R	.7000	VEL = 3.0000			
F1	767.3174	RE1	RE2	CD1	CD2
		.1551E 05	.1543E 05	1.0291	1.0347
F2	771.4282				
R	1.4000	VEL = 4.0000			
F1	1023.0898	RE1	RE2	CD1	CD2
		.2068E 05	.2057E 05	1.1578	1.1640
F2	1028.5701				
R	2.8000	VEL = 5.0000			
F1	1278.8625	RE1	RE2	CD1	CD2
		.2585E 05	.2571E 05	1.4820	1.4899
F2	1285.7134				
R	3.9500	VEL = 6.0000			

CD2
1.4596

CD1
1.4518

RE2
.3085E 05

RE1
.3102E 05

F2
1542.8567

F1
1534.6353

VEL 7.0000

R 5.0500

CD2
1.3710

CD1
1.3637

RE2
.3600E 05

RE1
.3619E 05

F2
1799.9990

F1
1790.4070

RLTH

RHO

RNEW

DIA2

DIA1

T

20.6880

1.9330

.9075

.5490

.5630

DIA3
.5489

500.0000

VEL 1.0000

R .0500

CD2
.6785

CD1
.6616

RE2
.5041E 04

RE1
.5170E 04

F2
262.2949

F1
255.7726

VEL 2.0000

R .2500

CD2
.8481

CD1
.8270

RE2
.1008E 05

RE1
.1034E 05

F2
524.5898

F1
511.5452

VEL 3.0000

R .6000

CD2
.9046

CD1
.8821

RE2
.1512E 05

RE1
.1551E 05

F2
786.8848

F1
767.3174

VEL 4.0000

R 1.1500

CD2
.9753

CD1
.9510

RE2
.2016E 05

RE1
.2068E 05

F2
1049.1797

F1
1023.0898

R = 1.8000 VEL = 5.0000
 F1 1278.8625
 F2 1311.4746
 RE1 .2585E 05
 RE2 .2521E 05
 CD1 .9527
 CD2 .9770

R = 2.6000 VEL = 6.0000
 F1 1534.6353
 F2 1573.7695
 RE1 .3102E 05
 RE2 .3025E 05
 CD1 .9556
 CD2 .9800

R = 3.6000 VEL = 7.0000
 F1 1790.4070
 F2 1836.0645
 RE1 .3619E 05
 RE2 .3529E 05
 CD1 .9721
 CD2 .9969

R = 5.0500 VEL = 8.0000
 F1 2046.1797
 F2 2098.3584
 RE1 .4136E 05
 RE2 .4033E 05
 CD1 1.0441
 CD2 1.0707

T DIA1 DIA2 RNEW RTH RLTH
 DIA3 1000.0000 .5630 .5200 .9075 1.9330 21.5000
 .5384

R = .0500 VEL = 1.0000
 F1 255.7726
 F2 276.9229
 RE1 .5170E 04
 RE2 .4775E 04
 CD1 .6616
 CD2 .7163

R = .2500 VEL = 2.0000

F1 511.5452 F2 553.8459 RE1 1034E 05 RE2 9550E 04 CD1 .8270 CD2 .8954

R 6000 VEL 3.0000

F1 767.3174 F2 830.7688 RE1 1551E 05 RE2 1432E 05 CD1 .8821 CD2 .9551

R 11000 VEL 4.0000

F1 1023.0898 F2 1107.6909 RE1 2068E 05 RE2 1910E 05 CD1 .9097 CD2 .9849

R 18000 VEL 5.0500

F1 1291.6497 F2 1398.4597 RE1 2611E 05 RE2 2411E 05 CD1 .9339 CD2 1.0112

R 25000 VEL 6.0500

F1 1547.4224 F2 1675.3821 RE1 3128E 05 RE2 2889E 05 CD1 .9038 CD2 .9785

R 33000 VEL 7.0000

F1 1790.4070 F2 1938.4607 RE1 3619E 05 RE2 3342E 05 CD1 .8911 CD2 .9648

R 42500 VEL 8.0000

F1 2046.1797 F2 2215.3828 RE1 4136E 05 RE2 3820E 05 CD1 .8787 CD2 .9513

R 54000 VEL 9.0500

F1 2314.7405 F2 2506.1526 RE1 4679E 05 RE2 4321E 05 CD1 .8724 CD2 .9445

T	DIA1	DIA2	RNEW	RH6	RLTH
1500.0000 DIA3 .5323	.5630	.5200	.9075	1.9330	22.0000
R .0500	VEL .9500				
F1 242.9339	F2 263.0767	RE1 .431E 04	RE2 .4536E 04	CD1 .7331	CD2 .7937
R .2500	VEL 1.9000				
F1 485.9678	F2 526.1536	RE1 .9823E 04	RE2 .9072E 04	CD1 .9163	CD2 .9921
R .6500	VEL 3.0500				
F1 780.1062	F2 844.6150	RE1 .157E 05	RE2 .1456E 05	CD1 .9246	CD2 1.0010
R 1.1000	VEL 4.0000				
F1 1023.0898	F2 1107.6909	RE1 .2068E 05	RE2 .1910E 05	CD1 .9097	CD2 .9849
R 1.7000	VEL 5.0000				
F1 1278.8625	F2 1384.6150	RE1 .2585E 05	RE2 .2387E 05	CD1 .8998	CD2 .9742
R 2.4500	VEL 6.0500				
F1	F2	RE1	RE2	CD1	CD2

