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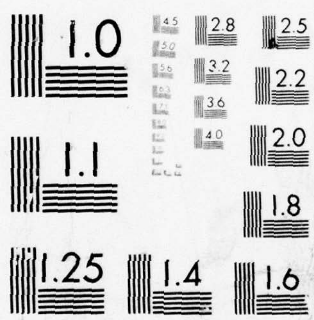

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Bethesda, Md. 20084

A NOTE ON BLOCKAGE CORRECTION

by

Kwang June Bai

SHIP PERFORMANCE DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

November 1978 DTNSRDC-78/081

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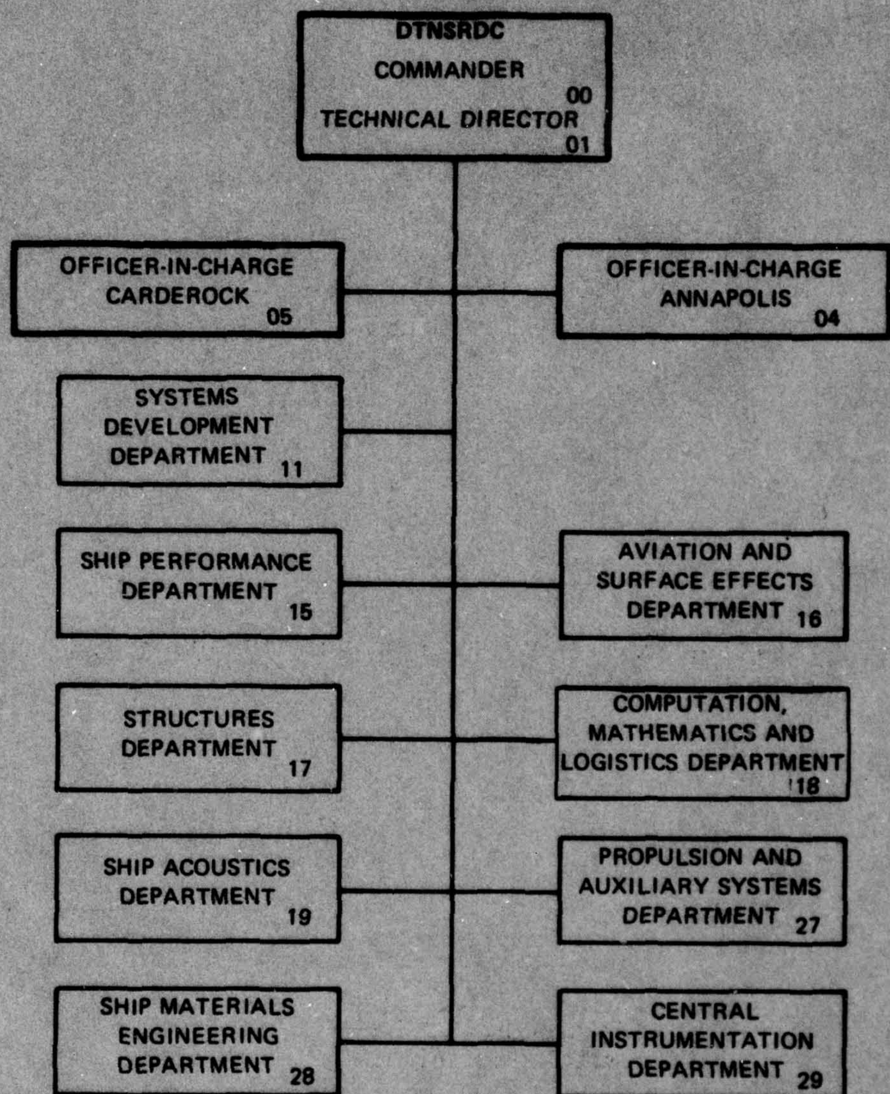

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) DTNSRDC-78/081	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) A NOTE ON BLOCKAGE CORRECTION,		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Kwang June/Bai		8. CONTRACT OR GRANT NUMBER(s) (16) ZR01102
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship Research and Development Center Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (17) ~~Task Area~~ ZR 011 0201 Element 61152N
11. CONTROLLING OFFICE NAME AND ADDRESS David W. Taylor Naval Ship Research and Development Center Bethesda, Maryland 20084		12. REPORT DATE (11) November 1978
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (9) Research and development rept.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

(12) 35p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Blockage correction, Mean speed correction formula, Towing tank experiment, Wind tunnel experiment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

It has recently been shown that a jump in velocity potential exists between infinite upstream and downstream directions when a body translates uniformly along a channel of finite cross section such as a towing tank or wind tunnel. In this report a new blockage correction formula for body speed is proposed. The speed correction formula due to blockage is → next page

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obtained by dividing computed potential jump by body length, assuming that the body is slender or flat in the direction of motion. The potential jump is expressed explicitly in terms of the effective volume, i.e., the sum of the displaced volume and added mass/density of the submerged body, and the depth Froude number, if a free surface is present. As a test of the present speed correction formula, two cases are considered: (1) the Wigley parabolic ship model, tested in both a small and a large towing tank, (2) a body of revolution (prolate spheroid) tested in a circular wind tunnel. In each case the mean-speed increment averaged over the entire body surface is computed by a three-dimensional, finite-element method applicable to free-surface flow problems. These are shown to be in good agreement with those obtained by the approximate speed correction formula. At high values of Froude numbers, the main difference in the total resistance coefficients measured in the two towing tanks by Tamura is due primarily to difference in model wave resistance computed for the two tanks by a full-fledged, three-dimensional, finite-element method. Results are also compared to those obtained by using the speed correction formula of Lock and Johansen. The present formula renders a better approximation than that of Lock and Johansen when the cross sectional area of a flow tunnel is not much larger than the maximum cross section area of the body.

