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Report No. CG-D-63-79

TOWBOAT MANEUVERING SIMULATOR
VOLUME III - THEORETICAL DESCRIPTION

LEVEL III

EUGENE R. MILLER, JR.

FINAL REPORT

MAY 1979

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U.S. DEPARTMENT OF TRANSPORTATION
United States Coast Guard
Office of Research and Development
Washington, D.C. 20590

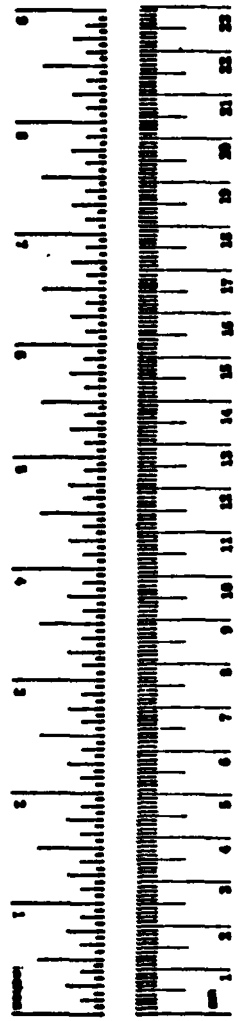
NOTICE

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

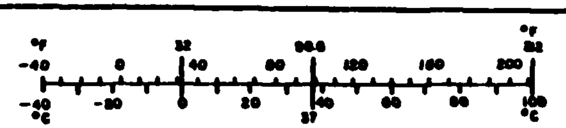
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

The Towboat Maneuvering Simulator is based on the integration in time of the differential equations which describe the motions of the towboat and barge string in three degrees of freedom, i.e., yaw, sway and surge.

This volume of the simulator documentation provides a description of the basic equations of motion included in the simulator and the relationships used to determine external forces and moments due to a bow thruster and wind. These equations are completely general in nature and could be used, with the proper hydrodynamic coefficients, to describe the maneuvering of vessels other than towboats.

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NOTATION

DIRECTIONAL STABILITY AND CONTROL

The following nomenclature conforms to DTMB Report 1319 and NSRDC Report 2510 where applicable. The positive direction of axes, angles, forces, moments, and velocities are shown by Figure 1.

Symbol	Nondimensional Form	Definition
a_i		Constant in quadratic fit to axial propeller force equation $X'_{\beta=\delta_r=0} = f(\eta)$ for each of i^{th} segments where $i = 1,2,3,4$; $a_i = X_{uu}'$ at $\eta = 0$ in appropriate segment
b_i		First order coefficient in quadratic fit to axial propeller force equation $X'_{\beta=\delta_r=0} = f(\eta)$ for each of i^{th} segments where $i = 1,2,3,4$
c_i		Second order coefficient in quadratic fit to axial propeller force equation $X'_{\beta=\delta_r=0} = f(\eta)$ for each of i^{th} segments where $i = 1,2,3,4$
AD	$AD' = \frac{AD}{L}$	Advance
CB		Center of buoyancy
CG		Center of mass of ship
D		Propeller diameter
D_s	$D_s' = \frac{D_s}{L}$	Steady-turning diameter
I_x'	$I_x' = \frac{I_x}{\frac{1}{2}\rho L^5}$	Moment of inertia of ship about x axis
I_y	$I_y' = \frac{I_y}{\frac{1}{2}\rho L^5}$	Moment of inertia of ship about y axis
I_z	$I_z' = \frac{I_z}{\frac{1}{2}\rho L^5}$	Moment of inertia of ship about z axis
J	$J' = \frac{u}{nD}$	Propeller advance coefficient based on ship speed u
J_c	$J_c' = \frac{u_c}{n_c D}$	Propeller advance coefficient at steady ship command speed u_c
k_x	$k_x' = \frac{k_x}{L}$	Radius of gyration of ship about x axis
k_y	$k_y' = \frac{k_y}{L}$	Radius of gyration of ship about y axis
k_z	$k_z' = \frac{k_z}{L}$	Radius of gyration of ship about z axis
ℓ	$\ell' = 1$	Characteristic length; length between perpendiculars for commercial ships