•9589

•8857

•2889E 05

•3128E 05

1675•3821

1547•4224

R • 3•3000 VEL • 7•0000

CD2 •9648

CD1 •8911

RE2 •3342E 05

RE1 •3619E 05

F2 1938•4607

F1 1790•4070

R • 4•3000 VEL • 8•0000

CD2 •9625

CD1 •8390

RE2 •3820E 05

RE1 •4136E 05

F2 2215•3828

F1 2046•1797

R • 5•4500 VEL • 9•0000

CD2 •9639

CD1 •8903

RE2 •4297E 05

RE1 •4653E 05

F2 2492•3062

F1 2301•9514

RLTH

RH8

RNEW

DIA2

DIA1

T

22•3120

1•9330

•9075

•5200

•5630

2000•0000

DIA3 •5285

R • 1000 VEL • 1•0000

CD2 1•4326

CD1 1•3232

RE2 •4775E 04

RE1 •5170E 04

F2 276•9229

F1 255•7726

R • 3000 VEL • 2•0000

CD2 1•0745

CD1 •9924

RE2 •9550E 04

RE1 •1034E 05

F2 553•8459

F1 511•5452

R • 6500 VEL • 3•0500

F1 780.1062
F2 844.6150
R = 1.2000
VEL = 4.0500
RE1 .1577E 05
RE2 .1456E 05
CD1 .9246
CD2 1.0010

F1 1035.8789
F2 1121.5374
R = 1.7500
VEL = 5.0000
RE1 .2094E 05
RE2 .1934E 05
CD1 .9680
CD2 1.0481

F1 1278.8625
F2 1384.6150
R = 2.4500
VEL = 6.0500
RE1 .2585E 05
RE2 .2387E 05
CD1 .9262
CD2 1.0028

F1 1547.4224
F2 1675.3821
R = 3.2000
VEL = 7.0000
RE1 .3128E 05
RE2 .2889E 05
CD1 .8857
CD2 .9589

F1 1790.4070
F2 1938.4607
R = 4.2000
VEL = 8.0000
RE1 .3619E 05
RE2 .3342E 05
CD1 .8641
CD2 .9356

F1 2046.1797
F2 2215.3828
R = 5.1000
VEL = 8.9000
RE1 .4136E 05
RE2 .3820E 05
CD1 .8683
CD2 .9401

F1 2276.3752
F2 2464.6143
R = 6.5000
VEL = 10.0000
RE1 .4601E 05
RE2 .4250E 05
CD1 .8519
CD2 .9224

F1 2557.7241
F2 2769.2285
R = 6.5000
VEL = 10.0000
RE1 .5170E 05
RE2 .4775E 05
CD1 .8601
CD2 .9312

T DIA1 DIA2 RNEW RH0 RLTH

DIA3 2500.0000 .5630 .5150 .9075 1.9330 22.6250

DIA3 .5249

R 1000 VEL 1.0000

F1 255.7726

F2 279.6116

RE1 .5170E 04

RE2 .4729E 04

CD1 1.3232

CD2 1.4465

R 3000 VEL 2.0000

F1 511.5452

F2 559.2231

RE1 .1034E 05

RE2 .9458E 04

CD1 .9924

CD2 1.0849

R 6000 VEL 3.0000

F1 767.3174

F2 838.8342

RE1 .1551E 05

RE2 .1419E 05

CD1 .8821

CD2 .9643

R 1000 VEL 4.0500

F1 1035.8789

F2 1132.4268

RE1 .2094E 05

RE2 .1915E 05

CD1 .8874

CD2 .9701

R 1750 VEL 5.1000

F1 1304.4397

F2 1426.0181

RE1 .2637E 05

RE2 .2412E 05

CD1 .8903

CD2 .9732

R 24500 VEL 6.0000

F1 1534.6353 F2 1677.6689 RE1 .3102E 05 RE2 .2837E 05 CD1 .9005 CD2 .9844