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NOTATION

A	Cross sectional area of towing tank
a	One-half of length of prolate spheroid
B	Beam of ship
b	Radius of maximum cross section of spheroid
C_B	Block coefficient
C_F	Frictional resistance coefficient
$\hat{C}_F$	Frictional Resistance Coefficient
C_T	Total resistance coefficient
C_W	Wave resistance coefficient
C_p	Prismatic coefficient
F	Hull fineness parameter
F_H	Water depth Froude number
F_L	Ship length Froude number
g	Acceleration of gravity
H	Water depth
K	Potential jump due to blockage
k_L	Partial form factor
L	Body length; length between perpendiculars
L_w	Length of waterline
m'	Added mass of submerged body
$\bar{m}$	Added mass coefficient

R	Radius in cylindrical coordinates
R_F	Frictional resistance
R_T	Total resistance
R_W	Wave resistance
R_n	Reynolds number
R_o	Radius of tunnel wall
S_o	Wetted surface
T	Draft of ship
U	Uniform incoming stream velocity at upstream infinity
$\bar{u}$	Mean speed due to blockage
$\bar{u}_o$	Mean speed on the body in unbounded water
W	Width of towing tank
x,y,z	Right-handed rectangular coordinates
Δu	Speed increment
$\Delta\bar{u}$	Mean-speed increment averaged over body
ν	Kinematic viscosity of water
ρ	Density of water
$\vec{\tau} = (\tau_1,\tau_2,\tau_3)$	Tangential unit vector
Φ	Total velocity potential
Φ_o	Total velocity potential in absence of tank (or tunnel) walls
ϕ	Perturbation velocity potential
ϕ_o	Perturbation velocity potential in absence of tank (or tunnel) wall

$\forall$ Displaced volume; volume

∇ Gradient operator

ABSTRACT

It has recently been shown that a jump in velocity potential exists between infinite upstream and downstream directions when a body translates unformly along a channel of finite cross section such as a towing tank or wind tunnel. In this report a new blockage correction formula for body speed is proposed. The speed correction formula due to blockage is obtained by dividing computed potential jump by body length, assuming that the body is slender or flat in the direction of motion. The potential jump is expressed explicitly in terms of the effective volume, i.e., the sum of the displaced volume and added mass/density of the submerged body, and the depth Froude number, if a free surface is present. As a test of the present speed correction formula, two cases are considered: (1) the Wigley parabolic ship model, tested in both a small and a large towing tank, (2) a body of revolution (prolate spheroid) tested in a circular wind tunnel. In each case the mean-speed increment averaged over the entire body surface is computed by a three-dimensional, finite-element method applicable to free-surface flow problems. These are shown to be in good agreement with those obtained by the approximate speed correction formula. At high values of Froude numbers, the main difference in the total resistance coefficients measured in the two towing tanks by Tamura is due primarily to difference in model wave resistance computed for the two tanks by a full-fledged, three-dimensional, finite-element method. Results are also compared to those obtained by using the speed correction formula of Lock and Johansen. The present formula renders a better approximation than that of Lock and Johansen when the cross sectional area of a flow tunnel is not much larger than the maximum cross section area of the body.

ADMINISTRATIVE INFORMATION

This work was authorized and funded by the Independent Research Program at the David W. Taylor Naval Ship Research and Development Center, Task Area ZR 011 0201, Element 61152N.

INTRODUCTION

Many authors have investigated blockage effect and proposed approximate blockage formulas to account for towing tank or wind tunnel boundaries.[1-9*] The first approximation concerning towing tank blockage effects date back more than four decades. Owing to the difficulty encountered in computing flow separation, wake flow, free-surface effects, etc., the exact

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*A complete listing of references is given on page 21.

magnitude of the blockage effect on fluid force acting on a body is too complicated to analyze by purely theoretical means. However, these difficulties did not stop engineers from attempting to make simple engineering approximations of the blockage problem. For engineering purposes, computation of a mean-speed increment on a body due to blockage effects has been the main focus of interest in order to make a blockage correction to frictional drag. In the computation, the incremented change in frictional drag due to blockage is determined directly from the computed incremental increase of mean speed over the body surface caused by flow blockage.

Two basic inviscid flow-theory approaches have been previously employed. The first approach is based on the so-called one-dimensional, mean-flow theory, using the Kreitner equation, which was first obtained by Kreitner[3] from the Bernoulli and the mass continuity equations under the assumption that velocity is uniform in each cross sectional plane. To name a few, Hughes[4] and Kim[5] used this approach. The second approach is based on successive reflection of images in the walls of a rectangular tank or simpler axisymmetric singularities in case of axisymmetric flows. In this approach, the velocity potential of the flow inside a specified tank boundary can be computed exactly in principle; usually, the potential is represented by a series expansion, and only the first few terms are computed. Ogiwara,[6] Tamura,[1,2] and Landweber and Nakayama[7] have used the latter approach.

