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# Dissipation of an Axially Symmetric Turbulent Wake in the Very Far Field

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ABSTRACT

A wake visualization technique has been used to observe the turbulent wake at distances of $10^6$ diameters behind an axially symmetric streamlined body traveling submerged in water. It has been found that a transition occurs in the rate of wake growth between $10^4$ and $10^5$ diameters which is attributed to a "reverse transition" from turbulent to laminar flow.

The wake visualization technique involves dropping a dye-coated body down a taut vertical guide wire into a large water-filled tank. Measurement of the wake growth and dissipation is made from a time series of photographs.

The bodies tested were 6 x 1 prolate spheroids of two sizes. Body density was varied to change velocities.

INTRODUCTION

A moderate amount of experimental work has been done in the laboratory in the study of the aerodynamic and hydrodynamic characteristics of axisymmetric wakes. Wind tunnels have been used for studies of wake behind flat disks and rectangular plates by Cooper and Lutzky,[1] Carmody,[2] and Hwang and Baldwin,[3] and for studies of wake behind a streamlined body by Chevray.[4] Water-tunnel work with axisymmetric wakes has been done by Gibson, et al.[5] Observation of wake in wind and water tunnels is limited to a distance behind the model of about $10^3$ diameters because of the physical size of the test facilities. This distance can be increased by going to a range facility in which the model is propelled past the observation station(s). In this case, the wake can be observed from a fixed position as it grows older, until it becomes too weak to observe, or until it is influenced by range hardware. Herrmann, et al.,[6] used a ballistics range to observe wake behaind a hypervelocity sphere out to 5 x $10^4$ diameters.

The test technique described here is a type of range technique which allows observation of wake in water to about $10^6$ diameters behind a body. Basically, the technique is to drop a model into a large water tank and observe the wake from a fixed submerged position. With a body and tank of realistic dimensions, the wake at the observation position is unaffected by the water surface, the tank walls, or the downstream stopping of the body for a very great time, so that the distance behind the body at which wake can be measured is dependent only on the sensitivity of the observation equipment.* Tests can thus be made with this technique in a reasonable size facility at distances behind a body which would require a wind tunnel or water tunnel of prohibitive size. Laser anemometer and flow visualization methods are adaptable to this test technique. Unfortunately, hot-film anemometer methods are not well adapted to the test technique because the relative turbulence intensity is of the order of 100 percent and the fluid velocities are soon down to the level of the anemometer-induced convection currents. In this work only flow visualization was used.

EXPERIMENTAL

A. Apparatus and Procedures

The model shape used for these tests was a 6 x 1 prolate spheroid, the same shape used by Chevray.[4] Three models were tested, the physical characteristics of which are given in Table 1.

* See discussion under THEORETICAL CONSIDERATIONS

Table 1

Prolate Spheroid Models Used

| Model No. | Length Inches | Diameter Inches | Material | Weight Pounds |
|---|---|---|---|---|
| 1 | 3 | 0.5 | Tungsten Alloy | 0.237 |
| 2 | 6 | 1 | Aluminum | 0.324 |
| 3 | 6 | 1 | Brass | 0.941 |

The metals were picked for their densities, which determined their relative velocities. Each model had a .037-inch diameter hole the length of its major axis which allowed it to slide down a .034-inch diameter taut guide wire which provided model stability. This stabilizing technique was used because the model weight required to achieve the desired velocities made sufficient model weighting to produce stability impossible. The guide wire has some effect on the experiment, but it was felt that this is insignificant because of the very low relative velocity between the wake and the guide wire--it should be noted that this relative velocity is not $U_\infty - U_1$ as is the case with a sting in a wind or water tunnel, but is the much smaller velocity defect $U_1$.

Figure 1 shows the experimental setup made in the Naval Ordnance Laboratory's Hydroballistics Tank. This tank is 35 feet wide by 100 feet long and can be filled to a depth of 65 feet. A model, coated with dye, was positioned on the release mechanism and then dropped into the water. The air-drop height was chosen so that the model entered the water at its terminal velocity in water.