R = 3.3000 VEL = 7.0000

F1 1790.4070 F2 1937.2803 RE1 .3619E 05 RE2 .3310E 05 CD1 .8311 CD2 .9742

R = 4.3000 VEL = 8.0000

F1 2046.1797 F2 2236.8914 RE1 .4136E 05 RE2 .3783E 05 CD1 .8890 CD2 .9719

R = 5.5000 VEL = 9.0000

F1 2301.9514 F2 2516.5034 RE1 .4653E 05 RE2 .4256E 05 CD1 .8985 CD2 .9822

R = 6.7500 VEL = 9.9500

F1 2544.9360 F2 2732.1345 RE1 .5144E 05 RE2 .4705E 05 CD1 .9022 CD2 .9862

T DIA1 DIA2 RNEW RUTH

DIA3 = 3000.0000 .5630 .5020 .9075 1.9330 22.8750

R = 1000 VEL = 9500

F1 242.9839 F2 272.5098 RE1 .4911E 04 RE2 .4379E 04 CD1 1.4661 CD2 1.6443

R = 2500 VEL = 2.0000

F1
511.5452

F2
573.7051

RE1
.1034E 05

RE2
.9219E 04

CD1
.8270

CD2
.9275

R = 6000 VEL = 3.0000

F1
767.3174

F2
860.5576

RE1
.1551E 05

RE2
.1383E 05

CD1
.8821

CD2
.9893

R = 1.1000 VEL = 4.0000

F1
1023.0898

F2
1147.4092

RE1
.2068E 05

RE2
.1844E 05

CD1
.9097

CD2
1.0202

R = 1.7000 VEL = 5.0000

F1
1278.8625

F2
1434.2622

RE1
.2585E 05

RE2
.2305E 05

CD1
.8998

CD2
1.0091

R = 2.4000 VEL = 6.0000

F1
1534.6353

F2
1721.1145

RE1
.3102E 05

RE2
.2766E 05

CD1
.8821

CD2
.9893

R = 3.2000 VEL = 7.0000

F1
1790.4070

F2
2007.9666

RE1
.3619E 05

RE2
.3227E 05

CD1
.8641

CD2
.9691

R = 4.2500 VEL = 8.0000

F1
2046.1797

F2
2294.8186

RE1
.4136E 05

RE2
.3688E 05

CD1
.8787

CD2
.9855

R = 5.4500 VEL = 9.0500

F1 2314.7405 F2 2596.0144 RE1 .4679E 05 RE2 .4172E 05 CD1 .8805 CD2 .9875

R 6.6000 VEL 10.0000

F1 2557.7241 F2 2868.5237 RE1 .5170E 05 RE2 .4610E 05 CD1 .8733 CD2 .9794

T DIA1 DIA2 DIA3 RNEW RTH RLTH

DIA3 = 50.0000 .6250 .6880 .9438 1.9326 21.0000

R .0500 VEL .9500

F1 218.8799 F2 198.8371 RE1 .5242E 04 RE2 .5771E 04 CD1 .6605 CD2 .6000

R .1500 VEL 2.0000

F1 460.7998 F2 418.6045 RE1 .1104E 05 RE2 .1215E 05 CD1 .4471 CD2 .4061

R .7000 VEL 3.1000

F1 714.2397 F2 648.8369 RE1 .1711E 05 RE2 .1883E 05 CD1 .8684 CD2 .7889

R 1.5000 VEL 4.0500

F1 933.1196 F2 847.6741 RE1 .2235E 05 RE2 .2430E 05 CD1 1.0902 CD2 .9934

R 2.6000 VEL 5.0500

F1
1163.5181

F2
1056.9753

RE1
.2787E 05

RE2
.3068E 05

CD1
1.2154

CD2
1.1041

R 4.2000 VEL 6.0500

F1
1393.9177

F2
1266.2776

RE1
.3339E 05

RE2