In all, there exist about a dozen formulas proposed for blockage corrections, and each is somewhat different from the other. Some formulas introduce empirical correction factors,[5] whereas others claim to be based on analytical derivations. Some formulas are proposed to be used only for frictional resistance corrections, whereas other formulas are used for total resistance corrections. An extensive review of the subject has been made by Gross and Watanabe.[9]

In the present preliminary study, skepticism is exercised about proposals in speed correction formulas that can be used to correct the total resistance which include the wave resistance in water of finite depth with sidewalls. Herein is proposed a new speed correction formula to be used only for frictional resistance. The wave resistance which has been computed for any towing tank and/or model conditions by using the localized finite-element method previously developed by the author.[10-12] It seems to be impossible to make blockage corrections to total resistance by using only a single-speed correction formula, even though such formulas have been proposed in the past.

The approach used to derive a blockage correction formula herein is different from the two inviscid flow-theory approaches described previously. Derivation of a mean-speed correction formula in this report is based on the potential jump occurring in the three-dimensional flow in a towing tank or wind tunnel. To test the new speed correction formula, numerical computations for a full-fledged, three-dimensional wave resistance problem were made. The numerical mean-speed increment on a spheroid was computed exactly for a circular wind tunnel and compared with the results obtained by the new formula; results obtained agree reasonably well with exact numerical results.

BLOCKAGE CORRECTION

EXACT MEAN-SPEED INCREMENT

Steady uniform flow past a ship fixed in a channel has been considered; see Bai.[12] The coordinate system is right handed and rectangular. Under the usual assumptions, steady uniform flow may be described by a total velocity potential Φ defined by

$$\Phi\ (x,y,z) = Ux + \phi\ (x,y,z) \tag{1}$$

where ϕ is the perturbation-velocity potential in a channel of finite cross section. Similarly the total velocity potential

$$\Phi_o\ (x,y,z) = Ux + \phi_o\ (x,y,z) \tag{2}$$

is defined to describe the flow about the same body in an unbounded fluid, i.e., in the absence of channel boundaries. The fluid speed on a body surface in general increases due to the blockage effect when compared with that of unbounded fluid. However, the speed increment on the body surface is not uniform over the entire surface. For example, the forward stagnation point of an axisymmetric body remains the same whether in an unbounded fluid or in a wind tunnel of circular cross section. Nevertheless, a mean speed correction has been traditionally employed for the blockage correction mainly due to its simplicity. To describe a mean-speed increment, speed increment due to blockage locally on the body surface is defined as

$$\Delta u = \nabla (\Phi - \Phi_o) \cdot \vec{\tau}$$

$$= \nabla (\phi - \phi_o) \cdot \vec{\tau} \qquad (3)$$

where $\vec{\tau} = (\tau_1, \tau_2, \tau_3)$ is a unit tangential vector on the body surface; τ_1 is the component along the x-axis, i.e., the longitudinal direction, and τ_2 and τ_3 are, respectively, the normal and tangential components in the cross sectional plane of the body. Then the "exact" mean speed increment averaged over the entire submerged body surface is given by

$$\Delta\bar{u} = \frac{1}{S_o} \iint_{S_o} \nabla (\phi - \phi_o) \cdot \vec{\tau} \, ds \qquad (4)$$

where S_o is the wetted surface area, and $\vec{\tau}$ is specified. One natural way of specifying $\vec{\tau}$ would be as the unit potential flow streamline vector on the body. However, streamlines on a body in bounded and unbounded flows, described by Φ and Φ_o, respectively, do not coincide in general, except in the special case of an axisymmetric body in a flow facility of circular cross section. In the case of a ship hull, if $\vec{\tau} = (1,0,0)$, and $S_o = 2 \cdot L \cdot T$ under the assumption that the ship is thin, Equation (4) can be reduced to

$$\Delta\bar{u} = \bar{u} - \bar{u}_o \qquad (5)$$

where

$$\bar{u} = \frac{1}{L \cdot T} \int_{-T}^{0} \left[\phi\left(\frac{L}{2}, y, o\right) - \phi\left(-\frac{L}{2}, y, o\right) \right] dy$$

$$\bar{u}_o = \frac{1}{L \cdot T} \int_{-T}^{0} \left[\phi_o\left(\frac{L}{2}, y, o\right) - \phi_o\left(-\frac{L}{2}, y, o\right) \right] dy$$

where L and T are the ship length and draft, respectively. In Equation (5), the draft T is assumed to be uniform from the bow at $x = -L/2$ to the stern at $x = L/2$; the centerplane of the ship is on $z = 0$.

Similarly, for a slender axisymmetric body of revolution in a wind tunnel of circular cross section, the mean-speed increment averaged over the body surface is given by

$$\Delta\bar{u} = \bar{u} - \bar{u}_o$$

where

$$\bar{u} = \frac{1}{L} \left[\phi\right]_{x=-\frac{L}{2},\ R=0}^{x=\frac{L}{2},\ R=0}$$

$$\bar{u}_o = \frac{1}{L} \left[\phi_o\right]_{x=-\frac{L}{2},\ R=0}^{x=\frac{L}{2},\ R=0} \qquad (6)$$

where

$$R = \sqrt{y^2 + z^2}$$

and the peripheral length along a body meridian is approximated by the body length, assuming that the body is slender.

