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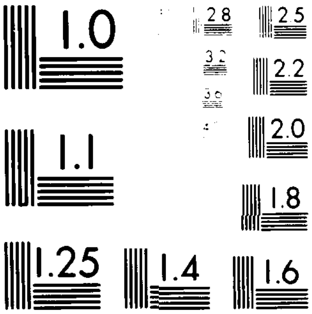

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HYDRODYNAMIC DRAG MEASUREMENTS ON COMPLIANT SURFACE DISKS

by

T. D. REED & G. R. HOUGH

OCTOBER 1978

TECHNICAL REPORT

ATC REPORT NO. B-91100/8CR-77

Prepared Under
Contract No. N00014-77-C-0133
Department of the Navy
Office of Naval Research
Arlington, Virginia 22217

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ABSTRACT

The rotational drag of a disk, with interchangeable faces of compliant membrane/substrate combinations, has been measured in a water tank. A device for stretching a membrane uniformly and with repeatable results was designed, built, and successfully employed. The test procedure was selected as a simple means of screening potential drag reducing compliant surfaces as suggested by previous experimental and analytical studies. Nearly 40 different disks were tested in turbulent flow over a Reynolds number range of 1.7 - 3.0 x 10^6. Membrane thickness and tension, as well as substrate thickness, was varied. The membranes were bonded, unbonded, and separated by an air gap with respect to the substrates. The measured drag was compared to that of a corresponding hard reference disk. In most cases, no drag reduction occurred. The few measured drag reductions were within the estimated experimental inaccuracy.

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1.0 INTRODUCTION

Since the studies by Kramer[1,2] in the early 1960's, there has been considerable interest in the possibility of skin friction drag reduction resulting from the use of compliant surfaces. If a significant drag reduction can be shown to exist, this concept would be very attractive for use in hydrodynamic applications such as submarine or torpedo hull coatings. Although numerous investigations have been conducted during the past ten years, there are still no established criteria for designing compliant boundaries which reduce turbulent boundary layer skin friction. No satisfactory theory exists, and conflicting experimental results have been reported. While some large drag reductions have been noted,[3,4] most of the data indicates that this is not the case (either from direct measurement[5,6] or from critical reexamination[7] of apparent drag "reduction").

One hypothesis as to how compliant boundaries could conceivably reduce turbulent shear stress was suggested in Reference 7 and may be summarized as follows. Previous investigations of the structure of turbulent boundary layers on rigid walls have established the existence of bursting frequencies which characterize the ejection of low momentum fluid away from the wall. This low momentum fluid is replaced with higher momentum fluid coming from upstream of the burst and moving toward the wall. Thus a successful compliant boundary should modulate or damp the burst phenomena so as to reduce the rate at which low momentum fluid is ejected. If this were affected, a smaller velocity gradient and a reduced shear stress at the wall would result. It was also suggested that this requires surfaces which can respond with high frequencies and low to moderate amplitudes, at least in an aerodynamic environment. For the hydrodynamic case, no such estimates are available.

The problem is not straightforward. It combines a structural analysis interaction with complex induced hydrodynamic forces. Furthermore, numerous prime variables exist. These include flow parameters such as fluid density, pressure gradient, and Reynolds number; material properties such as stiffness, density, and degree of anisotropy; and structural characteristics such as tension and thickness. Obtaining general analytical solutions will take a considerable effort.

The purpose of the present tests was fourfold. First, they were planned to investigate a variety of compliant membrane/substrate combinations since previously reported cases of drag reduction have utilized membranes. Next, the measurements were to be carried out in water since only limited previous data was available for this fluid medium. Also, a relatively simple device for applying repeatable, known tensions to the membrane surfaces was to be designed and constructed. Finally, the test procedure was to be suitable for use as a simple means of screening candidate materials for subsequent, more detailed, examination of boundary layer profiles and surface motions.

To achieve these goals, a special compliant disk was designed and subsequently tested in the Vought Advanced Technology Center rotating disk facility. The only previous compliant disk experiments that we are aware of are those conducted by Hansen and Hunston.[8,9] There, the hydrodynamic drag of disks with 1/3 cm coatings of 10, 15, 20 and 25% PVC plastisol were measured. Radial standing waves were observed in the compliant surfaces when the disk rotational speed exceeded a critical value that was dependent on the shear modulus of the surface coating. An increase in drag followed the onset of these waves and was ascribed to an effective increase in surface roughness. However, no drag reduction was measured, even before the onset of surface waves. In the present tests, the membrane tension could be controlled to delay the onset of such standing surface waves to beyond the nominal disk rotational speeds.

In the following Sections, the experimental setup and details of the compliant disk are described, after which the results of the surface drag measurements are discussed.

2.0 EXPERIMENTAL SETUP

2.1 ROTATING DISK FACILITY

The rotating disk facility consists of a motor driven shaft supported by precision bearings and extending into a rectangular tank 165 cm long, 95 cm wide, and 65 cm deep. The top of the tank is hinged for access and seals against a rubber gasket when closed. Power is provided by a constant speed 7.5 horsepower electric motor with a belt driven, variable speed transmission connecting the motor to the drive shaft. The transmission is continuously variable in output speed from 500 to 5000 rpm. A right-angle gear box is used in the drive shaft to provide a vertical rotation axis for the facility. The ratio of the input to output speeds for this gear box is 2:1.

For most of the tests, the shaft speed was measured by means of a strobe light arrangement. During the final runs with the thick membranes, an electronic "counter" was designed and used, and provided a more accurate method for determining this speed.

Variable reluctance (no slip rings) torque transducers were mounted beneath the right-angle gear box and in-line with the drive shaft to directly measure torque (and so drag). Transducers with full scale ranges of 115 and 576 cm Kg were utilized for the compliant disk tests. These were calibrated statically with known loads periodically throughout the tests to minimize errors from this source.

2.2 BASIC DISK DESIGN

A schematic of the compliant disk is presented in Figure 1 showing the relevant dimensions of the basic aluminum frame, substrate cavities, membrane retainer rings, and center hub. Four O-rings were used beneath the retainer rings and the center washers in order to obtain an air tight seal beneath membranes. This feature, along with three gas passages through the side of the disk, provided a means for inflating the disk and measuring membrane tension.

The disk, with Plexiglas substrates, was spin balanced on a vibration analyzer at speeds up to 1400 rpm. A satisfactory balance was achieved by drilling three holes in the frame normal to the plane of the disk. These holes were located beneath the retainer rings so that the external shape was unaltered.

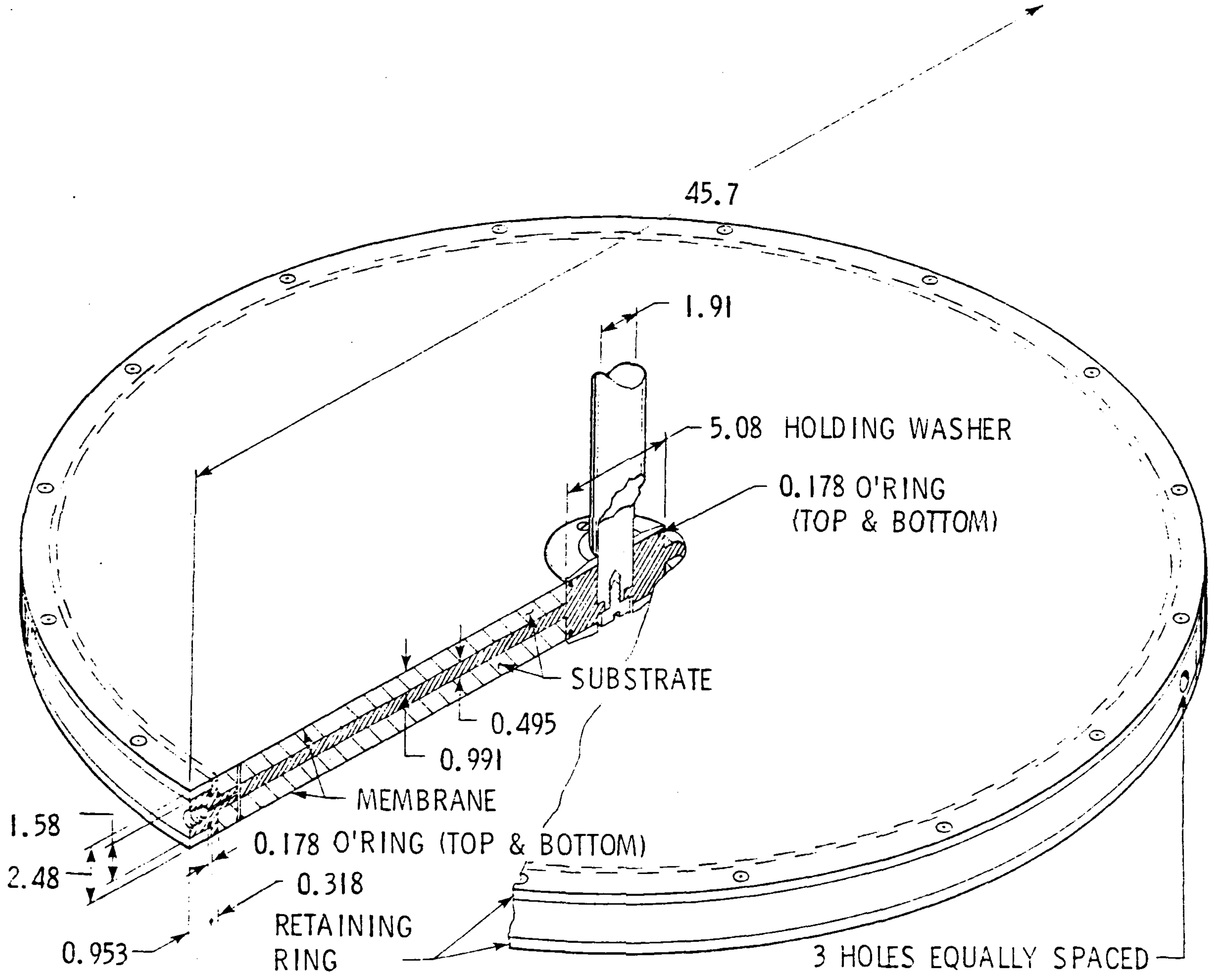

FIGURE 1. COMPLIANT SURFACE DISK (DIMENSIONS IN CENTIMETERS)

The total compliant surface area (top plus bottom) is 3000 cm^2. The cavity in the frame is scaled to take a nominal substrate thickness of approximately 1 cm; thinner substrates can be accommodated by using appropriate Plexiglas or styrofoam spacers.

