HYDRODYNAMIC DRAG OF THREE-DIMENSIONAL BODIES

BY MEANS OF A LASER DOPPLER WAKE SURVEY

by

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B.S., Webb Institute of Naval Architecture
(1973)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF

MASTER OF SCIENCE IN NAVAL ARCHITECTURE AND MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(February, 1978)

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Archives

MAR 31 1978
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ABSTRACT

An investigation of the application of Laser Doppler Anemometry to the determination of hydrodynamic drag by means of a wake survey is described. The experimental study, which was limited to viscous drag, is discussed.

The particular objects studied were a MIT Series of yacht keels, with and without turbulence stimulation, at varying angles of attack, and varying Reynolds number.

A discussion is given of the theory relating to the calculation of drag from a wake velocity survey.

A series of guidelines are given for the use of the Laser Doppler Anemometer System for future studies in the MIT Water Tunnel facility.

Graphs and tabulated results of the calculated drag coefficients versus Reynolds number are given, along with a commentary on the particular results.

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ACKNOWLEDGEMENTS

The author wishes to thank his thesis advisor, Professor J. E. Kerwin for his support and guidance in the writing of this thesis. He also wishes to express his gratitude to Dean Lewis and Peter Minh for their assistance with the experimental apparatus, and to Kathleen McGotty for assistance in preparing the manuscript.
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I. **INTRODUCTION**

1.1 **General**

Of considerable interest to all those engaged in the design of hydrodynamic vehicles is their motive power requirement. Whether one is transporting a payload from one point to another, or racing a sailboat, one is always concerned with getting the most distance traveled in the shortest amount of time, with a minimum expenditure of energy. This requires that the designer of any vehicle to have a good understanding of the nature of the forces acting upon his craft, so that he may in turn be able to predict their magnitudes and design the vessel accordingly. In this particular case we are concerned only with the hydrodynamic drag upon an ocean vessel, and the utilization of a fairly new tool, the Laser Doppler Anemometer, to determine it.

1.2 **Wake Survey**

A well known and often used method of determining the drag of some vehicle, or part of some craft, is by means of a wake survey. Any object moving through a viscous fluid has in the region behind it an area where the flow is disturbed to some extent. This might be due to flow separation, cavitation, lift, or the existence of a boundary layer. A wake survey is a determination of some property of the fluid in motion behind the body such that the drag of the body in that condition of motion can be determined. In most cases this survey takes the form of the measurement of the pressure at a series of discrete points behind the form, and in this case the direct measurement of the velocity behind the body.
1.3 Laser Doppler Anemometer

The Laser Doppler Anemometer (LDA) is a device used to obtain the velocity of a fluid flow without inserting any physical probes into the fluid, which would in turn influence the flow patterns. The LDA device is actually a system of electronic units and laser optics. This system is comprised of the laser and its transmitting optics, the receiving optics, and the electronic tracker with its signal processors. The laser generates a beam of coherent light that is split into two beams, which cross at the point where you wish to measure the fluid flow, with a known angle of intersection. Where the beams cross they create interference bands, the size of which are determined by the wavelength of the laser light and by the angle of intersection. With a perfectly clear fluid these bands would not be visible, so the fluid is either seeded with small particles, or the matter already suspended in the fluid makes them visible. Each time a particle moving with the flow goes through these bands it in some way scatters light. The receiving optics pick up these disturbances of the light pattern, the frequency of which depends on the velocity of the particle. The particle velocity is assumed to be the same as that of the flow. The electronic tracker is a device which determines the frequency of the particles crossing the interference bands and generates a voltage which is linearly proportional to this frequency, and thus proportional to the velocity of the flow.

1.4 Limitations of this Study

The original intent upon the start of this work was to obtain the total drag coefficient of a series of yacht keels, using the LDA, and to compare the values found to those found by previous tests on the same models with a normal dyna-
mometer. During the initial months of study it was found that this would involve a number of points, and testing time so large as to be prohibitive. As this was the first attempt at a drag calculation based on a wake survey at the MIT water tunnel, the effort was directed towards finding out what measurements were feasible with the LDA, and to develop techniques to use the instrument. After becoming acquainted with the instrument, it was decided that with the present equipment the only suitable investigation at this stage was a study of the viscous drag to the keels, and to assume that in the mid-span they could be treated as two-dimensional sections.
2. THEORY

2.1 Wake Survey (General Case)

The underlying theory behind all wake surveys is the conservation of momentum. The survey consists of a set of measurements across the flow downstream of the object being studied. Assuming that the flow is relatively uniform before reaching the object, we hope to gain some information about the hydrodynamic characteristics of the object by examining the disturbances created by its passing. These can be either three-dimensional or two-dimensional surveys. In this case we are working with a small section in mid-span of the keel, and are assuming it can be treated as two-dimensional. The drag hereafter discussed is the drag per unit span, and does not include any tip or edge effects. In this instance we are attempting to determine the viscous drag of a yacht keel by calculating the difference in momentum between the non-viscous and viscous flow pattern.

Using Fig. 2.1 as an illustration we shall assume a streamlined body

![Diagram](image)

with an axis of symmetry aligned with the flow. The flow into the control surface surrounding the body is through face "A", and it has a momentum flux of;

\[ \int_A \rho U^2 dA \]
The units of the momentum flux being ML/T^2, mass per unit time multiplied by its velocity. The additional assumptions needed in this model are those of incompressible flow, and that the control surface boundaries are sufficiently removed from the body so that the pressure has returned to its free-stream value.

The flow out of the control surface has a momentum flux of;

\[ \int_{S} \rho U_b^2 \, dA \]

As the flow is symmetric about the body's centerline, the only other possible flow entering or leaving the control surface is through "S". By conservation of mass this flow must have a magnitude of;

\[ \rho \int (U_{\lambda} - U_b) \, dA \]

And, as it is leaving the control surface in the free-stream region, its momentum must be;

\[ \rho \int U_s (U_{\lambda} - U_b) \, dA \]

These formulas deal only with the velocity and momentum components parallel to the centerline of the object. They are all readily expanded to include the three-dimensional case. As "S" is far from the body it is assumed to have a constant velocity, U_s.