APPROXIMATE MEAN-SPEED INCREMENT

In this subsection, the method of obtaining an approximate speed correction formula is given, based on the potential jump discussed earlier by Bai.[12] Define K as a jump in the velocity potential ϕ given in Equation (1) between the infinite upstream and downstream directions. The potential jump K is given by integrating the speed increment along a line in the fluid from a point infinitely far upstream to a point infinitely far downstream. Numerical solutions for practical ship forms at subcritical speeds in towing tanks and for slender bodies of revolution in wind tunnels indicate that most of the potential jump occurs along the body length. This finding, observed in numerical solutions, will be used as the basis for obtaining the present approximate formula for the speed correction. It is possible to prove this empirical finding by showing that the values of the potential at the upstream and downstream stagnation points are approximately equal to the corresponding asymptotic values of the potential in the simple case of axisymmetric flow. However, the proof will not be discussed here. Thus, the mean speed increment $\bar{u}$ due to blockage is approximated by

$$\Delta\bar{u} = \frac{K}{L} \tag{7}$$

In a recent simple analysis,* the expressions for the potential jump K in terms of the effective volume and the depth Froude number F_H in three dimensions with a free surface were

$$K = \frac{(\forall + m'/\rho)\ U}{WH\ (1-F_H^2)} \tag{8}$$

*A more detailed analysis in general cases has been submitted in a paper to the Journal of Fluid Mechanics (1978).

where $\forall$ = displaced volume

ρ = density of water

U = towing speed

W = tank depth

H = water depth

$m' = m'(F_H)$ = added mass in the longitudinal direction

$F_H = U/\sqrt{gH}$

In the derivation of Equation (8), it is assumed that the waterplane area of the ship hull is so thin that a line integral term is neglected, and the body boundary condition is satisfied exactly on the body surface. From Equations (7) and (8) is obtained

$$\frac{\Delta u}{U} = \frac{\forall + m'/\rho}{AL\ (1-F_H{}^2)} \tag{9}$$

where A = WH is the cross sectional area of the tank. It is of interest to note that when the value of g approaches infinity, F_H approaches zero, and Equation (9) reduces to the case of a wind tunnel, where

$$\frac{\Delta\bar{u}}{U} = \frac{\forall + m'/\rho}{AL} \tag{10}$$

It is also of interest to note that when the body boundary condition is linearized, i.e., satisfied on the body centerplane, Equations (9) and (10) further reduce to

$$\frac{\Delta\bar{u}}{U} = \frac{\forall}{AL\ (1-F_H{}^2)} \tag{9'}$$

in the presence of a free surface and

$$\frac{\Delta \bar{u}}{U} = \frac{\forall}{AL} \tag{10'}$$

in the absence of a free surface.

APPLICATIONS

TOWING TANK EXPERIMENT

To test the new blockage correction formula, three sets of computations were first made for the same model in three different towing tanks. The first two tanks had the dimensions given by Tamura;[1,2] see Table 1. The third tank was approximately four times greater in cross sectional area than the large tank listed in Table 1, i.e., W = 24 m and H = 12 m. The specific ship model considered was the Wigley parabolic model (Model M1719 in Tamura), and the equation of the hull surface was given by

$$z = \pm \frac{B}{2} \left\{ 1 - \left(\frac{x}{L/2} \right)^2 \right\} \left\{ 1 - \left(\frac{y}{T} \right)^2 \right\} \tag{11}$$

where L/B = 10, and T/L = 0.0625. The geometric particulars of the models have been given in Table 2.

In the computations, the ship hull boundary condition was linearized; thus, speed correction formula (Equation (9')) was used. To test the present mean-speed correction formula, computations were also made from Equation (5) the exact mean-speed increment averaged over the hull surface from the local velocities obtained by the finite-element method.[12] In computing the value of $\bar{u}_o$ from Equation (5), the numerical result for the extra large tank was used in place of the perturbation potential for unbounded water ϕ_o because the effect of the tank wall and the bottom was found to be negligibly small. Comparisons between the "exact" and approximate mean-speed increments are given in Table 3. Agreement is reasonably good. It should be noted in Table 3 that the exact mean speed averaged on the hull surface $\bar{u}_o$, defined by Equation (5), is not only nonzero but also independent of Froude number. It should also be noted

TABLE 1 - DIMENSIONS OF SMALL, LARGE, AND EXTRA LARGE TOWING TANKS[1,2]

	Small Tank	Large Tank	Extra Large Tank
Width in meters	6.09	12.5	24
Mean Water Depth in meters	3.555	6.268	12

TABLE 2 - WIGLEY PARABOLIC MODEL (TAMURA MODEL M1719)

Length between Perpendiculars in meters	8.000
Length of Waterline in meters	7.984
Beam in meters	0.800
Draft in meters	0.500
Volume in meters	1.422
Wetted Surface in meters	9.408
Block Coefficient	0.4453
Prismatic Coefficient	0.6680

TABLE 3 - COMPARISONS OF MEAN-SPEED INCREMENT, COMPUTED BY NUMERICAL RESULTS AND BY PRESENT FORMULA FOR $F_L = 0.4$*

Tank	Exact Numerical Results			Equation (9')
	$\bar{u}_o/U$	$\bar{u}/U$	$\Delta\bar{u}/U = (\bar{u}-\bar{u}_o)/U$	$\Delta\bar{u}/U$
Small	0.017198	0.030514	0.0133	0.0128
Large	0.017198	0.019425	0.0022	0.0029

*Results of extra large tank were used to compute $\bar{u}_o$ as discussed in text.

that the free surface effect on the velocity profile on the body surface would be significantly dependent upon whether the hull is in a shallow towing tank or in unbounded water. The present study indicates that the approximate speed correction formula satisfactorily treats the seemingly complicated free-surface effect on the mean-speed increment on the body.