2.3 ATTACHMENT OF MEMBRANES AND MEASUREMENT OF TENSION

A schematic of the apparatus for stretching a circular membrane is shown in Figure 2. The rig is designed both to apply uniform tension to a membrane and to insure repeatable results. The procedure used in constructing a typical membrane is as follows. The disk, with a substrate bonded in place, is placed inside the stretcher ring. The depth of the cavity is approximately 0.05 cm greater than the thickness of the disk frame so that a membrane does not usually touch the substrate during application of tension. Next, the support plate is placed on top of the corner bolts, and the membrane, with bar weights attached to the edges, is placed on the support plate. The clamping plate, which has a nonskid rubber sheet bonded to the bottom side, is then placed on top of the membrane. Four to eight C-clamps are attached around the periphery to sandwich the membrane between the support plate and clamping plate.

The bar weights are then removed, and primary tension is applied by the stretcher ring as the clamped plates are lowered. The magnitude of the tension is controlled by height of the nuts on the four corner bolts. In order to complete attachment of the membrane, the applied tension must be held while the membrane retainer ring is attached with screws. This is done by placing the entire tension rig in a press. A heavy cover plate is then placed on top of the membrane. The outer diameter of this cover plate is sized to rest on the outer wall of the substrate cavity and allow the retainer ring to slide over it onto the membrane. Pressure is then applied to the cover plate, the C-clamps are removed, and the retainer ring is attached with screws to the disk frame. Finally, a center holding washer is attached and the edges of the membrane are trimmed flush with the disk.

This rather elaborate procedure is not necessary for constructing hard reference disks. In these cases, the hard substrate is simply sprayed with an adhesive, the membrane lowered onto the stretcher ring, and subsequently rolled onto the substrate. After bonding, the C-clamps are removed, the retainer ring and center holding washer are attached, and the membrane edges are trimmed.

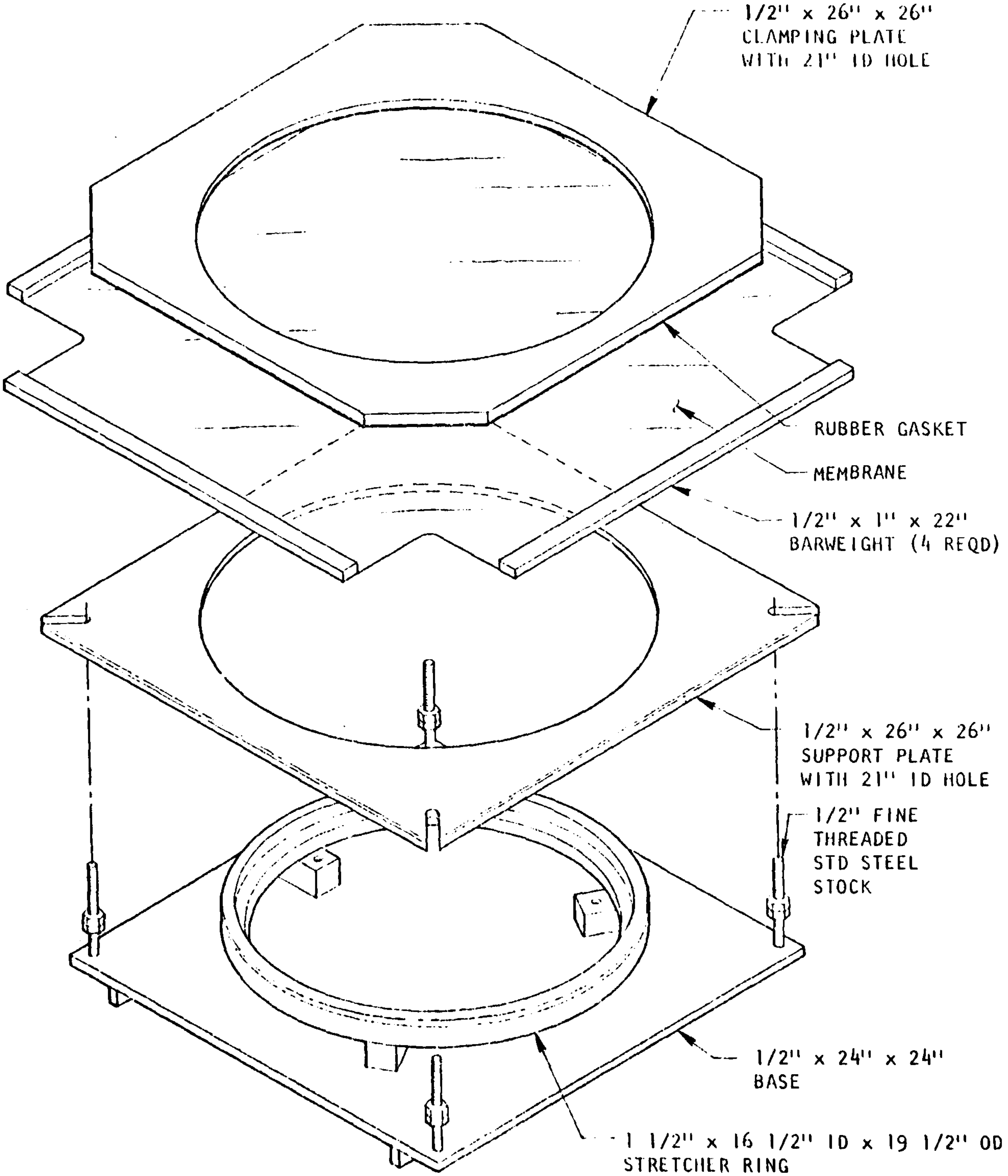

FIGURE 2. MEMBRANE TENSION RIG.

The membrane tension was measured by inflating the membrane with pressurized nitrogen gas through the three gas passages. Since a membrane is on each side of the disk, a holding ring is used to support the disk around its outside edge. The pressure is typically varied over a range from 0.02 to 0.3 N/cm^2.

Deflection of the membrane was measured via a 400x microscope. The microscope is simply focused on a reference point on the membrane before and after pressurization. Since the depth of focus of this instrument is less than one mil, measurements of deflection are conservatively estimated to be accurate within one mil.

The membrane tension T can then be calculated from the following equation:

$$T = (p/4\eta)\left[a^2 - r^2 + \frac{a^2 - b^2 \ln (r/a)}{\ln (a/b)}\right] \qquad (1)$$

where p is the gas pressure, a the outer radius, b the inner radius, and η the membrane deflection at the radial location r.

Uniformity of tension may be checked by making deflection measurements at various circumferential locations and values of r. Measurements indicate the tension is uniform to within ± 6%. With regard to repeatability, the data showed that tension variations between membranes can be held to less than 10%. Generally, the membrane tension measurements can be accomplished with minimum difficulty using this inflation-deflection technique. An alternate approach to applying tension is discussed in Reference 10.

However, when a Mylar membrane is in contact with substrates of either polyurethane foam or PVC plastisol, large scatter in the tension data was encountered. In the case of polyurethane foam, electrostatic charge between the foam and Mylar is suspected, although applications of an antistatic fluid to both the foam and Mylar did not help. In the case of plastisol substrates, nonuniformities in the thickness is suspected. By the time the membrane was inflated enough to completely clear all parts of the plastisol, the gas pressure begins to add significant tension to the membrane. In an attempt to alleviate this particular problem, a number of these membranes were made, without the substrates, to a given tension, and the height of the nuts on the four corner bolts carefully noted. Then the membranes were placed over the foam or plastisol substrates, at the same corner nut setting, and it was tacitly assumed that the presence of the flush substrate did not significantly alter the previously measured membrane tension.

2.4 MEMBRANE AND SUBSTRATE MATERIALS

The membrane materials were selected based on past experience and on their ability to resist radial surface wave formation. These waves are characteristic of compliant disks and were discussed by Hansen and Hunston.[8] It was found in the present experiments that the formation of these waves could be delayed until a Reynolds number Re of approximately 4.6×10^6 (c.f., a wave onset Re of 4.2×10^5 in Ref. 8) by using a Mylar membrane and controlling the tension. Here, Re is based on the disk radius and edge speed.

Table 1 provides a summary of the membrane materials and thicknesses tested in this program. Two thicknesses of mylar were tested in order to investigate the effects of plate bending stiffness which is proportional to thickness cubed. The limited experimental results, reported in the following Section, did not indicate any effect of this variable.

Three compliant substrate materials were used. Polyurethane (PU) foam was selected on the basis of the successful results reported by Walters,[3] Mattout,[11] and Fischer.[4] Both Walters and Mattout used PU foam with 16 pores per cm (ppc) while Fischer used PU foam with 39 ppc. Examination under a microscope indicated the material used in the ATC tests had nearly 50 ppc. This material, as measured at ATC, had a Young's modulus of 3.45×10^4 N/m^2 and a density of 0.029 gm/cc. Two thicknesses of approximately 1 cm and 1/3 cm were tested.