Summing the momentum flows into and out of the control volume we have a term for the drag of the object;

\[ \text{DRAG} = \rho \int \left[ (U_{\lambda}^2 - U_b^2) - U_s (U_{\lambda} - U_b) \right] \, dA \]
In cases where the control surface "A" is very far upstream, and "S" is far from the object the equation can be further simplified by equating $U_a$ and $U_s$. This results in the form:

$$\text{DRAC} = \rho \int U_b (U_s - U_e) \, dA$$

which is found in most texts, and even when all the assumptions required are not met exactly, can still give fairly good results.

2.2 Wake Survey (Laser Doppler Anemometer)

In previous wake surveys of airfoil shapes, with the measurements of drag as the intent, the pressure was measured at a series of points downstream of the object. For practical reasons it was usually found difficult to measure the flow sufficiently far from the object so that all the previously mentioned assumptions could not be met. This gave rise to a number of correction formulas, notably those of Jones and Betz, as found in Schlichting. As pressure was the quantity measured, these formulas list the drag coefficient of the object directly in pressure terms, without ever finding the velocities.

The Laser Doppler Anemometer gives us the capability to measure the fluid velocity at any point behind the object being studied without affecting the flow. Thus the pressure terms are no longer needed to find the drag coefficient, if one can satisfy the assumptions of the pressure returning to free stream values.

If we were to attempt to measure the total drag of the keel being studied we would again need corrections for the pressure field created by the foil if the survey was done close behind the trailing edge. In this study we are concerned only with the viscous drag of the keel. The reasons behind this specialization
are discussed under "Preliminary Testing", Section 4.1. For zero angles of attack the pressure drag for a streamlined body is small compared to the viscous drag. For a fifteen percent thickness section the pressure drag is roughly three percent of the viscous drag. If one is interested solely in the viscous drag one can look at the momentum difference between the viscous and non-viscous case.

At this point we make the simplifying assumption that, at the point where we are measuring the viscous flow behind the body, the observed flow outside the wake is not significantly affected by the presence of the wake.

If this was so then the velocity difference in the wake, and the corresponding difference in momentum between the experimental situation and the ideal case of non-viscous flow would be the viscous drag. Rather than risk this possibly unwarranted assumption, we will define the viscous drag found here to be that found by the wake survey when comparing the momentum in the wake to the flow that would have been in the wake if the actual pressure distribution (boundary layer included) was present but no viscous forces. This is equivalent to adding the momentum thickness to the outside of the foil and then treating it as a case of ideal flow.

If we are considering a small region through the wake it appears reasonable to assume that the pressure through the section remains roughly constant. This assumption is supported by Prandtl, as reported in Abbot and Von Doenhoff in the simplification of the "Navier-Stokes Equations". The finding was that the pressure was transmitted essentially unchanged through the boundary layer. Within a wake the same considerations should still apply. A check of the velocity variations induced by a source-sink pair representing the foil is included in the Appen-
The keel was modeled on a Rankine Ovoid, a "worst case", and the velocity differences were calculated. They were less than one percent of the flow velocity and are believed to be low enough to ignore in the present study. With these assumptions we can consider a non-viscous wake profile to be similar to "A" in the previous example, and our viscous profile as boundary "B". As the two profiles are the same outside the wake region the integral need only be evaluated over the wake. The assumption is still made that the flow leaving the boundary transversely, through "S", leaves at axial velocity $U_s$.

2.3 Turbulence Stimulation

As previously discussed, the drag of an object in a mixed laminar and turbulent flow is dependent on the extent of the laminar region. The NACA 66 series of foil shapes tries to maximize this region by delaying the location of the increase in pressure on the surface of the foil. As the extent is also dependent upon the Reynolds number and the surface roughness these items have to be taken into account when expanding model tests to full size. Not only must the Reynolds number of the model match that of the full size section, but the regions of laminar and turbulent flow should be as close to identical as possible.

It is widely believed that yacht keels operate in an almost full turbulent fashion on any but extremely small craft. In order to simulate this in testing facilities for keels and hull shapes, it is common practice to install some kind of turbulence stimulator to the forward edge of the body being tested. It is hoped that this device, which could be a wire, or a row of pins, or sand grains, would cause turbulent flow to exist over the same region on the model as is experienced by the full size shape. Any of the devices mentioned do this, but also add their
own drag forces. They may be located in such a fashion that the laminar flow ahead of them will cancel the effect of the increased drag, or the estimated added drag may be subtracted from the test results. The precision of the LDA should make it possible to see what effect these devices have upon the drag.
3. EQUIPMENT

3.1 Water Tunnel

The testing was done in the MIT Department of Ocean Engineering Water Tunnel. This is a recirculating flow, variable pressure, variable speed tunnel with a constant cross section through the test area. With no object in the test section the flow through that section is usually quite uniform. The models of the yacht keels were mounted on a dynamometer that could vary their angle of attack. The test section incorporates a splitter plate to minimize the effects of the upper boundary layer of the flow on the flow at the model. The test section arrangement is shown in Fig. 3.1.

3.2 Models

The models tested were an MIT series of yacht keels. These were developed under sponsorship of SNAME. Previous testing with these keels was done at the MIT water tunnel and is reported in "Water Tunnel Tests of a Series of Yacht Keels with Varying Reynolds Numbers", by Kerwin and Lewis. This is an unpublished paper for SNAME research panel H-13. The illustrations of the test section and the keels are taken from that report. Their platform, which was the same for all of the models tested for this work, is shown in Fig. 3.2.

The models were mounted in the same fashion as the previous study, so that the results would be directly comparable. All three keel models were tested in the smooth condition, and model one was tested again with the addition of turbulence stimulators.

The turbulence stimulators consisted of number 20 carborundum grit.
Fig. 3.1 Test Section
Fig. 3.2 Keel Planform
Models 1, 2 & 3

Fig. 3.3 Keel Model Sections
These particles were epoxied to the surface of the keel. The keel was first tested with the addition of one row of the stimulators ten millimeters behind the leading edge, and then later with another row added five millimeters further back. In both cases the spacing of the individual grains was roughly three grains per centimeter. It was originally planned to add a third row and test the model again, but this was not done due to a lack of available time in the water tunnel.