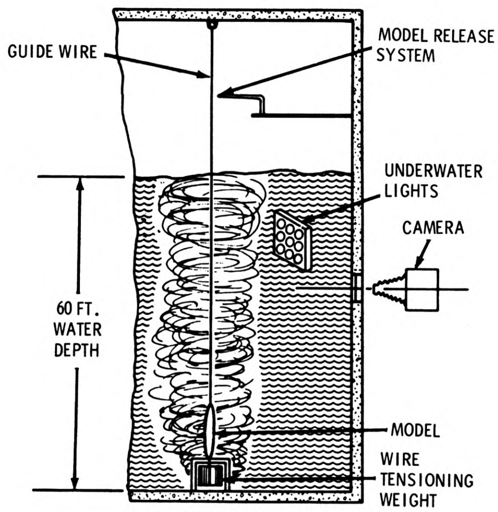


Figure 1 - Experimental Setup

Two cameras were used to record each test. The first camera was a 16 mm, 75-frame-per-second camera which was run only for a few seconds to determine model velocity. The wake was photographed by a second 35 mm camera capable of taking a single frame whenever triggered by an electrical pulse. This camera and high-intensity underwater lights were connected to an electrical sequencer set to periodically turn the light on and trigger the camera. The lights were kept on for only one second so as not to generate unwanted convection currents. About 20 pictures were taken of each wake in this manner over a 30- to 45-minute period. The time increment between pictures was increased logarithmically from 0.1 second to 15 minutes. Color film was used in the camera. It was much superior to black-and-white because the dye color could be seen long after its density could no longer be detected on black-and-white film. The dye used on the model was croceine scarlet, a product of Eastman Kodak Company, manufactured for retouching photographic negatives.

## THEORETICAL CONSIDERATIONS

It was previously stated that the finite size of the test facility does not influence the test results. A fuller discussion of that follows. We shall take the specific example of the tests described here, and first calculate model and wake velocities and wake dimensions.

The drag of a body is a function of its shape and the Reynolds number:

$$C_{DS} = C_R + C_F \qquad (1)$$

where $C_{DS}$ = total drag coefficient based on surface area, $C_R$ = residual (pressure) drag coefficient, and $C_F$ = friction drag coefficient ( a function of Reynolds number). From Reference 7, the 6 x 1 prolate spheroid shape is seen to closely approximate Models 4156 and 4163, Series 58, with

$$C_R = 0.20 \times 10.^{-3}$$

Also from Reference 7, the Schonherr equation gives $C_F$ as:

$$\frac{0.242}{\sqrt{C_F}} = \log_{10} (R \times C_F) \qquad (2)$$

where R is the Reynolds number based on length:

$$R = \frac{V_t L}{\nu} \qquad (3)$$

$V_t$ is the terminal velocity, L the body length, and $\nu$ the kinematic viscosity. The terminal velocity of the model is found from:

$$W - B = 1/2\, \rho V_t^2\, C_{DS} S \qquad (4)$$

where W = model weight, B = bouyancy, $\rho$ = fluid density, and S = surface area. Solving Equations 1 through 4 simultaneously produces the values for $C_{DS}$, $V_t$, and R given in Table 2 for the test models. $C_D$ is the drag coefficient based on cross-sectional area.