Polyvinyl chloride (PVC) plastisol was chosen as a second substrate material because Young's modulus can be easily varied by changing the resin content. This material was apparently first used in compliant disk tests, without any membrane covering, by Hansen and Hunston.[8] It has also been employed as a substrate on flat plates at NASA Langley by Fischer.[4] The use of PVC plastisol as a substrate was further explored in the ATC tests by using it both in its natural condition and with powder on the plastisol to make it dry and nonsticky. The nontacky condition was considered to be an important test since Walters[3] reported drag reduction only occurred without the membrane bonded to the substrate.

TABLE 1. MEMBRANE AND SUBSTRATE MATERIALS AND THICKNESSES.

MEMBRANE MATERIAL	THICKNESS (cm)
Mylar	0.0025 & 0.0051
Latex	0.023
Neoprene	0.157
Polyurethane	0.234
Polyvinyl Chloride	0.0076
SUBSTRATE MATERIAL	**THICKNESS (cm)**
PU Foam	1/3 & 1
PVC Plastisol	1
Organic Rubber	1/3 & 1

Substrates of 1 cm plastisol with 20, 25 and 30% resin content were fabricated and tested. Although a rubber cement was used to attach the plastisol to the disk, it tended to pull and stretch away from the center hub during the spin tests. In addition, it is suspected that the entire plastisol substrate stretched nonuniformly and distributed the mass unsymmetrically over the faces of the disks. This undoubtedly caused larger amplitude vibration and more drag. The combination of softness (Young's modulus = 7.58×10^3 N/m^2 for 20% PVC plastisol) and a relatively high density (ρ = 1.06 gm/cc) probably measured for a corresponding disk with perfect balance.

The third substrate material was chlorinated polyethylene which is referred to in the remainder of the text as organic rubber. This closed-pore organic rubber was selected because theoretically it can be molded with a smooth surface, does not absorb water, has a relatively low density (ρ = 0.246 gm/cc), and a Young's modulus of 2.45×10^5 N/m^2. Originally, it was planned to test this material both with and without a membrane, but unfortunately the material could not be supplied with the required size and a sufficiently smooth surface. Thus, organic rubber was used exclusively as a substrate with thicknesses of 1 and 1/3 cm.

3.0 TEST RESULTS

3.1 HARD REFERENCE DISK

Initial tests were carried out with hard surface (non-compliant) disks. This was done to compare the measured drag for this case with previous analytical results, and to provide a reference drag value against which the subsequent compliant disk data could be contrasted.

The first hard disk was made of a 2 mil mylar membrane bonded to a 1 cm Plexiglas substrate. Drag measurements for this disk at various rpm were approximately 7% lower than an estimate obtained from the semi-empirical "thin" disk results of Goldstein,[12] corrected for thickness using the rotating cylinder drag correlation of Theodorsen and Regier.[13] However, it was found that this substrate deformed slightly after several tests, and also gave rise to some vibration problems at higher rpm.

Thus a second hard reference disk was fabricated using 2 mil mylar bonded to a 1 cm thick styrofoam substrate. This reduced the overall disk weight considerably and decreased the vibration problems. The measured drag for this disk was very slightly less than that using the Plexiglas substrate. In Figure 3, the measured drag moment coefficient C_M is plotted as a function of Reynolds number for this reference disk. For comparison, the semi-empirical estimate based on References 12 and 13 is also plotted, along with the more recent numerical results of Cooper,[14] and the "thin" disk prediction of Goldstein.[12] It is seen that the applied thickness correction appears overestimated, and that the measurements lie between Goldstein's and Cooper's predictions.

In the compliant surface tests, the following data reduction procedure has been adopted. Unless specifically noted, all compliant disk data are normalized with respect to the mylar/styrofoam hard disk results.

3.2 COMPLIANT SURFACE DISKS

Drag moment coefficient data for nearly 40 compliant disks were taken and the results of the various parametric studies are presented here in a normalized fashion, that is, the drag of the compliant surface divided by the drag of the hard reference disk. This form of data presentation is considered to be the most appropriate because it accounts for tank wall effects, changes

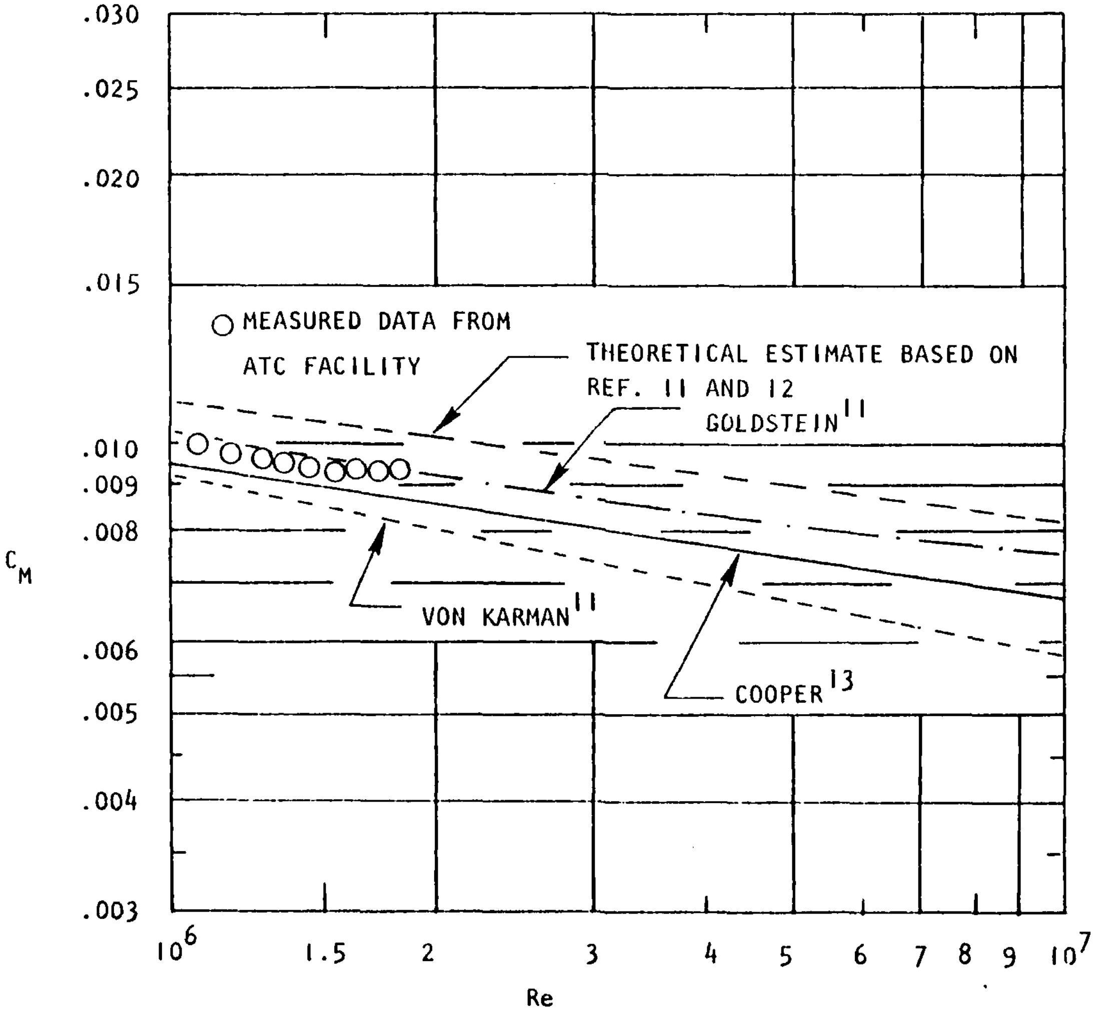

FIGURE 3. COMPARISON OF HARD REFERENCE DISK DATA WITH PREVIOUS CORRELATIONS OF TURBULENT MOMENT COEFFICIENT, C_M.

in bearing friction, instrumentation idiosyncrasies, and any other effects which might cause errors in absolute values of disk drag. The experimental uncertainty in these ratios is estimated to be ± 7%. However, uncertainty in differences for a given disk or between comparable weight cases is considered to be within ± 4%.

The data matrix includes effects of membrane and substrate thickness and material, membrane bonding and air gaps, and membrane tension. The tests were carried out at disk rotational speeds of between 300 and 500 rpm, which corresponds to a Reynolds number range of 1.7 - 3.0 x 10^6 and edge velocity of 13-22 knots.

Data for 1 mil mylar membranes over air substrates are shown in Figure 4. Two values of membrane tension were tested with an air gap of 0.132 cm separating the membrane from a styrofoam spacer. This configuration was designed to test the hypothesis of Reference 7 that membranes over thin air gaps will tend to respond to high frequencies and may be more effective in reducing drag. However, for the two values of membrane tension tested, this arrangement did not prove to be very promising. In fact, the measured drag was lower for the 1 cm air spacing. Although the membrane tension is slightly higher for this configuration, the small air gap data do not indicate any significant effect of tension. In all three cases, disk drag was higher than the hard reference disk.

Figure 5 presents drag results for disks with 1 mil mylar over two thicknesses of polyurethane (PU) foam. Membrane tension was held constant at 150 N/m, and was tested both bonded and unbonded to 1/3 cm PU foam with a 2/3 cm styrofoam spacer to fill the disk cavity. There are no detectable differences in drag of the bonded and unbonded cases. With regard to substrate thickness effects, the 1 cm PU foam gave slightly less drag (2 to 4%). In fact, it reproduced the hard disk data quite well. This trend, drag decreasing with increasing substrate thickness, is opposite to what might be expected, since zero thickness PU foam would correspond to the hard disk. However, the small differences in the data lie within the experimental uncertainty, and thus no definitive conclusions can be drawn.