The keel cross sections are shown in Fig. 3.3, and additional information on their development can be found in the report by Kerwin and Lewis.

3.3 Laser Doppler Anemometer System

The Laser Doppler Anemometer System is composed of two optics groups with their individual power supplies, and an electronics group which converts their output to a voltage.

A list of the individual items of equipment is included in the appendix. Referring to the pictorial and wiring diagram, Fig. 3.4, the following is a brief description of their set-up and operation.

The laser and transmitting optics are mounted together on a single baseplate. The transmitting optics take the single beam of light produced by the laser and split it into two parallel beams. In the set-up used for this test the beams were then passed through a frequency shifter. This device consists of a set of prisms and a Bragg cell. The Bragg cell operates on a piezoelectric principle, and shifts the frequency of one of the beams a selected amount. The selection of what frequency to be used is determined by the speed of the flow being measured, the particle size, and the optics being used. The frequency shift used throughout this
Fig. 3.4  Pictorial/Wiring Diagram
work was one megahertz. There are adjustments on the transmitting optics to adjust the relative brightness of the two beams, and the alignment of the shifted and the unshifted beam. After the frequency shifter the beams pass through a lens of known focal length. When properly adjusted, the shifted and unshifted beams should intersect at the point where one wishes to measure the fluid velocity, with a known angle of intersection. The velocity will be measured normal to the line that bisects their crossing point.

In the test set-up at the MIT water tunnel the beams travel through the plexi-glass wall of the test section before intersecting in the flow. Any imperfections in the walls will deflect and/or obscure the laser beams. Any deflection from their intended path will induce an error in the ultimate velocity reading, while if one of the beams is partially blocked it will decrease the usable signal, which could cause the electronics to track noise rather than the proper signal. The plexi-glass walls used were the best of those presently available at MIT but are still considered to be only marginally adequate. The imperfections were essentially random and no attempt was made to correct the data for these effects.

The receiving optics are mounted on a separate baseplate on the opposite side of the test chamber. They were adjusted to be parallel to the transmitting optics. As the receiving lens does not send any light through the walls, but rather collects the light scattered by the intersection of the two laser beams, the wall imperfections are only important as far as blockage is concerned. The optics focus the light upon a photo-detector. The induced voltages in the detector are then transmitted to the electronics.
The electronics are based around a tracker, or frequency following device. This unit senses the frequency of the signal from the photo-detector, which is that of the particles going through the beam intersection. The tracker generates a voltage directly proportional to that frequency, as the frequency is directly proportional to the velocity the voltage is proportional to the velocity as well. The electronics package also contains a signal conditioner to eliminate noise effects from the output and to bring the output voltage into a region where the recording meters were most sensitive.

The values of the adjustments on the signal conditioner and the tracker for all the tests were; one volt output per megahertz of the input signal, a five kilohertz low pass filter on the output, and a one volt suppression to eliminate the voltage induced by the frequency shifting. The low pass filter was used to eliminate transients and noise from the output. As we are averaging the flow over ten seconds it seems reasonable that any fluctuations in the flow greater than five kilohertz could be ignored.

The output from the tracker is in discrete voltage levels. The tracker will sense the input frequency, match that with its output voltage, and electronically verify the result. This results in the output of a square-wave type, centered around the voltage which would represent the average velocity. Viewing this output on an oscilloscope was found to be very useful in adjusting the various optical stages and the electronics.

In order to average the frequency over ten seconds the output of the tracker was then fed to a voltage to frequency converter, whose output was in turn fed to a frequency counter reading over ten seconds. It is felt that this is not the best
way to get numerical results, as each instrument added to the system introduces some error, but it was the only system available.
4. TESTING

4.1 Preliminary Tests

Whenever a new instrument is developed and put into use in the laboratory, there is inevitably a period of familiarization necessary before the tester can have confidence and expertise in its use. The LDA system is a new concept in flow measurement, and this particular study was the first of its type at the MIT water tunnel. Throughout the summer months of 1977 preliminary tests and wake surveys were done using the LDA and keel number one.

The initial experiments were not intended to yield numerical values, but to explore what regions of investigation would be open to this device. The original intent was to develop a method to calculate the total drag of a three-dimensional object, in this case a yacht keel, by means of a wake survey. This would be the sum of the viscous drag, tip and root drag, induced drag, and form drag. In order to accomplish this it would be necessary to have a wake survey that covered the entire test cross section behind the model. To account for effects caused by the wall boundary layers, and keel and wall interactions, it was thought that it would probably be necessary to do at least a partial survey in front of the keel model. From the initial work, and the time it took to make a single traverse and record the data, it was obvious that there would not be enough time to do this type of survey for all the models in the MIT keel series. Within the allowable time the available options were to do a complete study of one keel at a limited number of Reynolds numbers, or to investigate one component of the flow around a greater number of models at different speeds. A factor that influenced the decision was the results of an earlier study done on these models
at the water tunnel, with the standard dynamometer. Those results were drag coefficients substantially greater than those expected. It was decided to investigate the viscous drag component of a number of models at different Reynolds numbers to compare with this earlier data. It was thought that a survey of one keel, even if much more extensive, would not be as useful.

Once it was decided that the wake surveys were to be limited to the viscous effects the assumption was made that near the midspan of the section the flow was not seriously effected by tip and root effects, and could therefore be treated as two-dimensional. As the models are of keels with a forty degree sweep, this assumption may not be made lightly. It was thought that limiting the angle of attack to small values would necessarily follow this assumption. A considerable portion of the early tests were devoted to checking this assumption. With the admittedly crude data reduction method in use at that time it was decided that above six centimeters from the keel tip that the two-dimensional assumption was not unreasonable.

Items of particular importance that came to light during this trial period were the following:

The output voltage readings of the instruments were to some extent dependent upon the gain level set on the tracker. That is, turning the gain above a certain level in order to obtain higher data rates, resulted in picking up large amounts of background noise. This noise was for the most part thought to be stray light from the laser and which showed up on the oscilloscope as zero velocity readings. Thus with the gain turned up one could run the water tunnel at any velocity and still have a reading of zero velocity. The means used to avoid this
condition were to observe the output of the tracker on the oscilloscope. A gain setting that was too high would show the output jumping towards zero voltage. A plot was made of data rate versus output at a constant water tunnel speed. The point where this deviated from a straight line corresponds closely with the abnormalities seen on the oscilloscope.