.3675E 05

CD1
1.3680

CD2
1.2427

R 5.8500 VEL 7.0000

F1
1612.7983

F2
1465.1147

RE1
.3563E 05

RE2
.4252E 05

CD1
1.4233

CD2
1.2930

T

DIA1

DIA2

RNEW

RH0

RLTH

DIA3 500.0000
.6722

.6250

.6590

.9438

1.9326

22.0000

R .1000 VEL .9500

F1
218.8799

F2
207.5872

RE1
.5242E 04

RE2
.5528E 04

CD1
1.3210

CD2
1.2528

R .3500 VEL 2.0000

F1
460.7998

F2
437.0256

RE1
.1104E 05

RE2
.1164E 05

CD1
1.0432

CD2
.9893

R .7500 VEL 3.1000

F1

F2

RE1

RE2

CD1

CD2

714.2397 677.3899 .1711E 05 .1804E 05 .9304 .8824

R = 1.3500 VEL = 4.0000
 F1 921.5096 F2 874.0508
 RE1 .2207E 05 RE2 .2327E 05
 CD1 1.0059 CD2 .9540

R = 2.0000 VEL = 5.0000
 F1 1151.9988 F2 1092.5637
 RE1 .2759E 05 RE2 .2909E 05
 CD1 .9537 CD2 .9045

R = 4.0000 VEL = 7.0000
 F1 1612.7983 F2 1529.5889
 RE1 .3863E 05 RE2 .4073E 05
 CD1 .9732 CD2 .9230

R = 5.6000 VEL = 8.0000
 F1 1843.1982 F2 1748.1013
 RE1 .4415E 05 RE2 .4655E 05
 CD1 1.0432 CD2 .9893

T DIA1 DIA2 RNEW RLTH
 DIA3 = 1000.0000 .6250 .6280 1.9326 22.8130
 .6501

R = 1.0000 VEL = .9500
 F1 218.8799 F2 217.8343
 RE1 .5242E 04 RE2 .5267E 04
 CD1 1.3210 CD2 1.3147

R = .3500 VEL = 1.9000

F1 437.7598
F2 435.6685
RE1 .1048E 05
RE2 .1053E 05
CD1 1.1559
CD2 1.1503

R 8000 VEL 3.0500

F1 702.7197
F2 699.3628
RE1 .1683E 05
RE2 .1631E 05
CD1 1.0253
CD2 1.0204

R 14500 VEL 4.0500

F1 933.1196
F2 928.6619
RE1 .2235E 05
RE2 .2246E 05
CD1 1.0539
CD2 1.0489

R 22500 VEL 5.0000

F1 1151.9988
F2 1146.4956
RE1 .2759E 05
RE2 .2772E 05
CD1 1.0730
CD2 1.0678

R 31500 VEL 6.0000

F1 1382.3987
F2 1375.7959
RE1 .3311E 05
RE2 .3327E 05
CD1 1.0432
CD2 1.0382

R 42000 VEL 7.1000

F1 1635.8386
F2 1628.0237
RE1 .3918E 05
RE2 .3937E 05
CD1 .9933
CD2 .9885

R 54500 VEL 8.0000

F1 1843.1982
F2 1834.3936
RE1 .4415E 05
RE2 .4436E 05
CD1 1.0152
CD2 1.0104

RLTH

RH8

RNEW

DIA2

DIA1

T

DIA3 1500.0000 .6250 .6210 .9438 1.9326 23.6250
 .6487

R . 1000 VEL . 1.0000
 F1 230.3999 F2 231.8840 RE1 .5518E 04 RE2 .5483E 04 CD1 1.1922 CD2 1.1999

R . 3500 VEL . 1.9500
 F1 449.2798 F2 452.1736 RE1 .1076E 05 RE2 .1069E 05 CD1 1.0973 CD2 1.1044

R . 8000 VEL . 3.1000
 F1 714.2397 F2 718.8403 RE1 .1711E 05 RE2 .1700E 05 CD1 .9924 CD2 .9388