The total resistance coefficient C_T, determined experimentally by Tamura, and the wave resistance coefficients C_w computed by the finite element method, are given in Table 4.

In presenting our results, the total resistance coefficient C_T and the wave resistance coefficient C_w are defined as

$$C_T = R_T \Big/ \frac{\rho}{2} U^2 \forall^{2/3}$$
$$C_w = R_w \Big/ \frac{\rho}{2} U^2 \forall^{2/3} \qquad (12)$$

where R_T and R_w are, respectively, the total and wave resistances. The frictional resistance coefficients, C_F and $\hat{C}_F$, are defined by

$$C_F = R_F \Big/ \frac{\rho}{2} U^2 S_o$$
$$\hat{C}_F = C_F \cdot \frac{S_o}{\forall^{2/3}} = R_F \Big/ \frac{\rho}{2} U^2 \forall^{2/3} \qquad (13)$$

where S_o is the model wetted surface area. The model length Froude number F_L and Reynolds number R_n are defined by

$$F_L = U/\sqrt{gL}$$
$$R_n = \nu/\sqrt{UL} \qquad (14)$$

where ν is the kinematic viscosity of water. Here the Reynolds number R_n is obtained by assuming that the freshwater temperature in two towing tanks was 20 C. Table 4 results are given in Figure 1; the wave resistance computed for the extra large tank was taken to be the same as for unbounded water, already mentioned. In Figure 1, hull wave resistance in the large tank is very close to that for the extra large tank. Thus, the blockage effect on wave resistance is very small for the large tank. Also, the main difference in the total resistance coefficients C_T measured in the small and large towing tanks is due primarily to the difference in the model wave resistance computed for the two tanks.

Table 4 gives the speed corrections computed from Equation (9') along with the corrected values of (C_T-C_w). The corrected value of (C_T-C_w) is given by $(C_T-C_w)\ (U/(U+\Delta\bar{u}))^2$. Table 5 gives the frictional resistance coefficients C_F and $\hat{C}_F$, computed from International Towing Tank Conference (ITTC) (1957) and American Towing Tank Conference (ATTC) friction formulas. In the present study, it is assumed that the total resistance less the computed theoretical wave resistance is approximately equal to the frictional resistance, since the ship hull is thin and smooth, i.e., form drag is assumed to be negligibly small. If we make use of the Granville[13] correlation of partial form factor k_L with hull-fineness parameter $F = C_B \sqrt{(B/L)(2T/L)}$ for the Wigley parabolic model with $F_L = 0.5$, we find that $k_L = 0.04$; i.e., form drag is estimated to be only 4 percent of the frictional drag and a still lower percentage of the total drag. Accordingly, speed correction Equation (9') was applied to the resistance component $\hat{C}_F = C_T - C_w$ to correct for blockage effect. Results given in Table 5 are shown in Figure 2. In Figure 2, the corrected values of (C_T-C_w) are lower than the values of C_F given by ITTC and ATTC friction formulations, indicating negative hull form drag, which is not acceptable. In other words, if the form drag coefficient and other corrections had been added to the values of ITTC and ATTC friction coefficients, this discrepancy would be even larger. The discrepancy seems to have been caused by computed values of the wave resistance being too large.