It was found that with the model in place the flow across the tunnel was fairly uniform, except for the wake of the model and the tunnel wall boundary layers. The most significant departures from this being at high velocities with large angles of attack. For this reason it was decided to do a survey of the keel wake that only covered a transverse distance large enough to determine the "free stream" velocity on both sides of the wake. This allowed the use of a transmitting optics lens of a smaller focal length, and reduced the required number of data points on each run.

In a survey of this type time is one of the limiting factors. The periods when the water tunnel is available are limited, and a survey with many discrete point data readings requires large amounts of time. As the testing was to be done over a range of Reynolds numbers, the tunnel speed as well as the transverse position of the laser had to be varied. In the preliminary period the method of changing velocity at a constant location, and that of holding the speed constant while moving the laser from point to point were tried. It was found that working at a constant speed was slightly faster, as well as eliminating some concerns about the transient speed response of the water tunnel.

The facility at present has no method of changing the streamwise location of the laser, which is the location of the survey. For these tests with sept back
keels, the tip of the keel was used as a reference point. The distance behind the keel was varied by changing the height of the laser.

As the velocity in the tunnel was not truly constant over the time it took to make a traverse, it was averaged over ten second intervals. The drive motor RPM was averaged and recorded over those same ten seconds. By varying the speed of the drive impeller, and reading the laser voltage while at a "free stream" position it was found that for practical purposes the flow in the tunnel was linear with the impeller RPM. This was used to normalize the recorded data in the laser wake surveys.
4.2 Production Testing

Keels number one, two and three were tested in sequence, the primary surveys being done at eight centimeters above the tip of the trailing edge. The laser was aligned with the tip of the keel while at zero angle of attack, and then raised to whatever height was being investigated. This resulted in the survey being slightly over six point seven centimeters behind the trailing edge of the keel at zero angle of attack. This distance increased with increasing angle of attack as the laser was left in a constant position and the keel rotated away from perpendicular to its axis. This should have no effects on the results as they should be independent of streamwise position.

Keel number one was later retested with the addition of turbulence stimulators as previously described. The tracker experienced some difficulty with the highly turbulent flows. It was much harder to obtain a high data rate, and losing track of the data was much more frequent than in the other tests. Possible reasons for this are the mixture of fluid flow velocities and directions and unsteady flow. If the flow contains fluid moving at different velocities, or at the same velocity but in different directions, it is possible that the bandwidth of the tracking electronics is being exceeded. If this were the cause then a switch to manual tracking might help. If this effect is caused by the unsteady nature of the flow, the solution would be to average the flow over a greater period of time, or to complete the entire traverse much more quickly. Switching the tracking unit to manual in this instance would result in a bias of the data obtained. As these problems were encountered at the very end of the test period it was not possible to determine which of these, or some other influence was causing the misbehavior. A switch
to a different frequency shift, in view of the high frequency components of the turbulent flow, might be of some help but it was not found possible to try this in the test period.

The procedure used to take one data "point", which consists of the voltage, impeller, RPM, and position was the following:

a) Check the RPM as shown on the counter and adjust to within one RPM
b) Position the Laser and Tracking optics on the desired point.
c) Check the output of the tracked and the input signal to the tracker on the oscilloscope. In this way one can tell if the optics are focused, if one is receiving a noisy signal, or if one is tracking one of the noise signals.
d) Reset the voltage and RPM counters at the same time. As these were both ten-second counters, one can then read them simultaneously.
e) Plot the point thus obtained to check if it agreed with previous points.

In some cases the tracker would lose the signal part way through a ten-second cycle. In this case the error would be small enough that it could slip through unnoticed if the data were not graphed.

Most of the testing consisted of measurements wither inside or adjacent to the wake. The spacing between data points across the wake was usually one millimeter, and outside the wake from one to four millimeters. In most cases the data was taken in two traverses, one for odd numbered data points, and another traverse in the opposite direction taking the even data points. In this fashion it was hoped that any irregularities caused by temporary misalignments or maladjustments would be quite visible on the graph.
The LDA system is a device for precise, and literally pinpoint velocity measurements. One of the chief drawbacks with the present installation for this type of study is the time required to make these measurements. With everything running smoothly the typical time for a traverse would depend on the number of data points being taken. The time required for each data point is approximately one minute. If one is receiving a weak signal from the optics, which could be caused by any number of factors; misadjustments in the equipment or flow conditions, one could expect to spend two minutes or more per data point until this condition is corrected.

The data was reduced by the use of a computer program, written in FORTRAN, for use on the MIT 370/168. The program is based on fitting a polynomial through the wake velocity profile and calculating the difference in momentum between the viscous and non-viscous flow. A program listing and further explanation are found in the Appendix.
5. RESULTS

5.1 Keels in Smooth Condition

As can be seen from the graphs of drag coefficient versus Reynold's number (Fig. 5.1, 5.2, 5.3) all the keels exhibit generally decreasing values of drag coefficient for increasing Rn at low angles of attack. The two keels with fifteen percent thickness exhibit this tendency to a greater extent than the keel with a ten percent of chord thickness. (Keel no. 3) At six degrees angle of attack one starts to see a rise in the drag coefficient at increasing Reynold's number, this tendency also exhibited by Keels nos. 1 and 2 greater than number three.