R . 14000 VEL . 4.0500
 F1 933.1196 F2 939.1296 RE1 .2235E 05 RE2 .2221E 05 CD1 1.0176 CD2 1.0241

R . 21500 VEL . 5.0500
 F1 1163.5181 F2 1171.0134 RE1 .2787E 05 RE2 .2769E 05 CD1 1.0051 CD2 1.0115

R . 31000 VEL . 6.1000
 F1 1405.4387 F2 1414.4915 RE1 .3366E 05 RE2 .3345E 05 CD1 .9932 CD2 .9996

R . 40500 VEL . 7.0000

CD2
.9917CD1
.9854RE2
.388E 05RE1
.386E 05F2
1623.1868F1
1612.7983

R ■ 5.3500 VEL ■ 8.0000

CD2
1.0030CD1
.9966RE2
.438E 05RE1
.441E 05F2
1855.0715F1
1843.1982

RLTH

RH9

RNEW

DIA2

DIA1

23.9380

1.9326

.9438

.6250

.6250

DIA3 ■
.6444

2000.0000

R ■ 1.000

VEL ■ 1.0000

CD2
1.1922CD1
1.1922RE2
.518E 04RE1
.551E 04F2
230.3999F1
230.3999

R ■ .3500

VEL ■ 2.0000

CD2
1.0432CD1
1.0432RE2
.110E 05RE1
.110E 05F2
460.7998F1
460.7998

R ■ .8000

VEL ■ 3.0000

CD2
1.0597CD1
1.0597RE2
.165E 05RE1
.165E 05F2
691.1997F1
691.1997

R ■ 1.4500

VEL ■ 4.1000

CD2
1.0283CD1
1.0283RE2
.226E 05RE1
.226E 05F2
944.6394F1
944.6394

R 2.1500 VEL 5.1000

F1
1175.0391F2
1175.0391RE1
.2814E 05RE2
.2814E 05CD1
.9855CD2
.9855

R 3.0500 VEL 6.0000

F1
1382.3987F2
1382.3987RE1
.3311E 05RE2
.3311E 05CD1
1.0100CD2
1.0100

R 4.1000 VEL 7.0000

F1
1612.7983F2
1612.7983RE1
.3863E 05RE2
.3863E 05CD1
.9975CD2
.9975

R 5.4500 VEL 8.0000

F1
1843.1982F2
1843.1982RE1
.4415E 05RE2
.4415E 05CD1
1.0152CD2
1.0152

T

DIA1

DIA2

RNEW

RH0

RLTH

DIA3 50.0000
.7680

.7500

.7680

.9552

1.9328

20.0000

R 1.1000 VEL 1.0000

F1
192.0000F2
187.4999RE1
.6543E 04RE2
.6700E 04CD1
.9934CD2
.9701

R 3.3500 VEL 2.0000

F1 383.9998 F2 374.9998 RE1 .1309E 05 RE2 .1340E 05 CD1 .8692 CD2 .8488

R . 8000 VEL . 3.0000

F1 575.9998 F2 562.4998 RE1 .1963E 05 RE2 .2010E 05 CD1 .8830 CD2 .8623

R . 1.9500 VEL . 4.0000

F1 767.9998 F2 749.9995 RE1 .2617E 05 RE2 .2680E 05 CD1 1.2107 CD2 1.1823

R . 3.3500 VEL . 5.0000

F1 959.9998 F2 937.4998 RE1 .3271E 05 RE2 .3350E 05 CD1 1.3311 CD2 1.2999

R . 5.0000 VEL . 5.9000

F1 1132.7983 F2 1106.2490 RE1 .3860E 05 RE2 .3953E 05 CD1 1.4269 CD2 1.3934

T DIA1 DIA2 DIA3 RNEW RLTH

DIA3 .500.0000 .7500 .7400 .9552 1.9328 20.4380

R . 1.0000 VEL . 1.0000