Data for 1 mil mylar over 1/3 cm organic rubber are shown in Figure 6. The membrane tension was again 150 N/m and was tested bonded and unbonded.

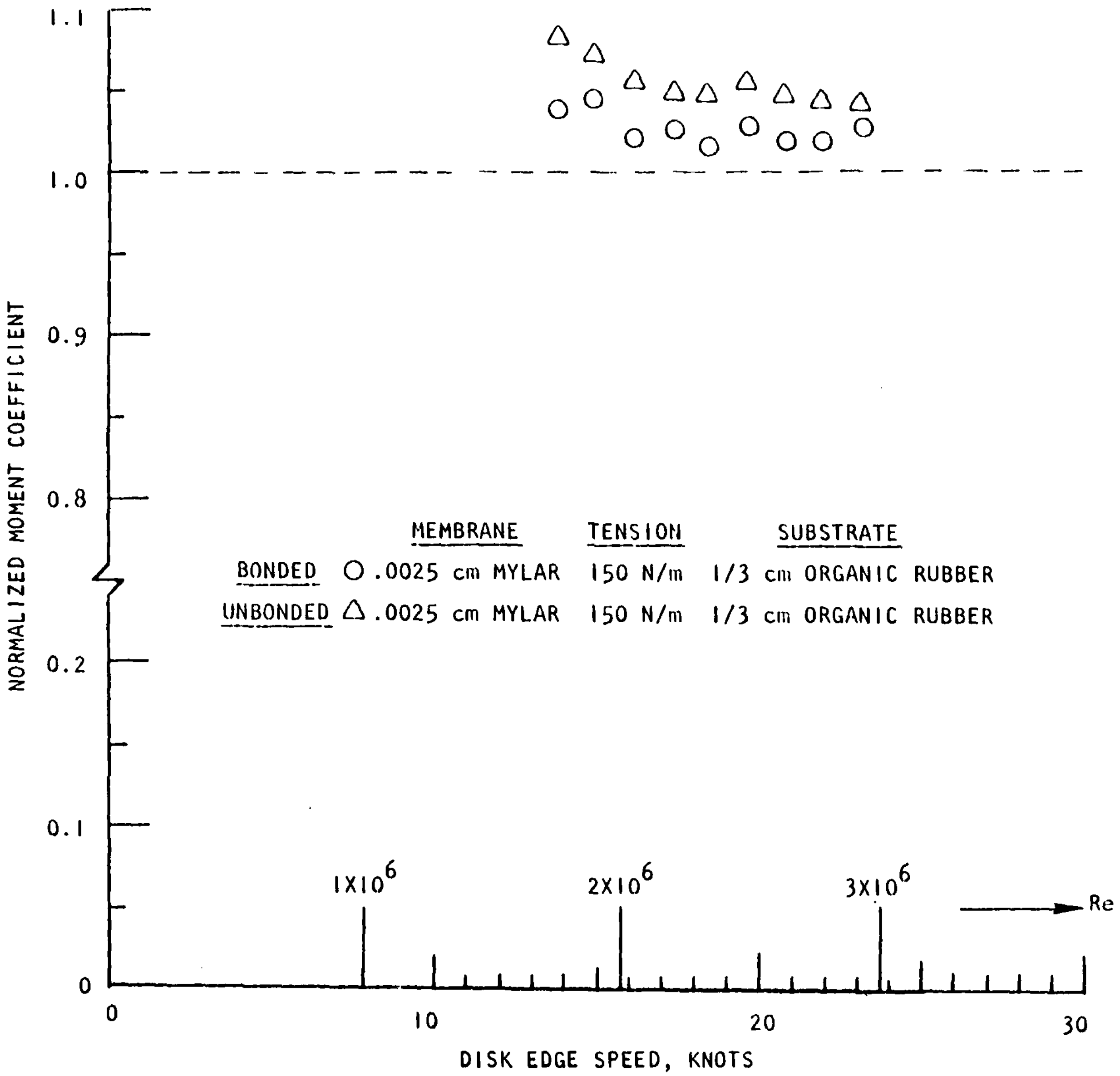

FIGURE 4. EFFECT OF AIR GAP, STYROFOAM SUBSTRATE

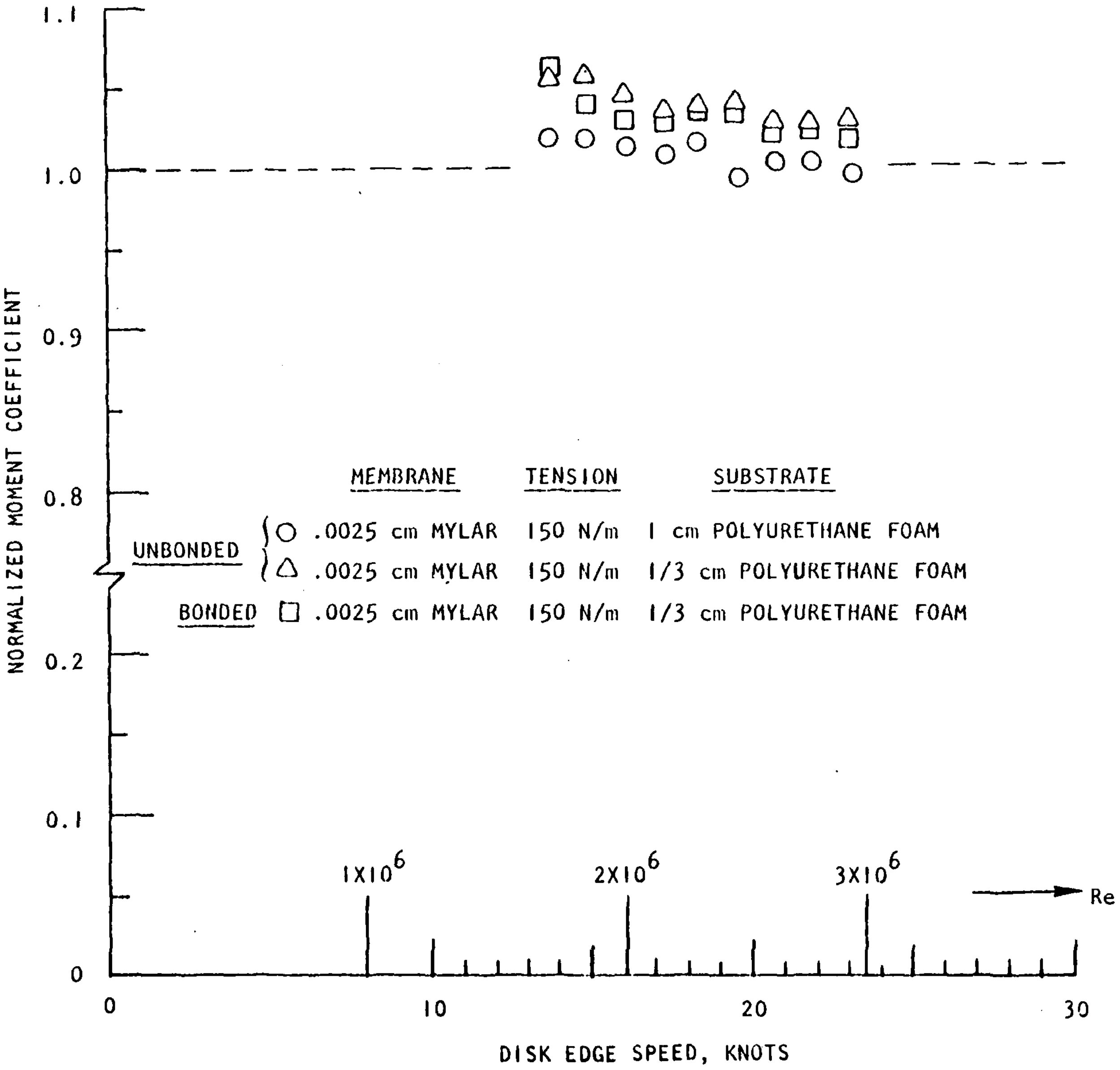

FIGURE 5. EFFECT OF SUBSTRATE THICKNESS AND BONDING, PU FOAM SUBSTRATE

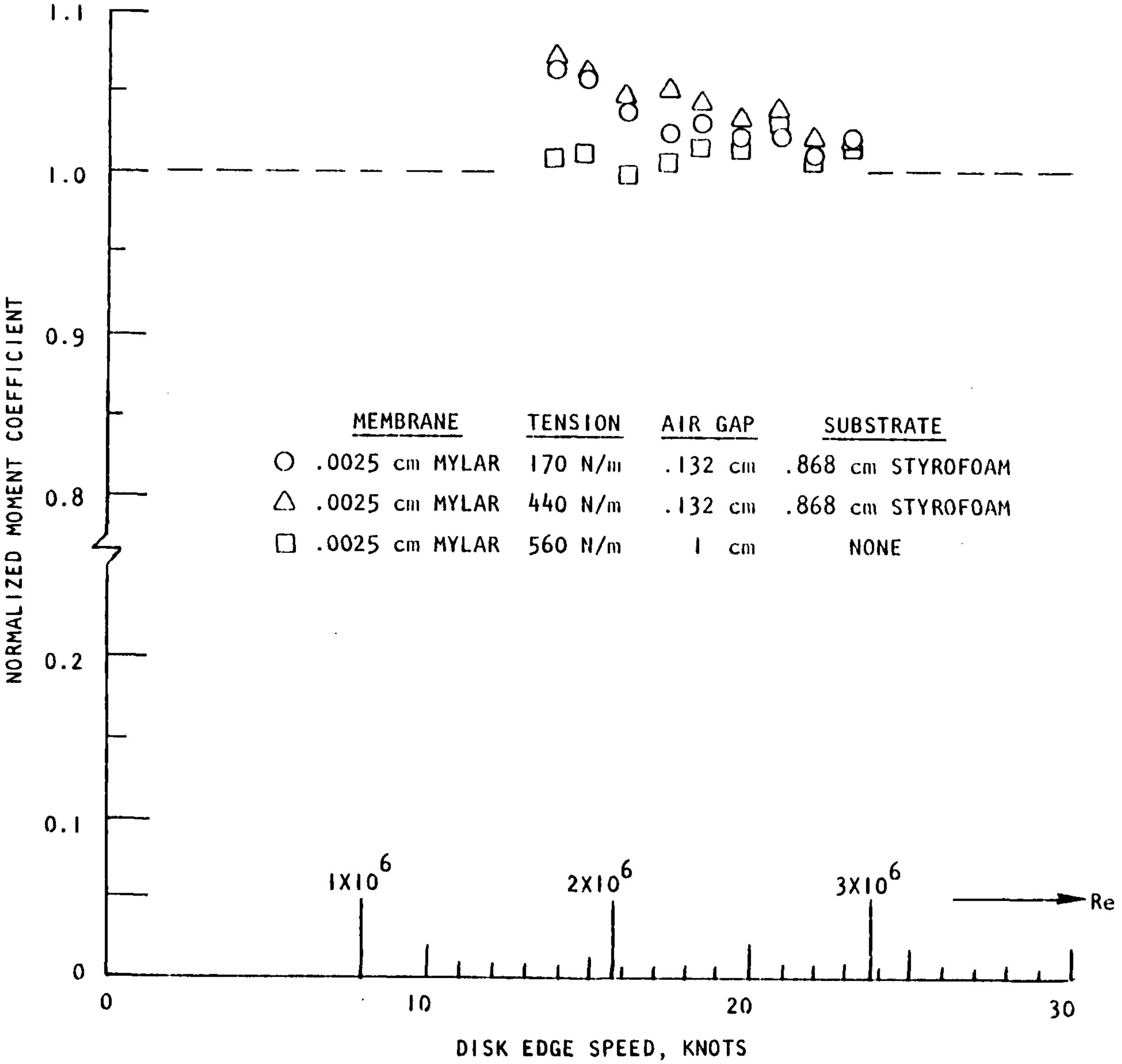

FIGURE 6. EFFECT OF MEMBRANE BONDING, THIN MYLAR MEMBRANE

The drag level is very similar to the data obtained with 1/3 cm PU foam; only in this case, the bonded surface exhibits slightly lower drag. Presumably, this is due to lower response amplitudes. The same membrane material and tension was also tested over 1 cm organic rubber. For this configuration, the bonded and unbonded cases agreed within 1% and the level of drag is very similar to the data obtained for the 1/3 cm organic rubber. Thus, it is concluded that the drag of 1 mil mylar-organic rubber disks is relatively insensitive to changes in substrate thickness.

Figure 7 shows the effects of varying tension in 1 mil mylar bonded to 1 cm organic rubber. Membrane tensions of 0, 125, and 190 N/m were tested. There appears to be a slight reduction in drag as tension is varied from zero to 125 N/m. However, there are negligible differences between the 125 and 190 N/m cases, and [illegible] in all three cases the drag was equal to or greater than the reference values.

One further 1 mil mylar membrane disk was tested. Here, the membrane was bonded to 20% PVC plastisol with a tension of 160 N/m. The data was normalized with both styrofoam and Plexiglas hard disks in order to ascertain the effects of vibration. When normalized with the styrofoam hard disk, the drag is generally higher than was measured for lighter weight substrates. When the data is normalized with the Plexiglas hard disk, the moment coefficient ratio drops much closer to one. Since the Plexiglas substrates caused