A quick look at the ITTC correlation line, of the ATTC friction line will indicate that these keels were not operating in a fully turbulent manner. As the drag coefficients here are based on the chord of the keel, they would have to be divided by two to get an equivalent flat plate friction coefficient. This would put typical values at about 0.003 at a Rn of $1.0 \times 10^6$. The Blasius solution for the drag coefficient of a flat plate in laminar flow is:

$$C_d = \frac{1.328}{(R_n)^{\frac{1}{2}}}$$

The corresponding drag coefficient for a flat plate at Rn = $10^6$ is 0.0013, so one is clearly operating in a region of partial laminar flow. In this case the drag coefficient is directly dependent on the extent of the laminar boundary layer. The transition point from laminar to turbulent flow will depend upon the pressure distribution in the flow. The laminar region can not exist to any extent in areas of increasing pressure. Comparing the results to those of Squire & Young, again
in Schlichting, at \( R_n \) of \( 10^6 \) and using a ten percent thickness ratio, the drag coefficient is seen to vary from 0.012 at no laminar flow, to 0.008 at a transition point of 0.4 chord. The values obtained in this study were a good bit lower than these predictions, which would seem to indicate a greater region of laminar flow.

The results agree with those published in Abbot & Von Doenhoff for keels numbers one and two within the limits of experimental error. While their figures are at a considerably higher Reynolds number, the drag coefficients are substantially the same. Abbot & Von Doenhoff do not list figures for keel number three, the 632-010 section, but the data agree fairly well with that on the 632-009 section. It should be mentioned that the data in Abbot & Von Doenhoff was obtained by wake surveys of the pressure type.

A comparison with the results Kerwin & Lewis shows that the values obtained in this work were approximately one-half of the drag coefficients obtained with the dynamometer. The data follows the same trends as observed in their work, but a decrease in drag coefficient from low values to about \( 1.0 \times 10^6 \) and then a leveling off with increasing Reynolds numbers.
Keel No. 1

- 0.0 deg. angle of attack
  4.0 cm above tip

- 6.0 deg. angle of attack
  8.0 cm above tip

- 4.0 deg. angle of attack
  8.0 cm above tip

- 2.0 deg. angle of attack
  8.0 cm above tip

- 0.0 deg. angle of attack
  8.0 cm above tip

Reynold's No. (x 10^-6)

Fig. 5.1
Keel No. 2

6.0 deg angle of attack
8.0 cm above tip

4.0 deg. angle of attack
8.0 cm above tip

2.0 deg. angle of attack
8.0 cm above tip

0.0 deg. angle of attack
8.0 cm above tip

Reynold's No. (x 10^-6)

Fig. 5.2
Keel No. 3

6.0 deg. angle of attack
8.0 cm above tip

4.0 deg. angle of attack
8.0 cm above tip

2.0 deg. angle of attack
8.0 cm above tip

0.0 deg. angle of attack
8.0 cm above tip

Drag Coefficient, $C_d$

Reynold's No. (x $10^{-6}$)

Fig. 5.3
Comparison of Keels 1, 2 & 3

Reynold's No. \( \times 10^{-6} \)  

Fig. 5.4
5.2 Results with Turbulence Stimulators

The graphs, Fig. 5.5, presents the results of the testing of keel no. 1 with the addition of the carborundum turbulence stimulators. There is considerably more scatter in this data than in the data for the keels in the smooth condition. It is believed this is a result of the electronics of the system having greater difficulty in tracking a turbulent flow. As the wakes for smooth keels are also turbulent it is conjectured that this might be unsteady rather than turbulent effects. As this testing was not completed until shortly before this writing there was no time to investigate the source of these effects.

Plotted on the zero degree angle of attack graph is the ATTC friction line, as developed by Schoenherr. The general trend of the data appears to be a gradual decrease in drag coefficient with Reynolds number, but with less slope than predicted by the ATTC line. The difference in drag coefficient produced by the addition of the second row of turbulence stimulators is slight. There is not enough data to develop a good estimate of the drag of a row of stimulators. The results do tend to indicate that the turbulence stimulators add a roughly constant increase in drag coefficient when compared to the keel in smooth condition. An interesting effect is that the drag coefficient does not appear to be influenced a great deal by the angle of attack when the turbulence stimulators are added. This is thought to be a scale effect, which unfortunately was not investigated further, as it might have some significance in other model tests.
Keel No. 1, The Effect of Turbulence Stimulators

0.0 Deg. Angle of attack
4. cm above tip

6.0 Deg. Angle of attack
8. cm above tip

4.0 Deg. Angle of attack
8. cm above tip

2.0 Deg. Angle of attack
8. cm above tip

0.0 Deg. Angle of attack
8. cm above tip

Reynold's No. \( \times 10^{-6} \)

Fig. 5.5
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<th>V avg. (cm/sec)</th>
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<td>Angle (deg)</td>
<td>Hgt. (cm)</td>
<td>V avg. (cm/sec)</td>
<td>R_n (x 10^-5)</td>
<td>C_d</td>
<td>C_d(S)</td>
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Table 5.5  Keel No. 1 with two rows of turbulence stimulators
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<th>Hgt. (cm)</th>
<th>V avg. (cm/sec)</th>
<th>$R_n$ ($\times 10^{-5}$)</th>
<th>$C_d$</th>
<th>$C_d(S)$</th>
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6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Experimental Conclusions

As can be seen in the results section, all the numerical values calculated from the data appeared quite reasonable. In fact, for the first testing done in the facility using the LDA device in this type of study, the agreement with published data in Abbot & Von Doenhoff is remarkable. In view of the crudeness of some of the data reduction, and the possible errors in collecting data it must be assumed that this device is quite forgiving as regards to its operation. This would tend to indicate that the LDA can be expected to give extremely accurate results if a large scale, well planned study is to be done. Conversely, one can quite possibly develop a technique to obtain drag coefficients to a level suitable for most non-critical engineering which would be very simple and easy to use.

Other possibilities for use of the instrument not touched upon in this study were the use of a frequency spectrum analyzer, and a wake survey with the intent of calculating lift. As the existence of the turbulent layer was quite visible on the oscilloscope, and to the LDA's capabilities, this layer constitutes an extensive region, investigations of the internal motions of wakes and boundary layers do not appear unreasonable.

Another feature of the device is its comparative freedom from ranges of greater or lesser accuracy. With the addition of a carriage capable of streamwise motion, one should be able to measure drag from one to thirty feet per second in the MIT water tunnel with a constant level of accuracy. This is not possible to do with any of the presently available dynamometers.
6.2 Recommendations

Assuming that there will be a continued interest in the study of wakes, boundary layers and flow patterns using the LDA, in view of the excellent results obtained by all the users of the instrument so far, it is felt that the following are possible methods for improving the facility.