F1 192.0000 F2 194.5945 RE1 .6543E 04 RE2 .6456E 04 CD1 .9934 CD2 1.0068

DIA3 = .7506

R = .1000 VEL = .9500

F1
182.3999

F2
183.6241

RE1
.6251E 04

RE2
.6210E 04

CD1
1.1008

CD2
1.1081

R = .4000 VEL = 2.0000

F1
383.9998

F2
386.5769

RE1
.1316E 05

RE2
.1307E 05

CD1
.9934

CD2
1.0001

R = .9000 VEL = 3.0500

F1
585.5999

F2
589.5300

RE1
.2007E 05

RE2
.1994E 05

CD1
.9611

CD2
.9676

R = 1.6500 VEL = 4.0500

F1
777.5999

F2
782.8184

RE1
.2665E 05

RE2
.2647E 05

CD1
.9993

CD2
1.0060

R = 2.4500 VEL = 5.0000

F1
959.9998

F2
966.4424

RE1
.3290E 05

RE2
.3268E 05

CD1
.9736

CD2
.9801

R = 3.5000 VEL = 6.0000

F1
1151.9988

F2
1159.7305

RE1
.3948E 05

RE2
.3922E 05

CD1
.9658

CD2
.9723

R = 4.6500 VEL = 7.0000

F1
1343.9985

F2
1353.0183

RE1
.4606E 05

RE2
.4575E 05

CD1
.9427

CD2
.9491

R = 6.0500 VEL = 8.0000

F1 1535.9985 F2 1546.3074 RE1 .5264E 05 RE2 .5229E 05 CD1 .9391 CD2 .9454

T DIA1 DIA2 RNEW RLTH
1500.0000 .7500 .9392 21.4380
DIA3 .7418

R .1000 VEL .10000
F1 192.0000 F2 194.0701 RE1 .6655E 04 RE2 .6584E 04 CD1 .9936 CD2 1.0043

R .3500 VEL .19500
F1 374.3997 F2 378.4365 RE1 .1298E 05 RE2 .1284E 05 CD1 .9145 CD2 .9244

R .9000 VEL .30000
F1 575.9998 F2 582.2100 RE1 .1996E 05 RE2 .1975E 05 CD1 .9936 CD2 1.0043

R .16000 VEL .40000
F1 767.9998 F2 776.2800 RE1 .2662E 05 RE2 .2634E 05 CD1 .9936 CD2 1.0043

R .25000 VEL .50500
F1 969.5984 F2 980.0518 RE1 .3361E 05 RE2 .3325E 05 CD1 .9740 CD2 .9845

R ■ 3.5500 VEL ■ 6.0000

F1 1151.9988 F2 1164.4197 RE1 .3993E 05 RE2 .3950E 05 CD1 .9798 CD2 .9903

R ■ 4.7500 VEL ■ 7.0000

F1 1343.9985 F2 1358.4895 RE1 .4658E 05 RE2 .4609E 05 CD1 .9632 CD2 .9736

R ■ 6.2000 VEL ■ 8.0000

F1 1535.9985 F2 1552.5593 RE1 .5324E 05 RE2 .5267E 05 CD1 .9625 CD2 .9729

T DIA1 DIA2 RNEW RLTH

DIA3 ■ 2000.0000 .7375 .7500 .7400 .9392 1.9324 21.6880

R ■ .1500 VEL ■ 1.0000

F1 192.0000 F2 194.5945 RE1 .6655E 04 RE2 .6566E 04 CD1 1.4904 CD2 1.5105

R ■ .4500 VEL ■ 2.0000

F1 383.9998 F2 389.1890 RE1 .1331E 05 RE2 .1313E 05 CD1 1.1178 CD2 1.1329

R ■ .9500 VEL ■ 3.1000

CD2
.9955CD1
.9822RE2
.2035E 05RE1
.2063E 05F2
603.2432F1
595.1997

R ■ 1.6000 VEL ■ 4.0000

CD2
1.0070CD1
.9936RE2
.2626E 05RE1