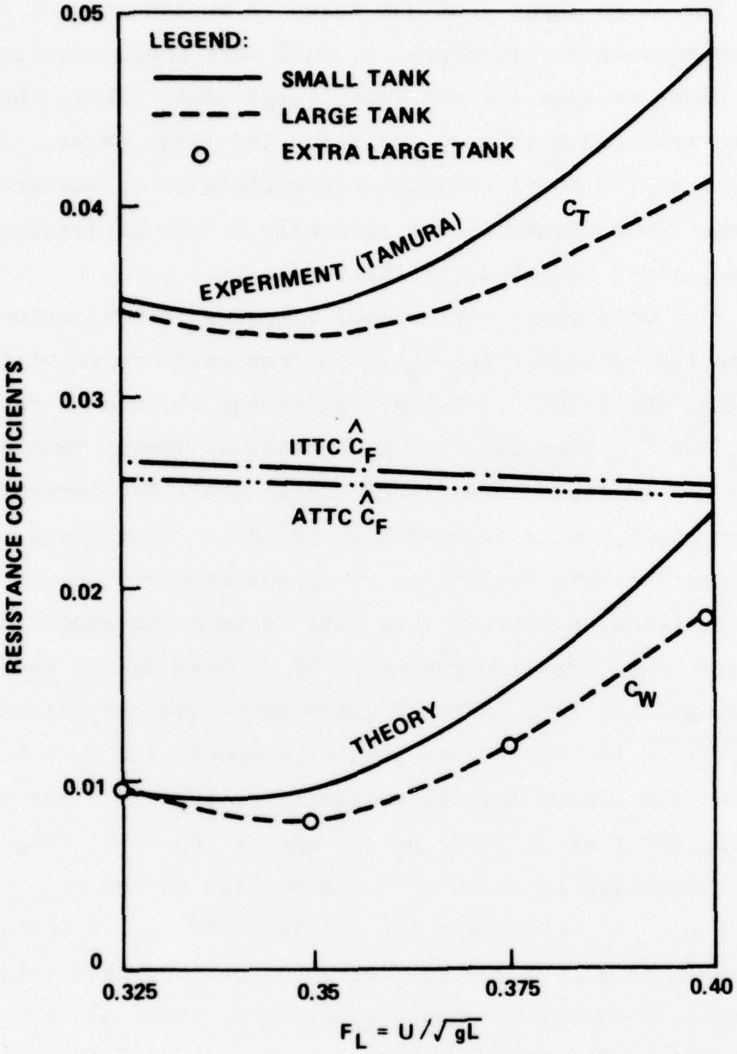

Figure 1 - Resistance Coefficients, C_T, C_w, and $\hat{C}_F$

TABLE 4 - RESISTANCE COEFFICIENTS OF THE WIGLEY PARABOLIC MODEL AT TWO DIFFERENT TOWING TANKS (MODEL M1719)

	F_L	C_T Experiment by Tamura	C_w Numerical by Bai	C_T-C_w	$\Delta\bar{u}/U$	(C_T-C_w) Corrected	(F_L) Corrected
Small Tank	0.325	0.0353	0.00959	0.0257	0.0108	0.0251	0.329
	0.350	0.0348	0.00981	0.0250	0.0113	0.0244	0.354
	0.375	0.0397	0.01543	0.0243	0.0120	0.0237	0.380
	0.400	0.0480	0.02364	0.0244	0.0128	0.0237	0.405
	0.425		0.03106				
Large Tank	0.325	0.0344	0.00971	0.0247	0.0026	0.0246	0.326
	0.350	0.0331	0.00785	0.0253	0.0027	0.0251	0.351
	0.375	0.0361	0.01203	0.0241	0.0028	0.0240	0.376
	0.400	0.0414	0.01865	0.0228	0.0029	0.0226	0.401
	0.425		0.02487				
Values in both tanks are converted to the case without blockage.							

TABLE 5 - FRICTIONAL RESISTANCE COEFFICIENTS C_F AND $\hat{C}_F$, COMPUTED FROM ITTC (1957) AND ATTC FRICTION FORMULAS, AT A FRESHWATER TEMPERATURE OF 20 C

F_L	R_n	ITTC 1957		ATTC	
		C_F	$\hat{C}_F$	C_F	$\hat{C}_F$
0.325	3.861×10^6	0.003565	0.0265	0.003444	0.0256
0.350	4.158×10^6	0.003516	0.0261	0.003400	0.0253
0.375	4.455×10^6	0.003470	0.0258	0.003360	0.0250
0.400	4.752×10^6	0.003429	0.0255	0.003323	0.0247

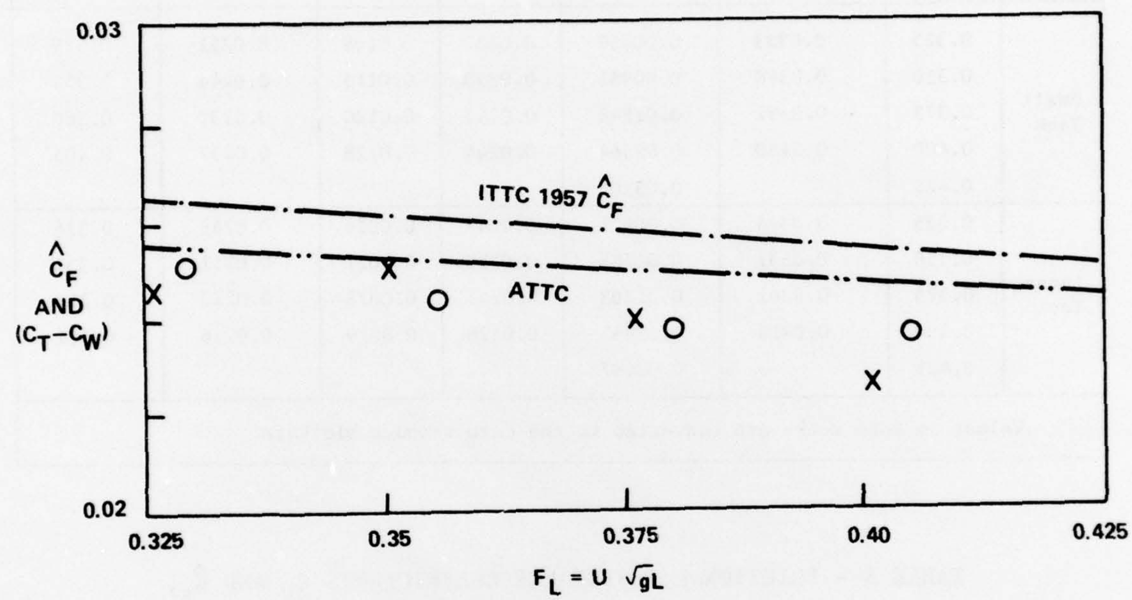

Figure 2 - Corrected Values of (C_T-C_w) from Small Tank o, Large Tank x, and ITTC 1957 and ATTC Curves $\hat{C}_F$

In the numerical computation of wave resistance by the finite-element method, 44 nodes on the ship hull surface, i.e., on the centerplane, and 1496 nodes for the entire fluid domain were taken. One may expect more refined results by reducing the size of finite elements. To treat low values of Froude number accurately, smaller and more elements are necessary.