The present carriage for the laser and the receiving optics was designed to move only vertically and transversely, as the propeller tunnel has the capability of moving the propellers axially. In order to check on the assumption that the pressure variations across the wake are not effecting the survey, the mounting should have a freedom of motion parallel to the flow in the tunnel. Aside from this it would also greatly simplify the initial setup of the unit. With this capability one would only need to align the unit so that it is perpendicular to the flow, without the added difficulty of trying to aim it at a specific location at the same time.

The present system has a handwheel and screw method for transverse motion. The transverse scale used was graduated in millimeters, and readings and adjustments were done by hand. As the water tunnel will only accept rather small models, the size of the wakes in this study was typically two or one centimeters across. A system that could be adjusted to a tenth of a millimeter would at times be useful. The LDA system can easily detect the changes in velocity that occur over a distance of one millimeter, and for high speed flows measured closely behind the keel these changes can be sizable.

It is thought that the system of a pointer and a graduated scale for transverse position location is not in keeping with the accuracy of the LDA. More important
perhaps is the time required to adjust the position by hand. The time required for each survey (one transverse at a constant flow) is not that large, approximately one-half hour. When the time of the data preparation is added on to this it grows considerably. Any wake survey which was to look at a keel as a whole, without the simplifying assumption of a two-dimensional section, would require a very large number of data points. As a result of these two effects, inaccuracy of positioning the unit, and time for data reduction, it is recommended that for any extensive study serious consideration be given to the installation of an automated carriage and data acquisition system. A unit which could traverse the tunnel, and automatically record the impeller RPM, the velocity of the flow, and the location (in three dimensions) on some medium capable of direct computer input would make extensive, and extremely accurate, drag calculations possible. Without such a system only two-dimensional studies are feasible, if only for the reason that test time in the water tunnel is not unlimited. As this study found, the two-dimensional drag is only a fraction of that measured on the dynamometer.

The system should, ideally, have the transmitting and receiving optics mounted on the same baseplate. This would help eliminate noise in the system caused by vibration, and misalignment between the two. Mis-aligned optics were probably the greatest cause of delay in the testing.

The system should also include some system for establishing a reference point with the tunnel or the model. In this study the aft end of the model was adequate as a reference point, but on other shapes that point might not be.

The plexiglass walls on the test section leave a great deal to be desired as
far as use with this instrument. Any imperfections on the transmitting side intro-
duces as error in the data that could not be reasonably detected or corrected.

The present method of mounting the models on the dynamometer and
splitter plate is fairly cumbersome. It has the advantage that one can compare
the drag measured with the dynamometer and the wake survey directly. With
the dynamometer and splitter plate setting up the system takes a good deal of
time, as does changing from one model to the next. The present mounting also
restricts the LDA to the bottom two-thirds of the keel. For these reasons it is
recommended that any new work with this equipment be preceded by the design and
installation of a new splitter-plate or mounting body that would permit more
rapid changes of models, and give an unrestricted view of them to the LDA.
REFERENCES


APPENDIX I

Data Reduction

The data reduction program that was used for this report is based on the fit of a polynomial to the experimental wake velocity survey. There were two variations of this program, the one listed herein was used to calculate the results. This version was probably slightly less rigorous than the other, but it was much easier to prepare the input data for it. This program also relies less on the assumption that you can get a good fit with a polynomial to the wake survey data.

The program requires input of the date of the test run, the water tunnel impeller RPM, the angle of attack, and the height of the laser above the tip of the keel. These values served merely to identify the computer run and the data at a later time. The approximate center of the wake is required. This value is input so that the curve fitting routine will have the data roughly centered, and so give a better fit with the polynomial. This value was usually obtained by eye from the graph of the wake survey data.

The actual data of wake velocity, transverse position, was split into two groups. These were the data points inside the visible wake region, and the free-stream flow outside the wake. Generally these were also obtained from the graph. Obviously, this is a point where different operators will make different choices as to the extent of the wake region. The program fits a separate polynomial to each of these data groups. The degree of the polynomial used is also left up to the operator, with an upper limit of a ninth order term. For the fairly smooth flows that can be assumed to exist outside the wake a low order polynomial is all that should be required. As the function for the drag is based on the difference
between these two polynomials, it is felt that the lower the order of the polynomial that can be used and still represent the flow the better. Higher order polynomials tend to introduce a number of "humps and hollows" which would probably not exist in a real flow. Once the polynomials are established, the value of the integrand in the drag function is calculated for each of the points in the wake. The drag function for a keel with span "b" is:

\[ D = \rho b \int_{-w}^{w} \left( U_a^2 - U_b^2 - U_s(U_a - U_b) \right) dA \]

\( U_a \) is the extrapolated free stream flow, \( U_b \) is the viscous flow, and \( U_s \) is the free stream flow at the edge of the wake region. A polynomial is fitted to this function and integrated between the limits of the wake region to calculate the drag. The program calculates the two-dimensional section drag coefficient based on the chord of the keel section. The value of the chord was a data point inside the program, as is the program's conversion from volts to cm/sec. As all of the keels tested had the same chord, and used the same optics and settings on the tracker this was a convenient method. The values are on lines twenty and twenty-one of the program.

The second variant of the program operated in exactly the same manner as the first, with the exception of the extent of the region of the wake polynomial. Here one polynomial is fitted to the free-stream points, and the other is fitted to all of the data. If a good fit can be obtained to the data by the polynomials then once outside the wake they should be substantially the same. Thus the end points chosen by the operator should make little difference to the integral, and so do not require the care in their choosing that the other variant should have.
I. (continued)

The difficulty encountered with this program was that if required more keypunching of
input data, or the development of a routine that could recognize a "wake". As
the function being integrated has comparatively very small values at the points
where the wake and the undisturbed flow intersect, it is felt that the operator
estimates involved in the first variation were adequate for the purposes of this
work. In view of the very small forces and low drag coefficients being measured,
small errors that might be induced by the operator are probably overshadowed by
other physical effects. These effects might be scale effects, tip effects,
imperfections on the optical surfaces, and calibration defects in the electronics.
The following is a table of the variation of the calculated drag coefficient as the
operator parameters were varied over a wide range. The table is based on the
test data of 11-13-77, Keel No. One, at two degrees angle of attack, the survey
being done eight centimeters above the tip of the model.