significant disk vibration, this form of data presentation indicates the plastisol disks also have significant vibration. In fact, 20% PVC plastisol is very difficult to place in the disk cavity so that the mass is uniformly distributed. Also, this material deforms under centrifugal loads which can cause further mass imbalance. The resulting transverse vibrations of the disk contribute additional drag.

The next disks tested were those with 2 mil mylar membranes. Membrane tension was varied first. Unbonded membranes with tensions of 346, 510, and 800 N/m, and a bonded membrane having a tension of 510 N/m, were stretched over 1 cm PU foam. The drag for all these configurations was higher than the reference value. Observations of these disks with a strobe light did not reveal any standing waves over the Reynolds number range.

Two mil mylar membranes were also tested over 1 cm organic rubber with a tension of 535 N/m, and reproduced the reference disk drag within about 2%.

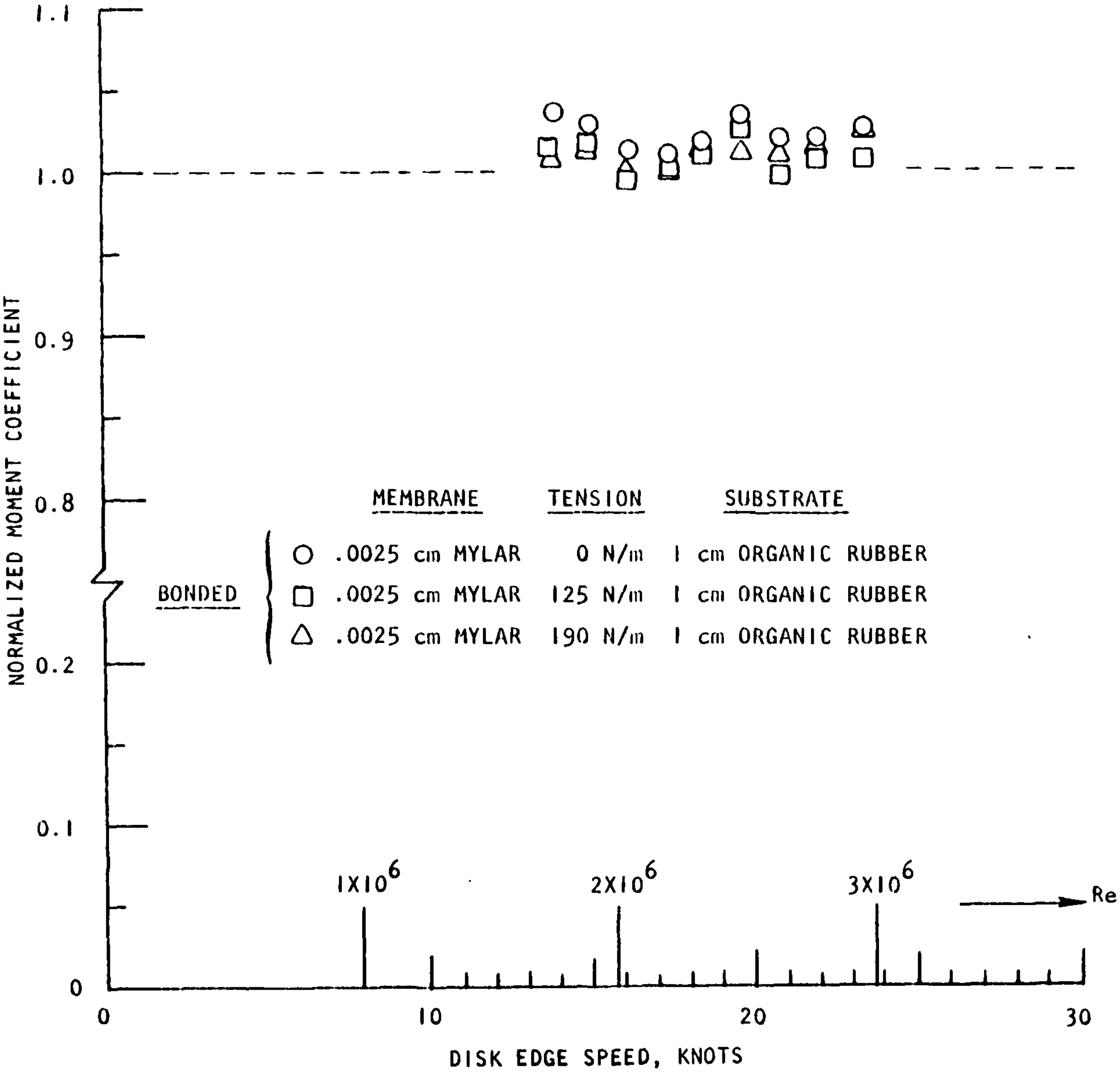

FIGURE 7. EFFECT OF MEMBRANE TENSION, ORGANIC RUBBER SUBSTRATES

The effects of varying resin content in PVC plastisol substrates is shown in Figure 8. The lowest drag was measured for the case of 20% plastisol. However, since the highest drag was measured for the case of 25% plastisol and the total spread in the data is approximately 6%, no definite conclusions can be made concerning the superiority of one resin content.

Note that the compliant surface drag is higher at the lower rpm's and decreases with increasing rpm. This indicates that the vibration amplitude decreases, rather than increases, with increasing rpm which, in turn, suggests that an additional phenomena is involved. One plausible explanation for this is that the drive shaft-disk-water system has a natural resonant frequency near 5 Hz (300 rpm)*, and so the vibrational amplitude will decay as the rotational speeds move away from this resonant condition.