Table 2

Calculated Values for Terminal Velocities

| Model No. | $C_{DS}$ | $C_D$ | $V_t$ fps | R |
|---|---|---|---|---|
| 1 | .00452 | .086 | 44 | $1.11 \times 10^6$ |
| 2 | .00455 | .087 | 21 | $1.07 \times 10^6$ |
| 3 | .00398 | .076 | 45 | $2.27 \times 10^6$ |

Chang and Oh[8] have derived relationships for axially symmetric turbulent wake velocities and diameters. These relationships are:

$$\frac{U_1}{U_\infty} = [(105)^{\frac{1}{3}}/54]\, \beta^{\frac{-4}{3}} (x^2/C_D d^2)^{\frac{-1}{3}} [1 - (y/b)^{\frac{3}{2}}]^2 \qquad (5)$$

$$\frac{b}{d} = [(105)^{\frac{1}{3}}/2]\, \beta^{\frac{2}{3}} (C_D \frac{x}{d})^{\frac{1}{3}} \qquad (6)$$

Figure 2 defines the nomenclature in the equations except for the previously defined drag coefficient, $C_D$, and the constant, $\beta = \frac{\ell}{b}$, where $\ell$ is Prandtl's mixing length. These equations are in agreement with the generally accepted decay relationships for circular wakes, i.e., $U_1$ and b are proportional to $x^{-\frac{2}{3}}$ and $x^{\frac{1}{3}}$, respectively. Since $\beta$ is a constant for a given shape, it may be calculated from the data of Reference 4 with either Eq. 5 or 6 above, which gives $\beta = 0.11$.

The tank facility is very large relative to the model. Therefore, it is assumed that the acoustic disturbances resulting from the motion of the model,

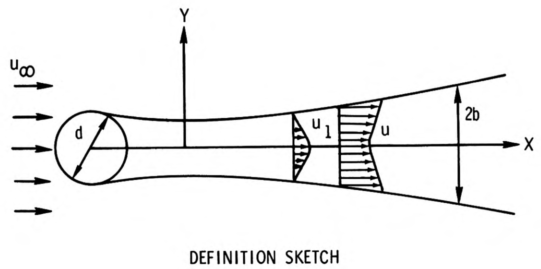


Figure 2 - Definition Sketch

which reflect from the tank and water surfaces, are too weak to affect the test results. (Use of models of different sizes serves to check this assumption.)

We are now ready to estimate the available test time before the finite size of the test facility influences the wake. The times of interest are the time for the wake at the air-water surface to reach the observation area, the time for the wake water at the bottom of the tank to make its presence felt at the observation area, and the time for the wake to reach the tank walls.

To determine these times, a computer program was written. In this program, Eq. 5 is integrated to give the distance water travels from the surface toward the wake observation area as a function of model distance and time, and Eq. 6 is used for calculation of wake diameter. Results for Model No.3 are given in Table 3, where $x_1$ is the distance water has traveled downward from the surface and $R_t$ is the Reynolds number based on $U_1$ and wake diameter. Since

Table 3

Model Travel vs Calculated Disturbed Distance

| Model Travel x/d or inches | Time min. | $U_1$ fps | $x_1$ feet | Wake Dia. $\frac{2b}{d}$ or inches | $R_t$ |
|---|---|---|---|---|---|
| $10^3$ | .0324 | .316 | 1.47 | 4.59 | 12,100 |
| $10^4$ | .324 | .0681 | 3.49 | 9.88 | 5,610 |
| $10^5$ | 3.24 | .0147 | 7.85 | 21.29 | 2,610 |
| $10^6$ | 32.4 | .00316 | 17.25 | 45.88 | 1,210 |

$U_1 \approx U'$,[1] this may be considered a turbulence Reynolds number. The data $x_1$ in the table are interpreted to indicate that wake from this model may be observed at distances up to $10^6$ diameters behind the body if the observation area is 17.25 feet or farther from both the water surface and tank bottom. About 18 inches should be added to the distance above the observation area as this is the experimentally observed distance required for water-entry cavity effects to disappear. Thus, the tank water depth of 60 feet gives an undisturbed observation length of about 20 feet or 5 wake diameters. The wake diameter of about 4 feet is much less than the tank width of 35 feet. From this reasoning, it is felt that the test tank size is sufficient for these experimental tests.