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<th>Degree of Free-Stream polynomial</th>
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<th>C_d</th>
<th>C_d (S)</th>
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</table>

U_{avg.} is in centimeters per second, and is the calculated velocity at
the edge of the wake based on the free-stream polynomial. This value was used
to determine the Reynolds Number. Thus, over a wide range of parameters the
drag coefficient is essentially constant at a value of 0.0071, and as most engineering
practice would use only two digits, this method should be adequate.
APPENDIX II

Effect of a body on wake velocity in an ideal fluid using a Rankine Ovoid to simulate the keel.

We are assuming the existence of an ideal two-dimensional fluid flow. The wake survey is done through a line some distance behind a body. Modeling the body, in this case a keel, as a Rankine Ovoid we will investigate the effect the body has on the Ovoid so that it has the same thickness as the keel models, and the same overall length, and lies on the "X" axis. As this is not nearly as streamlined a body as our keels it should exaggerate the difference in velocity in the wake.

We will consider a two-dimensional body of length 2L and of breadth 2B, with a source located at -A on the X axis, and a sink at +A on the X axis in a free stream flow of U. The formula for the velocity around the ovoid thus formed is:

\[
u = U + \frac{M(x+A)}{2\pi((x+A)^2+y^2)} - \frac{M(x-A)}{2\pi((x-A)^2+y^2)}
\]

At X=L, and Y=0.0 there should be a stagnation point and so at this point \( u \) would equal zero. Substituting these values and rearranging terms yields:

\[
\frac{U}{M} = \frac{1}{2\pi(L-A)} - \frac{1}{2\pi(L+A)}
\]

We know the flow inside the body must equal the strength of the source \( M \). This yields:

\[
\frac{M}{2} = \int_{0}^{b} U + \frac{M(x+A)}{2\pi((x+A)^2+y^2)} - \frac{M(x-A)}{2\pi((x-A)^2+y^2)} \quad dy
\]
Which after integrating and rearranging terms becomes:

\[
\frac{U}{M} = \frac{L}{2B} - \frac{L}{2\pi B} \tan^{-1} \frac{B}{A} + \frac{L}{2\pi B} \tan^{-1} \frac{B}{A} - \frac{U}{2M}
\]

Equating these two terms for \( \frac{U}{M} \), and substituting our values of \( L \) and \( B \) of 10.16 and 1.524 cm respectively we can solve numerically and obtain a value for \( \frac{U}{M} \) of 0.2953203.

For our test case of 100 RPM at 2 degrees angle of attack of 11/13/77, where \( U = 205.7 \text{ cm/sec.} \), \( M = 696.5319 \). As the keel is swept back at 40 degrees, and we are 8 cm above the tip the distance behind the keel is 6.7128 cm. Substituting these values into the formula for velocity \( u \), the difference in velocity across a typical half width of a wake of one cm is about 0.3 cm/sec. or less than two tenths of one percent of the flow speed. As this was for a "worst-case" body it was believed that at this distance behind the keel the pressure terms could be neglected.
APPENDIX III

Program Listing
C PROGRAM TO REDUCE THE LASER DOPPLER ANEMOMETER WAKE SURVEY TO A DRAG COEFFICIENT

C PROGRAM WRITTEN BY JOHN KNOBEL ROOM 5-330B COURSE 13

C

DIMENSION XW(40), VW(40), UW(40), CW(40)
DIMENSION XFS(20), VFS(20), UFS(20), CF5(20)
DIMENSION D(40), CD(10), DS(40), CDS(10)
INTEGER MO, DAY, YR, RPM, ALPHA, HGT

C

X IS THE TRANSVERSE DIMENSION IN CM
V IS THE ADJUSTED VOLTAGE READING
U IS THE VELOCITY
C IS THE COEFFICIENT OF THE POLYNOMIALS
IN ALL CASES THE SUFFIX 'W' REFERS TO WAKE REGION
AND 'FS' REFERS TO THE FREE STREAM

NC IS THE NUMBER OF COEFFICIENTS IN THE POLYNOMIAL
CU IS THE VELOCITY CALCULATED FROM THE POLYNOMIAL
VT0C IS THE VELTTS TO CM/SEC CONVERSION
VT0C=406.7
CHORD=20.32

C

333 IS THE RESTART FCNT FOR ADDITIONAL DATA
333 CONTINUE

C SET ALL ARRAYS TO INITIAL VALUE ZERO
CALL ERASE(XW,20, VW,20, UW,20, CW,20)
CALL ERASE(XFS,20, VFS,20, UFS,20, CF5,10, CD,10)