The next membrane tested was 3 mil vinyl. From common experience, it is known that vinyl is quite soft and pliable. In fact, tension measurements on membranes made of this material could not be obtained because the applied gas pressures caused the vinyl to creep and change deflection while pressure was held constant. This characteristic of thin vinyl prevents application of a known tension. Thus, during the fabrication of these disks a low, but sufficient, tension was applied to remove wrinkles in the surface. The resulting membranes appeared to be smooth and free of wrinkles immediately prior to insertion in the water tank.

The first test of vinyl was conducted with the membrane unbonded to 1 cm PU foam. Standing waves were observed at the beginning rpm, and resulted in drag being approximately 10% higher than the reference values, see Figure 9. Subsequently, vinyl membranes were bonded to 1 cm PU form and organic rubber. This did indeed delay the formation of standing waves. However, with the exception of one data point, no significant drag reduction was measured, as shown in Figure 9. Although a drag reduction of 4% is indicated at the initial rpm for the vinyl/PU foam case, this is within the experimental uncertainty (±7%) and is not considered to be a clear case of drag reduction.

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* The natural frequency for the drive shaft-plastisol disk combination is about 13 Hz, and the tank water will add an induced mass which could reduce this to the estimated 5 Hz (or below).

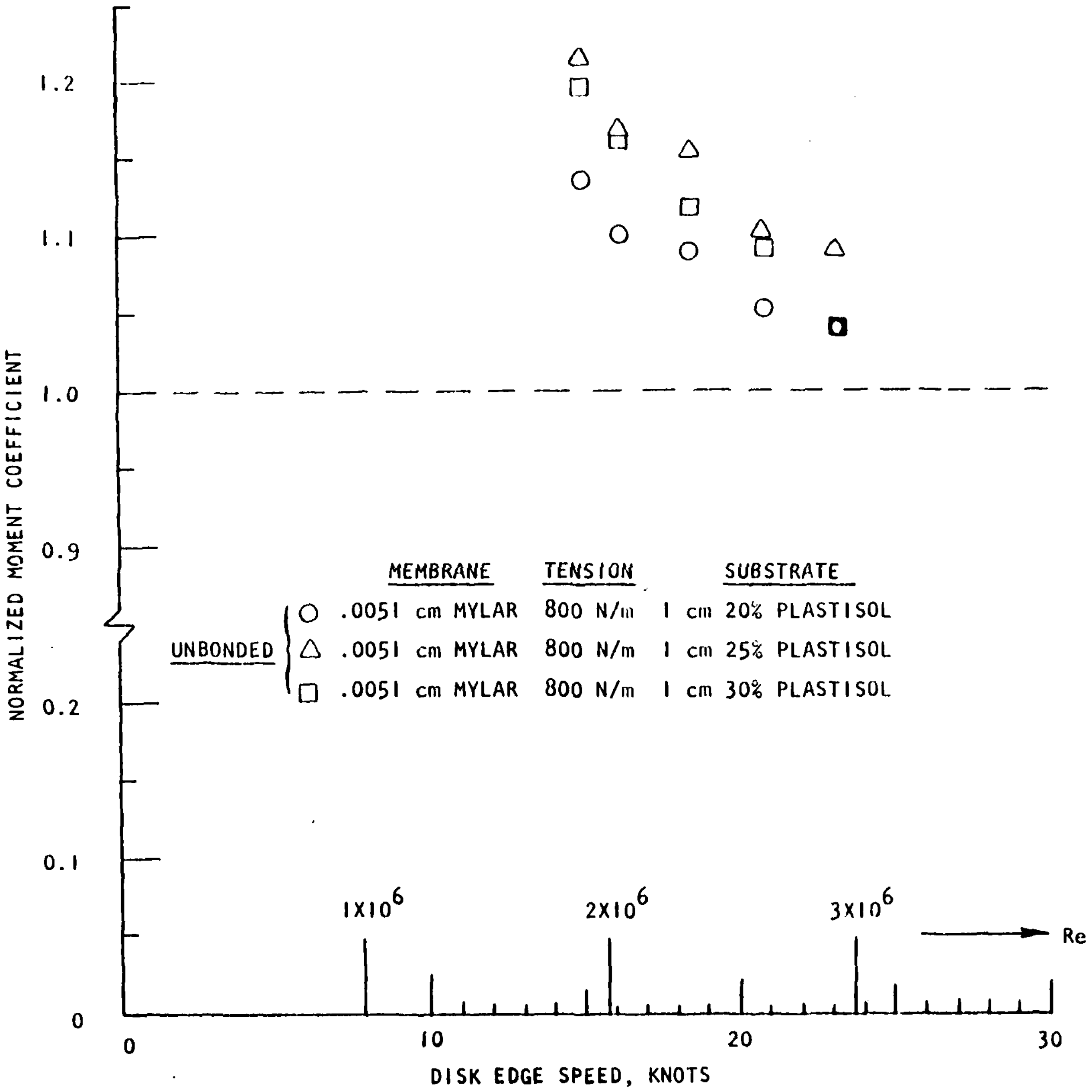

FIGURE 8. EFFECT OF PLASTISOL SUBSTRATE RESIN CONTENT

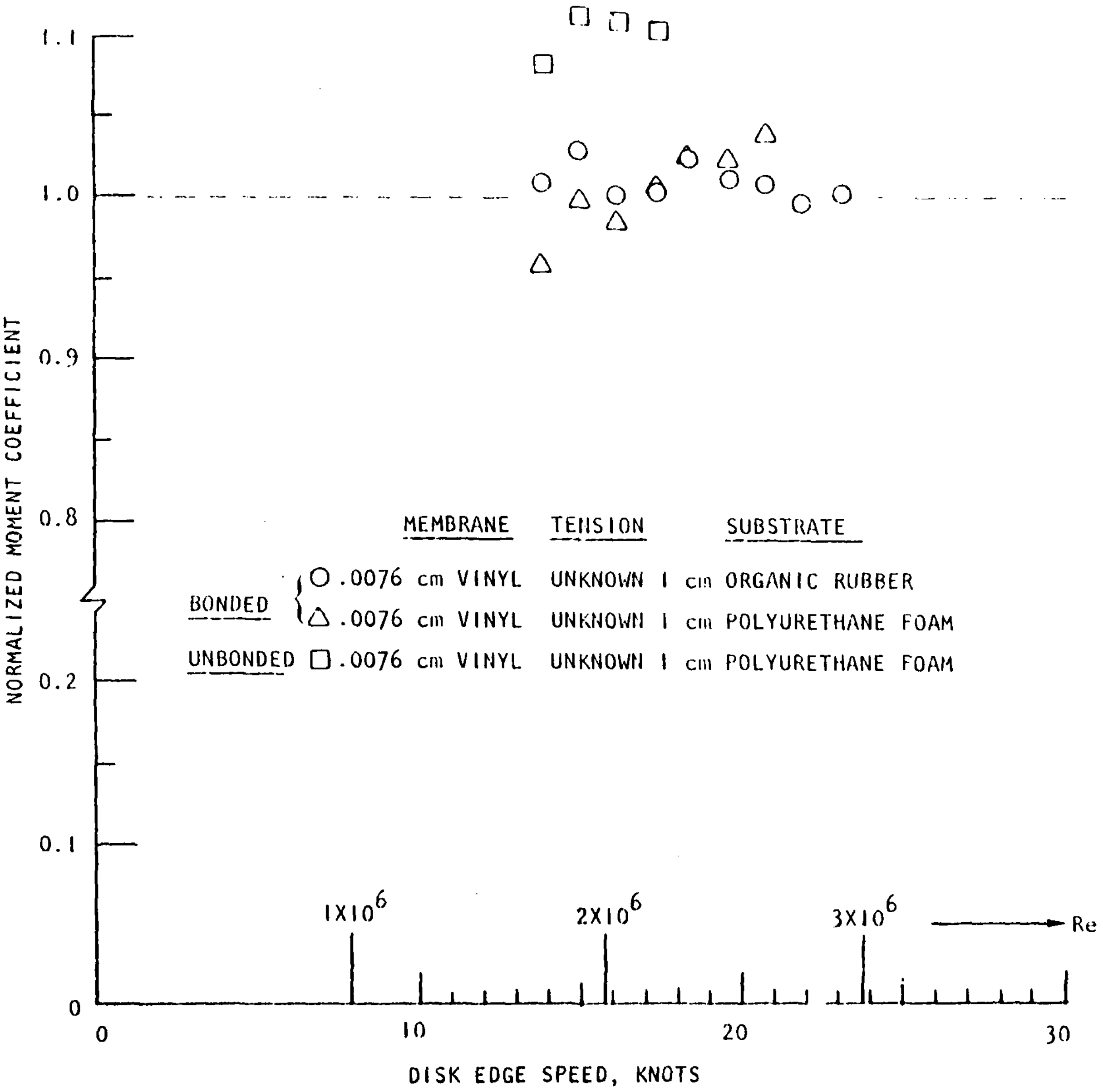

FIGURE 9. EFFECT OF MEMBRANE BONDING, VINYL MEMBRANE

As noted earlier, the thin mylar and vinyl membranes were tested because of previous "successful" drag reduction tests on flat plates. Unfortunately, these thin lightweight membranes were singularly unsuccessful in reducing hydrodynamic drag of rotating disks. The only other existing tool for guiding the selection of membranes was the frequency correlation of Ash.[15] This correlation of reported drag reductions on flat plates with membranes indicated that in the case of an annular membrane, with the dimensions of our disk, and subject to the flow conditions of these tests, heavier membrane materials were required to reduce the natural frequency. In addition, it was also desirable to select materials which would have negligible plate bending stiffness. In order to satisfy these two requirements approximately, membranes were fabricated using five sheets of 0.023 cm latex bonded together. The resulting data indicate a drag reduction of approximately 5% occurred at the beginning Reynolds number, but that the compliant disk drag increased rapidly with Re. This apparent drag reduction must again be viewed with caution since it is within the experimental uncertainty. The rapid rise in drag with increasing rpm is associated with the initiation of standing waves.