## RESULTS AND DISCUSSION

Figures 3, 4, and 5 are plots of the experimental data from Models 1, 2 and 3, respectively, in which wake diameter is plotted as a function of model distance traveled. The model velocities noted on these figures are lower than the calculated values shown in Table 2, which is attributed to friction on the guide wire. This effect does not, however, enter into any calculations of wake properties as long as the model velocity is constant, which was experimentally determined to be the case.

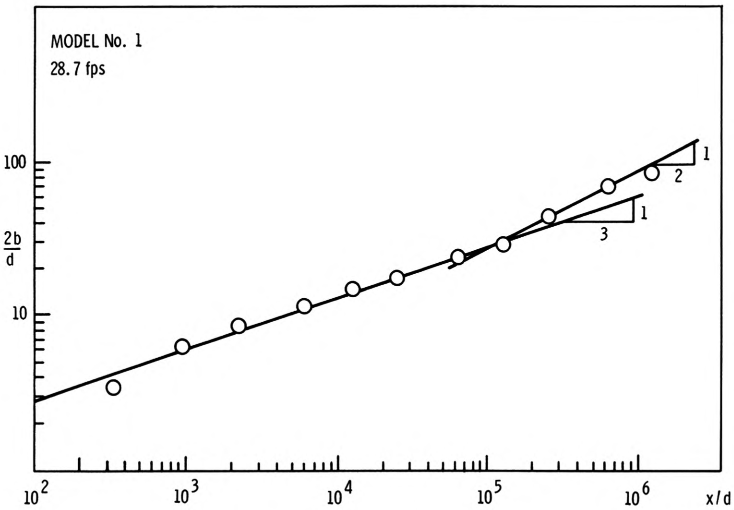


Figure 3 - Wake Diameter vs Distance

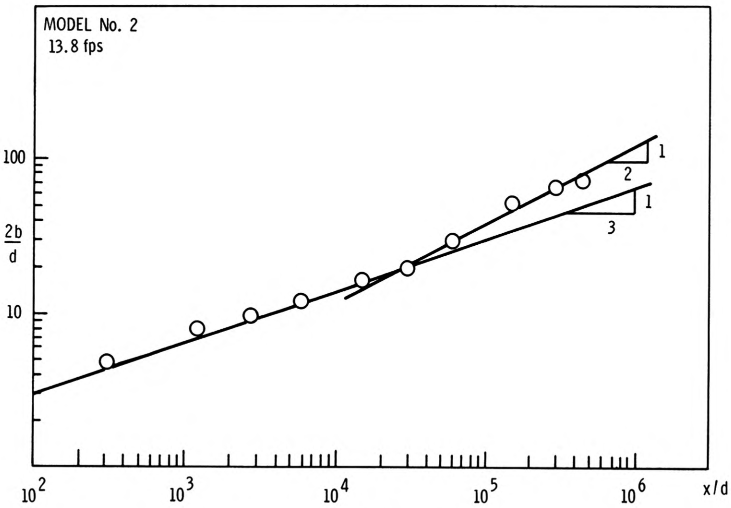


Figure 4 - Wake Diameter vs Distance

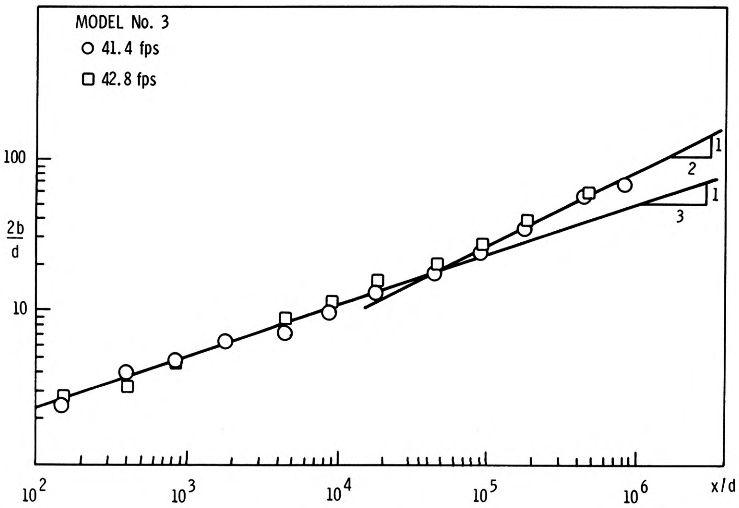


Figure 5 - Wake Diameter vs Distance

The most significant thing to be noted from the data plots is that there is a transition in the rate of wake growth at a distance behind the body of between about $10^4$ and $10^5$ diameters. The $b \sim x^{1/3}$ relationship changes to what appears to be an $x^{1/2}$ relationship. This can be explained by the phenomenon of "reverse transition" from turbulent to laminar wake. For laminar wake, Schlichting[9] indicates an $x^{1/2}$ wake growth relationship. Reverse transition has been observed in wind tunnels,[10, 11] resulting from accelerated flow or favorable pressure gradients. In this case, the reverse transition is simply the result of the decrease in Reynolds number, which is characteristic of decaying axisymmetric wake. It might be noted that the last data point in all three figures plotted is below the $x^{1/2}$ line. This is no doubt something of a coincidence, but, nevertheless, suggests that the wake may change back and forth between turbulent and laminar in the transition region.

Unfortunately, the experimental technique does not allow calculation of a true turbulence Reynolds number since fluid velocities cannot be measured, so a Reynolds number transition region cannot be defined unless it is based on calculated fluid velocity and wake diameter. On this basis, transition for Models 1, 2 and 3 occurred at Reynolds numbers of $R_t$ = 690, 1025, and 2720, respectively.