C

DATA INPUT SECTION
C SET UP AN ID SYSTEM FOR DATA
C FIRST 3I2 FCPR MONTH DAY YEAR, THEN 2X THEN13 FOR RPM 2X
C THEN 12 FOR ANGLE OF ATTACK AND 2X AND 12 FCPR HT ABOVE TIP
READ(5,310) MO, DAY, YR, RPM, ALPHA, HGT
310 FORMAT(3I2,2X,13,2X,I2,2X,I2)
C
C     READ(5,103) CL
103 FORMAT(F12.6)
C     CL IS THE APPROXIMATE CENTER OF THE WAKE
C     IT IS INPUT IN AN ATTEMPT TO GET A BETTER CURVE FIT 01/25/78
C
C     DATA FOR THE WAKE AND FREE STREAM IS INPUT SEPARATELY
C     THE WAKE VALUES ARE ALWAYS READ FIRST
C     VALUES OF XW MUST BE ENTERED SEQUENTIALLY
C
101 FORMAT(I2,2X,I2)
C
C     DO 10 I=1,NW
C
10     READ(5,102) XW(I),VW(I)
C
C     XW(I)=XW(I)-CL
C
C     VW(I)=VW(I)*VTCC
C
10     CONTINUE
C
C     READ(5,101) NFS,NCFS
DC 11 I=1,NFS
C
101     READ(5,102) XFS(I),VFS(I)
C
C     XFS(I)=XFS(I)-CL
C
C     VFS(I)=VFS(I)*VTOS
C
11     CONTINUE
102 FORMAT(2F12.6)
C
C     ECHO OF INPUT DATA
C
WRITE(6,208) MO,DAY,VR,RPM,ALPHA,HGT
208 FORMAT(2X,'DATE AND RUN ',6I6)
WRITE(6,200)
200 FORMAT(10X,'THIS IS THE LDA WAKE SURVEY DATA REDUCTION')
WRITE(6,313) NW,NCW,NFS,NCFS
313 FORMAT(2X,'NWF,NCW= ',2I4,' NFS,NCFS= ',2I4/) 
WRITE(6,201)
201 FORMAT(10X,'XFS',7X,'VFS',7X,'UFS')
DO 41 I=1,NFS
WRITE(6,202) XFS(I),VFS(I),UFS(I)
202 FORMAT(3F12.6)
41 CONTINUE
WRITE(6,203)
203 FORMAT(10X,'XW',7X,'VW',7X,'UW')
DO 42 I=1,NW
WRITE(6,202) XW(I),VW(I),UW(I)
42 CONTINUE
WRITE(6,207) CL
207 FORMAT('XW=XDATA-CL, CL= ',F12.6//)
C
C FIT A POLYNOMIAL THRU THE WAKE AND FREE STREAM REGIONS
C A SEPARATE POLYNOMIAL PCF EACH
C
CALL LSFIT(NFS,NCFS,XFS,UFS,CFS)
C
CALL LSFIT(NW,NCW,XW,UW,CW)
C
CALCULATE THE US PCF USE IN THE MOMENTUM TRANSFER
AVGFS1=CFS(1)
AVGFS2=CFS(1)
C AVERAGE FREE STREAM VELOCITY = AVGFS
DC 40 I=2,NCFS
C
12=I-1
AVGFS1=CFS(I) = (XW(I)**12)+AVGFS1
AVGFS2 = CPS(1)*(XW(NW)**2)*AVGFS2
C
40 CONTINUE
AVGFS = (AVGFS1 + AVGFS2)/2.0
C
C CALCULATE, AT EACH WAKE POINT, THE VELOCITY PREDICTED BY THE FREE STREAM CURVE FIT
C
WRITE (6,210)
210 FORMAT (5X,'AT XW, THESE ARE THE VALUES OF CUW,CUPS')
C
DC 20 I=1,NW
C
CUFS=CPS(1)
CUW=CW(1)
C
DC 21 K=2,NCFS
C
K2=K-1
CUFS=CPS(K)*(XW(I)**K2)*CUFS
C
21 CONTINUE
C
CALCULATE WAKE VELOCITY FROM THE POLYNOMIAL
C
DC 22 K=2,NCW
K2=K-1
CUW=CW(K)*(XW(I)**K2)*CUW
C
22 CONTINUE
C
WRITE (6,211) XW(I),CUW,CUPS
211 FORMAT (4X,F12.6,4X,F12.6,4X,F12.6)
C
D(I) = (CUFS*(CUFS-AVGFS)) - (CUW*(CUW-AVGFS))
DS(I) = CUW * (AVGFS - CUW)

C 20 CONTINUE
C
WRITE(6,212)
212 FORMAT(/)
C
D(I) IS NOW THE DATA SET FOR THE CURVE OF X VERSUS U (UFS - U)
C JAN 22 DRAG TERM IS D1**2 - U2**2 - US(U1 - U2)
C WE CAN INTEGRATE THIS TO GET THE DRAG
C
CALL LSFLT(NW,NCW,XW,D,C)
C
THE POLYNOMIAL IS INTEGRATED TO GET THE DRAG
C THE WAKE END POINTS ARE THE LIMITS FOR THE INTEGRAL
C DRAG COEFFICIENT = DC
DC=0.0
DC1=0.0
DC2=0.0
C
DO 30 I=1,NCW
C
DC1=CD(I) * ((XW(I)**I)/I) + DC1
DC2=CD(I) * ((XW(N)**I)/I) + DC2
C
30 CONTINUE
C
DC=2.0 * (DC2-DC1) / (AVGFS*AVGFS*CHCRD)
C
C CALCULATION OF SIMPLIFIED DRAG COEFFICIENT
C
CALL LSFLT(NW,NCW,XW,D,C)
DSC=0.0
DSC1=0.0
DSC2=0.0
DO 32 I=1,NCW
C DSC1=CDS(I)*((XW(1)**I)/I)+DSC1
DSC2=CDS(I)*((XW(NW)**I)/I)+DSC2
C 32 CONTINUE
C DSC=2.3*(DSC1-DSC2)/(AVGFS*AVGFS*CHORD)
C
C OUTPUT SECTION
C WRITE(6,209) AVGFS
209 FORMAT(5X,'AVGFS AT WAKE BCUNDARY=',F12.6/)
C WRITE(6,204)
204 FORMAT(5X,'COEFFICIENTS OF FS, WAKE')
DO 43 I=1,NCFS
WRITE(6,205) CFS(I)
43 CONTINUE
DO 44 I=1,NCW
WRITE(6,205) CW(I)
44 CONTINUE
205 FORMAT(5X,E12.5)
WRITE(6,206) EC,ESC
206 FORMAT(5X,'DRAG CCEF =',F12.6,' SIMPLIFIED EC =',F12.6)
WRITE(6,312)
312 FORMAT(1H1)
C PESTART SECTION
READ(5,300) INDEX
300 FORMAT(12)
IF (INDEX.EQ. 1.0) GO TO 333
END
APPENDIX IV

EQUIPMENT LIST

1. "Laser Doppler Anemometer Signal Processor", (Tracker), Thermo-Systems Inc. Model 1090


3. Laser, Helium-Neon, Spectrophysics Model 124A


5. "Photo-multiplier", (Photo-detector), Thermo-Systems Inc. Model 962, Optics 310 mm focal length.


8. Oscilloscope, Tektronix, Model 561B


10. Voltage-to-Frequency Converter, Dymec Model, 2210