Neoprene rubber was next selected as a candidate for a heavier membrane material. A military grade of neoprene was used because of its smoother surface finish. Disk drag for the case of unbonded 0.16 cm neoprene membranes over 1 cm PU foam was measured and it was found that a drag increase of 3 to 5% resulted, see Figure 10.

Data for a compound membrane is also included in Figure 10. This membrane was designed to see if a lightweight membrane might respond to the turbulence and pass its energy on to a heavier, foundational membrane. Unfortunately, standing waves occurred in the single sheet of latex and caused approximately 10% higher drag. The use of compound membranes is an unexplored possibility and is worthy of further study.

As indicated by the drag data shown in Figure 11, very severe standing waves occurred in 0.16 cm neoprene membranes when they were bonded, with near zero tension, to 1 cm organic rubber substrates. This is a good example of the effect of membrane tension, i.e., nonzero tension is essential whether the membrane is bonded or unbonded to a compliant substrate.

The same neoprene material was tested bonded to 1/3 cm PU foam and 1 cm 20% plastisol. In the case of the PU foam substrate, the membrane tension

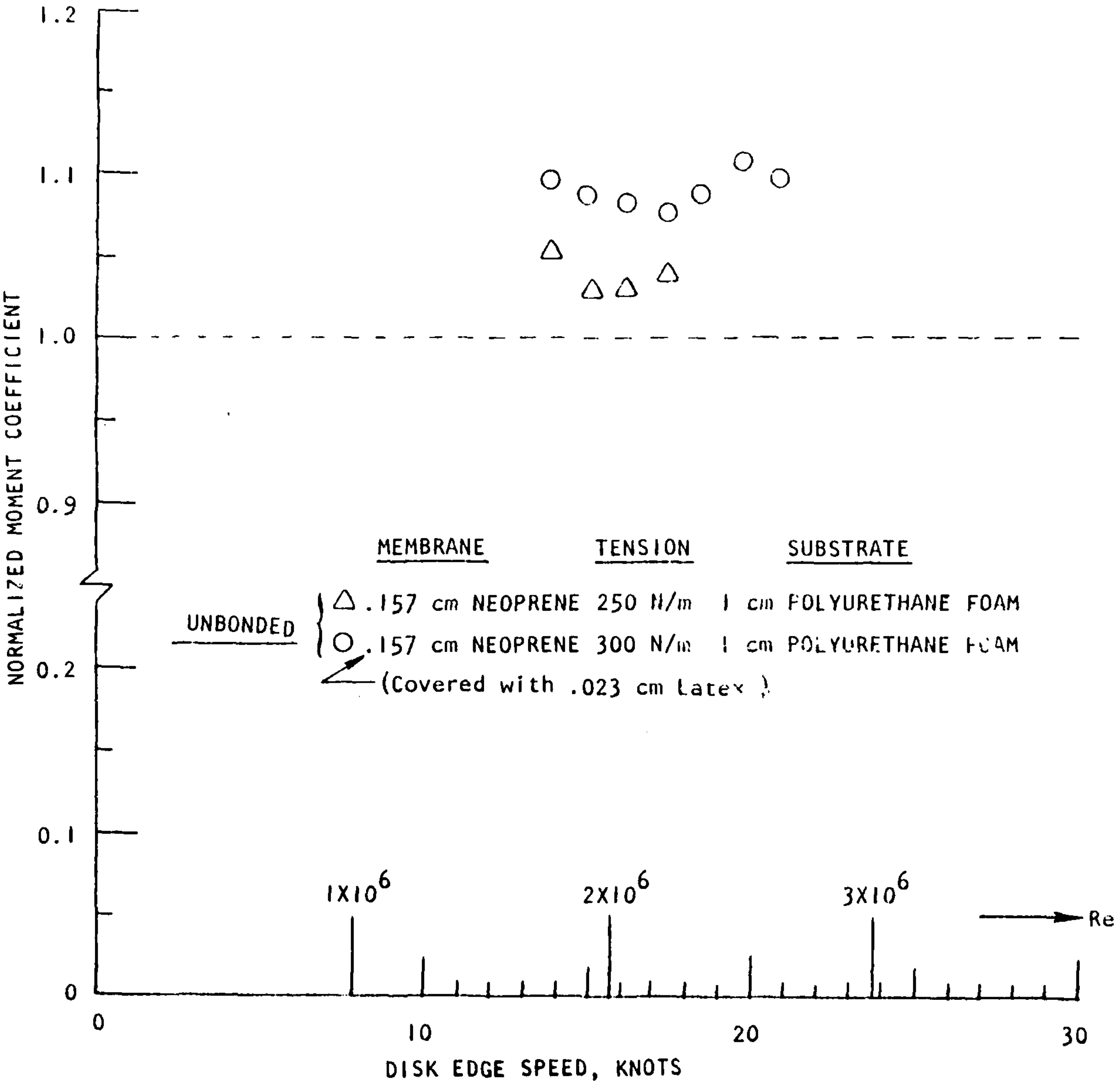

FIGURE 10. COMPOUND MEMBRANE TEST RESULTS

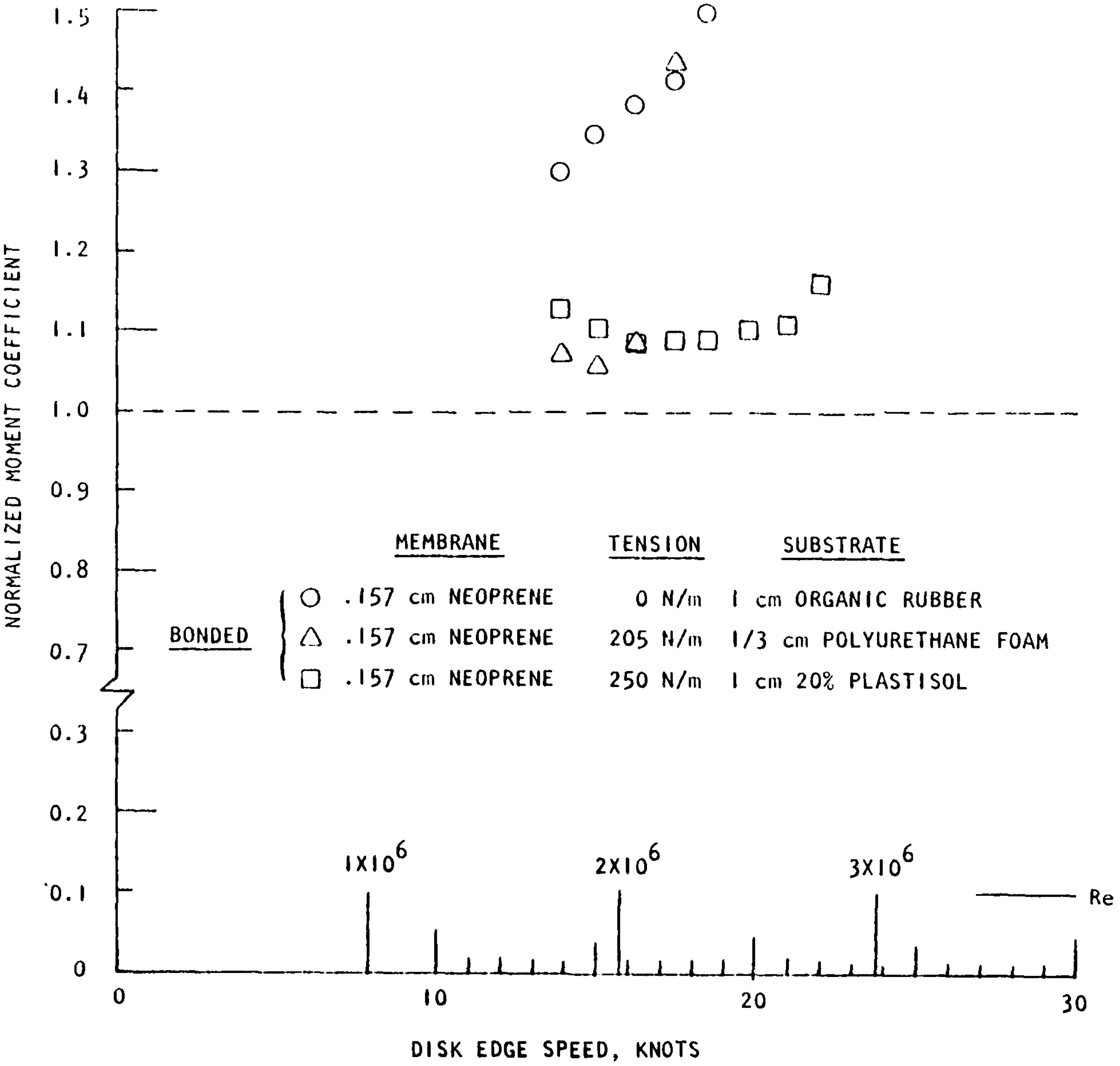

FIGURE 11. NEOPRENE MEMBRANE TEST RESULTS

was 205 N/m and standing waves formed very suddenly near 2.2 million Reynolds number which caused more than a 30% jump in drag, see Figure 11. Comparison of data for neoprene membranes unbonded to 1 cm PU foam and bonded to 1/3 cm PU foam indicates no significant difference in drag level (prior to radial wave formation). The drag of the plastisol disk is approximately 10% higher than the reference values. Thus, there was no indication that the relatively heavy, but soft, neoprene is a useful membrane material for disks.