WIND TUNNEL EXPERIMENT

As a second example, the blockage effect was considered for a wind tunnel having a uniform circular cross section of radius R_o. The specific body geometry considered was a prolate spheroid with its meridian profile given by

$$\frac{x^2}{a^2} + \frac{R^2}{b^2} = 1 \tag{15}$$

for the special case when a/b = 4.

The potential flow for the axisymmetric boundary configurations considered herein could have been computed by the conventional method of integral equations; i.e., the axial source and doublet distributions or the vortex sheet on the surface, etc., as discussed in Landweber.[14] However, the velocity potential has been computed by the finite-element method. Computations have been made for seven values of R_o/b = 1.25, 1.5, 2, 3, 4, 5, and 15 all for a/b = 4. When R_o/b = 15 was computed, the effect of the tunnel wall on the body surface was negligibly small as if the body were moving in an infinite fluid. The value of $\bar{u}_o/U$ defined in Equation (5), computed by using the result of R_o/b = 15, was 0.08185, whereas that computed by using the exact analytic result for the unbounded water, i.e., $R_o/b = \infty$, given in Lamb[15] was 0.08156.

The computed velocity potential ϕ is shown in Figure 3 for three values of R_o/b = 1.25, 1.5, and 15. To illuminate the assumption made to obtain the present approximate mean-speed correction, Figure 3 shows straight lines drawn from the origin to the asymptotic values of K/2 at the

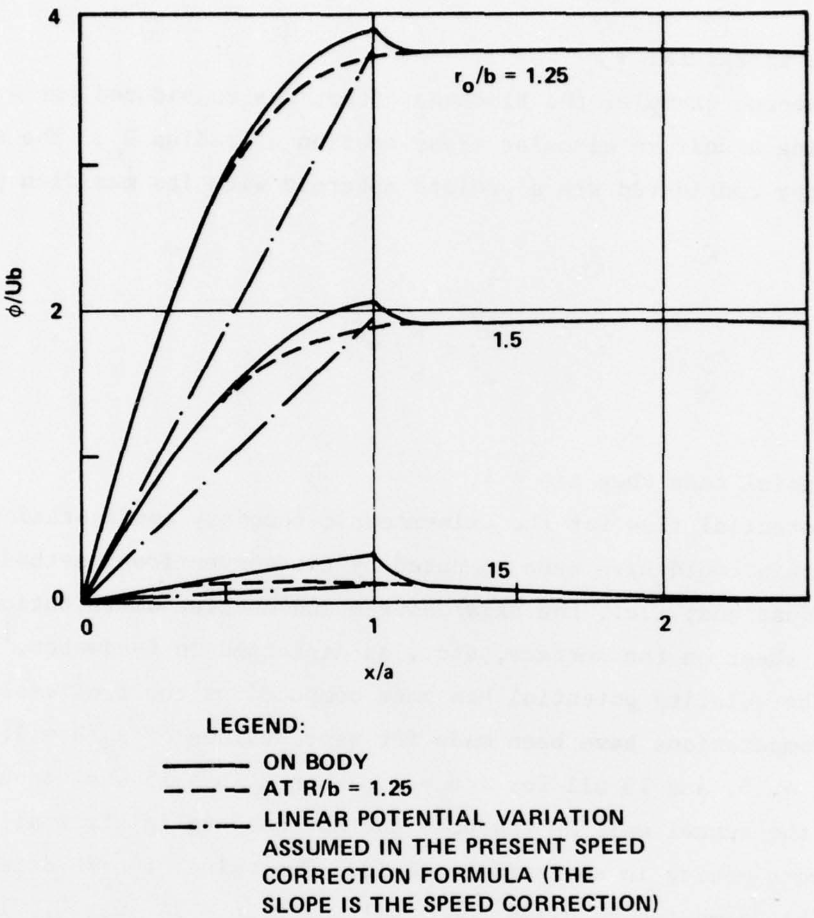

Figure 3 - Velocity Potential for a Spheroid (a/b=4) in a Wind Tunnel with a Circular Cross Section of Radius R_o

the downstream stagnation point $x = L/2$. The slope of each straight line is equal to the speed correction defined by Equation (7). Owing to the skew symmetry of the potential with respect to $x = 0$, the result for the upstream half-body can be obtained from the downstream potential shown in Figure 3. The velocity potential increases monotonically from a value slightly lower than $-K/2$ at the upstream stagnation point to a value slightly higher than $K/2$ at the downstream stagnation point on the body surface. However, the potentials at $R = 1.25b$ approach monotonically the asymptotic values at both ends for $R_o/b = 1.25$ and $R_o/b = 1.5$.

In Table 6 the approximate mean speed correction given by Equation (10) is compared with the exact mean-speed correction computed from Equation (6). Table 6 also gives the speed correction obtained by the Lock and Johansen formula, which is given in Pope[8] as

$$\frac{\Delta\bar{u}}{U} = 2.391 \left(\frac{b}{R_o}\right)^3 \qquad (16)$$

When $R_o/b < 3$, our approximate results show better agreement with the exact numerical results than with those of Lock and Johansen.