.2662E 05F2
778.3777F1
767.9998

R ■ 2.4000 VEL ■ 5.0000

CD2
.9567CD1
.9538RE2
.3283E 05RE1
.3327E 05F2
972.9719F1
959.9998

R ■ 3.4500 VEL ■ 6.0500

CD2
.9492CD1
.9365RE2
.3972E 05RE1
.4026E 05F2
1177.2957F1
1161.5981

R ■ 4.5500 VEL ■ 6.9500

CD2
.9486CD1
.9359RE2
.4563E 05RE1
.4625E 05F2
1352.4307F1
1334.3994

R ■ 5.9000 VEL ■ 8.0000

CD2
.9283CD1
.9160RE2
.5253E 05RE1
.5324E 05F2
1556.7554F1
1535.9985

RLTH

RH0

RNEW

DIA2

DIA1

T

24.9380

1.9328

.9552

.3490

.3750

50.0000

DIA3 ■ .3490

F1 3110.3997 F2 3342.1196 RE1 .2650E 05 RE2 .2466E 05 CD1 1.1507 CD2 1.2364

T DIA1 DIA2 RNEW RH0 RLTH *

500.0000 .3750 .9552 1.9328 25.1250

DIA3 .3477

R .0500 VEL = 1.0000

F1 383.9998 F2 424.7786 RE1 .3271E 04 RE2 .2957E 04 CD1 .9934 CD2 1.0989

R .1500 VEL = 2.0000

F1 767.9998 F2 849.5569 RE1 .6543E 04 RE2 .5915E 04 CD1 .7450 CD2 .8242

R .4500 VEL = 3.1000

F1 1190.3987 F2 1316.8130 RE1 .1014E 05 RE2 .9168E 04 CD1 .9303 CD2 1.0291

R .8500 VEL = 4.1000

F1 1574.3994 F2 1741.5920 RE1 .1341E 05 RE2 .1213E 05 CD1 1.0046 CD2 1.1113

R 1.3500 VEL = 5.1000

F1 1958.3979 F2 2166.3701 RE1 .1668E 05 RE2 .1508E 05 CD1 1.0312 CD2 1.1407

R = 2.0000 VEL = 6.0500

F1	F2	RE1	RE2	CD1	CD2
2323.1973	2569.9089	.1979E 05	.1789E 05	1.0856	1.2009

R = 2.5000 VEL = 7.0500

F1	F2	RE1	RE2	CD1	CD2
2707.1987	2994.6890	.2308E 05	.2085E 05	.9993	1.1054

R = 3.4000 VEL = 8.0500

F1	F2	RE1	RE2	CD1	CD2
3091.1982	3419.4670	.2635E 05	.2381E 05	1.0424	1.1531

T

DIA1	DIA2	RNEW	RH0	RLTH
.3750	.3250	.9552	1.9328	25.5630

DIA3 = 1000.0000
.3447

R = .0500 VEL = 1.1000

F1	F2	RE1	RE2	CD1	CD2
422.3999	487.3845	.3599E 04	.3119E 04	.8210	.9473

R = .2000 VEL = 2.0000

F1	F2	RE1	RE2	CD1	CD2
767.9998	886.1536	.6543E 04	.5670E 04	.9934	1.1462

R = .4500 VEL = 3.1000

F1	F2	RE1	RE2	CD1	CD2

1190.3987 1373.5381 .1014E 05 .8789E 04 .9303 1.0734

R = .7000 VEL = 4.1000
F1 1574.3994 F2 1816.6140 RE1 .1341E 05 RE2 .1162E 05 CD1 .8273 CD2 .9546

R = 1.1500 VEL = 5.1000
F1 1958.3979 F2 2259.6899 RE1 .1668E 05 RE2 .1446E 05 CD1 .8784 CD2 1.0136

R = 1.7500 VEL = 6.1000
F1 2342.3977 F2 2702.7666 RE1 .1996E 05 RE2 .1729E 05 CD1 .9344 CD2 1.0781

R = 2.3500 VEL = 7.1000