Polyurethane sheet was selected as the final membrane material. Polyurethane was suggested by the work of Pelt[16] who used it for compliant tube experiments. This material was chosen for the compliant disk tests because it has a relatively high density (ρ = 1.22 gm/cc), is commercially available in a large range of thicknesses, and is soft enough to have low flexural stiffness. Sheet material with a thickness of 0.23 cm (92 mil) and a dorometer rating of 50A was utilized for testing. For the selected thickness, this is the softest polyurethane sheet that was commercially available.

After installing membranes of this material on the disk, attempts to measure tension via inflation were unsuccessful because a constant pressure could not be maintained. It appeared that small, pinhole size leaks existed in the material. However, based on previous experience with 0.16 cm neoprene rubber, tension in the polyurethane membranes was estimated to be around 250 N/m.

An initial sample of the polyurethane sheet was used for unbonded membranes over both 1 cm PU foam and organic rubber substrates. Compared to the styrofoam reference disk, no drag reduction was measured. However, because of the noticeable polyurethane sheet roughness, it was decided to construct an alternate hard reference disk using the polyurethane sheet as a membrane instead of the 2 mil mylar. When the compliant surface data was normalized with respect to this alternate reference disk data, a significant drag reduction (up to 19%) was noticed.[17]

These tests were then repeated, using a smoother sample of the thick polyurethane membrane. The compliant disk was made by stretching the polyurethane sheet over a 1 cm thick organic rubber substrate. Two hard reference disks were used. One had a polyurethane membrane bonded to a rigid PU substrate 1 cm thick; the other a 2 mil mylar membrane bonded to a thicker rigid PU substrate such that the overall membrane/substrate thickness was the same.

The resulting drag moment data is shown in Figure 12. It is apparent that no measurable drag reduction exists. The drag of both the compliant and hard reference disks with the polyurethane membranes was the same within experimental accuracy. The drag of the compliant disk was higher than that of the mylar membrane reference disk for all speeds. This resulting difference in the hard disk drag can probably be attributed not only to surface roughness effects, but also to the fact that the thicker polyurethane could not be stretched as flat across the disk and so had "ridges" at the edge and innermost portions. The precise reason for the previously reported drag reduction[17] remains unclear. The likliest possibility is that the initial alternate hard reference disk drag was too high because of excessive ridge height caused by insufficient bonding or stretching.

3.3 COMPARISON WITH THEORETICAL PREDICTIONS

As mentioned in the previous section, Ash[15] had suggested that there should be a relation between the membrane vibrational frequency f_{vib} and the nominal peak frequency in the turbulent boundary layer f_{peak} for compliant surface drag reduction in air. A plot of the then existing drag data indicated that the frequency ratio f_{vib}/f_{peak} should be approximately one-half for maximum drag reduction. Subsequently, most of the experimental data which was used in the correlation has been discounted,[7] and so the particular optimum frequency ratio as well as the shape of the correlation curve of Reference 15 must be questioned.

Nevertheless, it is of interest to compute the frequency ratio for the present tests to see what ranges were present. Based on calculations outlined in Reference 17, we find that $f_{vib}/f_{peak} > 1$ for the various membrane materials and flow conditions. Thus, a necessary condition for possible hydrodynamic drag reduction may be that $f_{vib}/f_{peak} < 1$. This remains only a conjecture at present, as suggested by Ash's work.

Another attempt at compliant drag prediction was reported in Reference 18. There, an analytical model was developed for the calculation of the perturbation Reynolds stress induced in a compliant wall/turbulent flow interaction. It was shown that the drag ought to decrease as the fluid density, boundary layer thickness, and flow Reynolds number all increase. In the present tests, the effect of the Reynolds number can be seen, although only over a limited range. While the measured data generally showed a decrease or no change in drag levels as Re increased, no drag reduction compared to the hard reference disk was found.

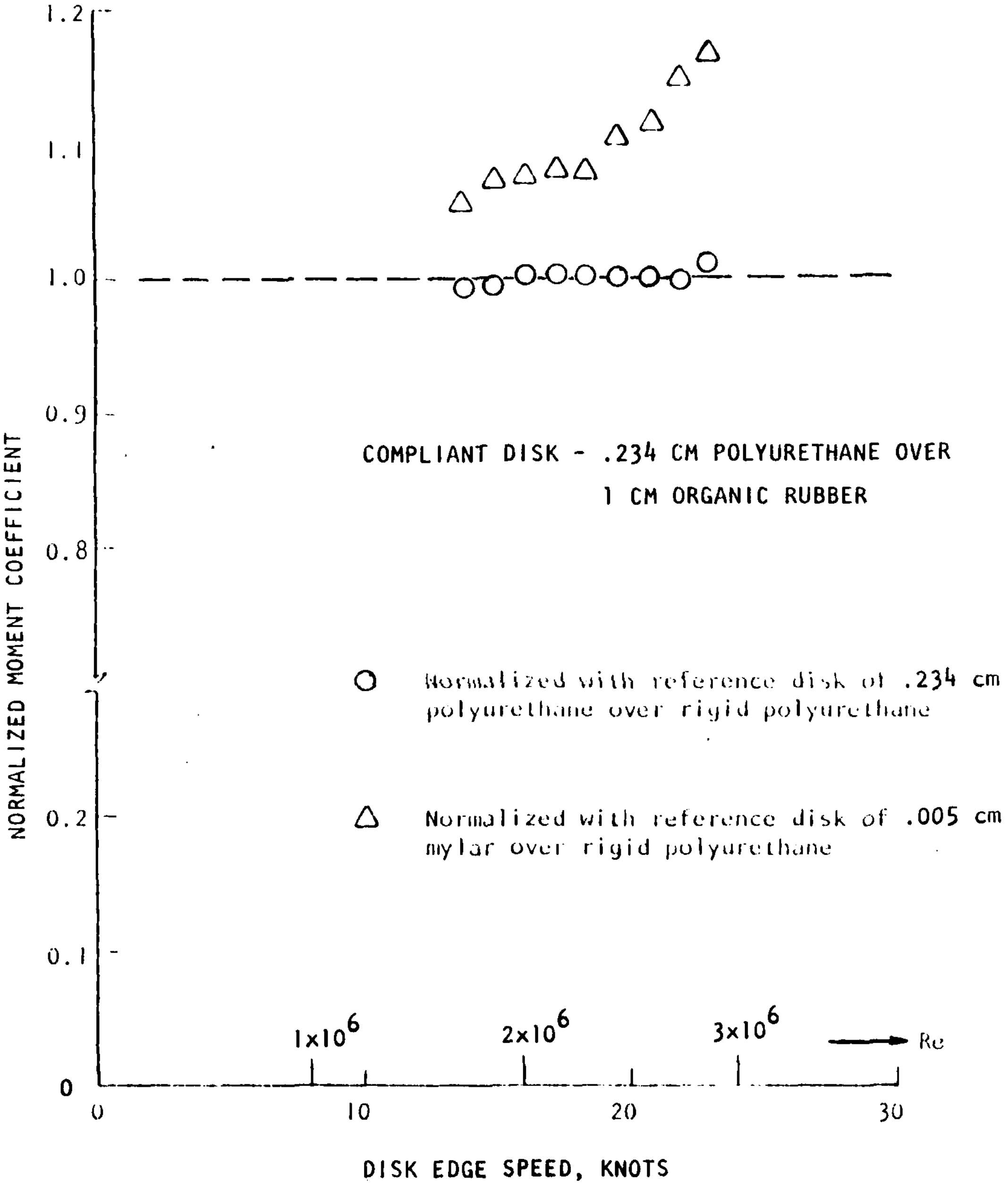

FIGURE 12. THICK POLYURETHANE MEMBRANE TEST RESULTS

Reference 18 also indicated an apparent non-monotonic dependence in drag on the compliant surface density and thickness. However, adaptation of the analysis to the current experiments was not carried out. This was due primarily to the appearance of certain "damping" factors in the theory which are not readily measurable. Hence, to apply the theory requires "fitting" the analysis to available experimental data, which of course almost ensures agreement between theory and experiment.*

Finally, Reference 18 indicated that a successful compliant material should have a low Young's modulus. The data obtained here did not reveal any pronounced effect of changing this parameter.

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* It should be noted that the test data used for comparison in Reference 18 had been judged previously[7] as being misinterpreted as a drag reduction which did not in fact exist.

4.0 CONCLUSIONS

Rotating disk drag tests in a water tank were carried out for nearly 40 compliant membrane/substrate surfaces at Reynolds numbers between 1.7 and 3.0×10^6. The results may be summarized as follows:

- Within experimental accuracy, none of the candidate membrane/substrate combinations tested were effective in reducing turbulent skin friction drag.
- Disk drag was not found to be very sensitive to values of membrane tension greater than 100 N/m. In cases where tension was near zero, standing waves tended to form at low rpm's, and disk drag increased.
- The formation of standing waves can be delayed to higher Reynolds numbers by bonding the membrane to the substrate and by increasing the Young's modulus of the substrate material.
- The rotating disk test arrangement provides a relatively simple method for screening a wide variety of compliant surface configurations.

However, these spin tests are not considered to be a reliable measure of the drag reducing potential of plastisol substrates because the contribution of vibration to the overall disk drag masks possible reductions in skin friction drag.

In order to avoid the vibration and flow measurement problem associated with this rotating apparatus, it is suggested that a flat plate be used as the basic test surface in future exploratory studies. This would allow detailed flow measurements, and thereby permit a better analysis of the interaction between turbulent hydrodynamic flows and compliant boundaries.

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