In Figure 4 computed values of the added mass coefficient and the mean speed correction $\Delta\bar{u}/U$ are shown as a function of b/R_o. In Figure 4, note that for $b/R_o > 0.765$, the contribution of the added mass to the speed correction in Equation (10) is more dominant than the contribution of the displaced volume, i.e., $\bar{m} \equiv m'/\rho\forall > 1$. This finding indicates that a crude blockage correction, based on only the local cross sectional area of the body using one-dimensional theory, cannot always give a good approximation of the mean-speed correction when the added mass coefficient is not small.

CONCLUSIONS

In the present study a new mean-speed formula for corrections caused by blockage is proposed. The approximate formula is tested by comparing

TABLE 6 - COMPARISONS OF MEAN-SPEED INCREMENTS ON A SPHEROID IN A WIND TUNNEL, COMPUTED BY A NUMERICAL METHOD, APPROXIMATE FORMULAS ($\bar{u}_o/U$=0.0813557 OBTAINED BY LAMB WAS USED)

R_o/b	$\bar{u}/U$	$\Delta\bar{u}/U$		
		Exact	Present Formula (Equation (6))	Lock and Johansen (Equation (16))
1.25	0.98204	0.90050	0.93965	1.22419
1.5	0.52285	0.44129	0.47716	0.70844
2	0.26702	0.18546	0.21559	0.29888
3	0.14442	0.06287	0.08505	0.08856
4	0.11088	0.02932	0.04624	0.03736
5	0.09748	0.01593	0.02920	0.01913
15	0.08185	0.00030	0.00320	0.00071

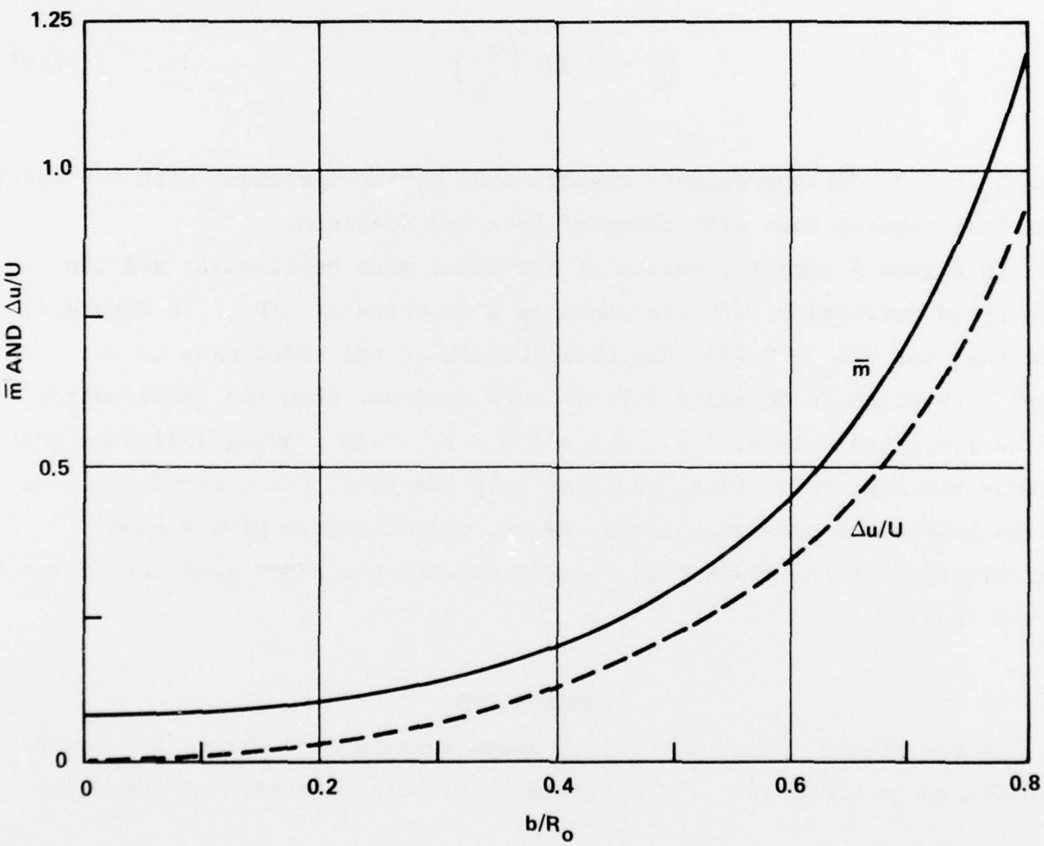

Figure 4 - Added Mass Coefficient $\bar{m}$ and Speed Correction $\Delta u/U$ for a Spheroid in a Circular Wind Tunnel

it with an exact numerical mean-speed correction, computed by the finite-element method for both a towing tank experiment and a wind tunnel experiment. The two predictions are shown to be in good agreement for both facilities. It is shown that the effect of added mass coefficient on the speed correction of a body is very significant as the blockage effect increases. It is also found that the main difference in the total resistance coefficient measured in a large and a small towing tank is due primarily to the difference in the model wave resistances computed for the two tanks. Further investigation is necessary to take into account other blockage corrections due to viscous effects such as flow separation and wake displacement thickness effects.

ACKNOWLEDGMENT

The author would like to thank Mr. Justin McCarthy for suggesting this problem and for his encouragement during the work.

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