F1 2726.3972 F2 3145.8435 RE1 .2323E 05 RE2 .2013E 05 CD1 .9262 CD2 1.0687

R = 3.3500 VEL = 8.1000
F1 3110.3997 F2 3588.9221 RE1 .2650E 05 RE2 .2297E 05 CD1 1.0144 CD2 1.1705

T DIA1 DIA2 RNEW RH9 RLTH
1500.0000 .3750 .3250 .9552 1.9328 25.7500
DIA3 = .3435
R = .1000 VEL = 1.1000

CD2
1.8946

CD1
1.6419

RE2
.3119E 04

RE1
.3599E 04

F2
487.3845

F1
422.3999

R = .2500 VEL = 2.0500

CD2
1.3637

CD1
1.1819

RE2
.5812E 04

RE1
.6706E 04

F2
908.3069

F1
787.1997

R = .5000 VEL = 3.1000

CD2
1.1927

CD1
1.0337

RE2
.8789E 04

RE1
.1014E 05

F2
1373.5381

F1
1190.3987

R = .9000 VEL = 4.1000

CD2
1.2273

CD1
1.0637

RE2
.1162E 05

RE1
.1341E 05

F2
1816.6140

F1
1574.3994

R = 1.4500 VEL = 5.1000

CD2
1.2780

CD1
1.1076

RE2
.1446E 05

RE1
.1688E 05

F2
2259.6899

F1
1958.3979

R = 1.8500 VEL = 6.1000

CD2
1.1397

CD1
.9878

RE2
.1729E 05

RE1
.1996E 05

F2
2702.7666

F1
2342.3977

R = 2.3500 VEL = 7.0500

CD2
1.0839

CD1
.9394

RE2
.1999E 05

RE1
.2306E 05

F2
3123.6914

F1
2707.1987

R = 2.9500 VEL = 8.1000

CD2
1.0307

CD1
.8933

RE2
.2297E 05

RE1
.2650E 05

F2
3588.9221

F1
3110.3997

T	DIA1	DIA2	RNEW	RH0	RLTH
DIA3	2000.0000	.3750	.9552	1.9328	25.8230
	.3430				
R	.0500	VEL	1.0000		
F1	383.9998	F2	443.0767	CD1	.9934
		RE1	.3271E 04	CD2	1.1462
		RE2	.2835E 04		
R	.2000	VEL	2.0000		
F1	767.9998	F2	886.1536	CD1	.9934
		RE1	.6543E 04	CD2	1.1462
		RE2	.5670E 04		
R	.4500	VEL	3.0500		
F1	1171.1992	F2	1351.3843	CD1	.9611
		RE1	.9978E 04	CD2	1.1089
		RE2	.8647E 04		
R	.8500	VEL	4.1000		
F1	1574.3994	F2	1816.6140	CD1	1.0046
		RE1	.1341E 05	CD2	1.1592
		RE2	.1162E 05		
R	1.3000	VEL	5.1000		
F1	1958.3979	F2	2259.6899	CD1	.9930
		RE1	.1668E 05	CD2	1.1458
		RE2	.1446E 05		
R	1.8500	VEL	6.1000		

F1	F2	RE1	RE2	CD1	CD2
2342.3977	2702.7666	.1996E 05	.1729E 05	.9878	1.1397

R ■ 2.4500 VEL ■ 7.1000

F1	F2	RE1	RE2	CD1	CD2
2726.3972	3145.8435	.2323E 05	.2013E 05	.9656	1.1141

R ■ 3.3000 VEL ■ 8.1000

F1	F2	RE1	RE2	CD1	CD2
3110.3997	3588.9221	.2650E 05	.2297E 05	.9993	1.1530

FORTRAN RUN-TIME ERROR IN '9BCOREAD' CALLED AT L9C X'02B13'.

END-OF-FILE ON UNIT 105

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