The constant, $\beta$, was calculated from the experimental data. Values of .151, .167, and .127, were obtained for Models 1, 2, and 3, respectively. Vibration of the guide wire or model surface roughness due to the dye coating might be responsible for the somewhat inconsistent values, all of which are higher than the value, $\beta$ = .11, calculated from Reference 4.

## SUMMARY

A flow visualization technique has been described which makes possible observation of wake at distances of the order of $10^6$ diameters behind a body. It has been shown that the wake diameter grows as $x^{1/3}$ to a distance of about $10^4$ to $10^5$ diameters behind the body, at which time the decreasing Reynolds number apparently causes a "reverse transition" from turbulent to laminar wake and the diameter grows as $x^{1/2}$.

## SYMBOLS

| | |
|---|---|
| $b$ | wake radius |
| $B$ | bouyancy |
| $C_D$ | drag coefficient based on cross-sectional area |
| $C_{DS}$ | drag coefficient based on surface area |
| $C_F$ | friction component of drag coefficient |
| $C_R$ | residual (pressure) component of drag coefficient |
| $d$ | body diameter |
| $\ell$ | Prandtl's mixing length |
| $L$ | body length |
| $R$ | Reynolds number = $\frac{V_t L}{\nu}$ |
| $R_t$ | Reynolds number = $\frac{2U_1 b}{\nu}$ |
| $S$ | body surface area |
| $U_1$ | velocity defect |
| $U_\infty$ | relative velocity between fluid ahead of body and body = $V_t$ |
| $U'$ | turbulence intensity |
| $V_t$ | body terminal velocity |
| $W$ | body weight |
| $x$ | distance traveled by body |
| $x_1$ | distance traveled by fluid |
| $y$ | wake radial coordinate |
| $\beta$ | constant = $\ell/b$ |
| $\nu$ | kinematic viscosity |
| $\rho$ | density of water |

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## DISCUSSION

J. HANSEN (Naval Research Laboratory): Does the presence of this stationary guide wire, even though it is very small in diameter, have some effect on the wake structure; or is there a way to convince oneself that the effect is negligible?

WASER: Well, the model would be unstable, I think for this shape. But we didn't try it without the wire.