ℓ_d	$\ell_d' = \frac{\ell_d}{L} = \frac{\ell_r - \ell_v}{L}$	Dynamic stability lever
ℓ_r	$\ell_r' = \frac{\ell_r}{L} = \frac{N_r'}{Y_r' - m'}$	Damping lever
ℓ_v	$\ell_v' = \frac{\ell_v}{L} = \frac{N_v'}{Y_v'}$	Static stability lever
m	$m' = \frac{m}{\frac{1}{2}\rho L^3}$	Mass of ship
N	$N' = \frac{N}{\frac{1}{2}\rho L^3 U^2}$	Hydrodynamic moment component about z axis (yawing moment)
N_A	$N_A' = \frac{N_A}{\frac{1}{2}\rho_A L^3 U_A^2}$	Aerodynamic moment component about z axis
N_*	$N_*' = \frac{N_*}{\frac{1}{2}\rho L^3 U^2}$	Yawing moment when $\beta = \delta r = 0$
N_r	$N_r' = \frac{N_r}{\frac{1}{2}\rho L^4 U}$	First order coefficient used in representing N as a function of r
$N_{r\eta}$	$N_{r\eta}' = \frac{N_{r\eta}}{\frac{1}{2}\rho L^4 U}$	First order coefficient used in representing N_r as a function of $(\eta-1)$
$N_{\dot{r}}$	$N_{\dot{r}}' = \frac{N_{\dot{r}}}{\frac{1}{2}\rho L^5}$	Coefficient used in representing N as a function of $\dot{r}$
$N_{r\|r\|}$	$N_{r\|r\|}' = \frac{N_{r\|r\|}}{\frac{1}{2}\rho L^5}$	Second order coefficient used in representing N as a function of r
$N_{\|r\|\delta r}$	$N_{\|r\|\delta r}' = \frac{N_{\|r\|\delta r}}{\frac{1}{2}\rho L^4 U}$	Coefficient used in representing $N_{\delta r}$ as a function of r
N_v	$N_v' = \frac{N_v}{\frac{1}{2}\rho L^3 U}$	First order coefficient used in representing N as a function of v
$N_{v\eta}$	$N_{v\eta}' = \frac{N_{v\eta}}{\frac{1}{2}\rho L^3 U}$	First order coefficient used in representing N_v as a function of $(\eta-1)$
$N_{\dot{v}}$	$N_{\dot{v}}' = \frac{N_{\dot{v}}}{\frac{1}{2}\rho L^4}$	Coefficient used in representing N as a function of $\dot{v}$
$N_{\|v\|r}$	$N_{\|v\|r}' = \frac{N_{\|v\|r}}{\frac{1}{2}\rho L^4}$	Coefficient used in representing N_r as a function of v
$N_{v\|v\|}$	$N_{v\|v\|}' = \frac{N_{v\|v\|}}{\frac{1}{2}\rho L^3}$	Second order coefficient used in representing N as a function of v
$N_{v\|v\|\eta}$	$N_{v\|v\|\eta}' = \frac{N_{v\|v\|\eta}}{\frac{1}{2}\rho L^3}$	First order coefficient used in representing $N_{v\|v\|}$ as a function of $(\eta-1)$
$N_{\delta r}$	$N_{\delta r}' = \frac{N_{\delta r}}{\frac{1}{2}\rho L^3 U^2}$	First order coefficient used in representing N as a function of δr
$N_{\delta r\eta}$	$N_{\delta r\eta}' = \frac{N_{\delta r\eta}}{\frac{1}{2}\rho L^3 U^2}$	First order coefficient used in representing $N_{\delta r}$ as a function of $(\eta-1)$

n		Propeller revolution rate
n_c		Propeller revolution rate at steady command speed
n_o		Ordered propeller revolution rate
O_y	$O_y' = \frac{O_y}{L}$	Overshoot width of path
O_ψ		Overshoot heading angle; measured from value at second execute
R	$R' = \frac{R}{L}$	Steady-turning radius
r_R	$r'_R = \frac{r_R L}{U}$	Angular velocity component about z axis relative to fluid
$\dot{r}$	$\dot{r}' = \frac{\dot{r} L^2}{U^2}$	Angular acceleration component about z axis relative to fluid
TD	$TD' = \frac{TD}{L}$	Tactical diameter
TR	$TR' = \frac{TR}{L}$	Transfer
t	$t' = \frac{tU}{L}$	Time
t_i	$t_i' = \frac{t_i U}{L}$	Time at i^{th} execute in an overshoot or zigzag maneuver
t_o	$t_o' = \frac{t_o U}{L}$	Time at initiation of a maneuver
t_{90}	$t_{90}' = \frac{t_{90} U}{L}$	Time to reach 90-degree change of heading in a turn
t_{180}	$t_{180}' = \frac{t_{180} U}{L}$	Time to reach 180-degree change of heading in a turn
U	$U' = \frac{U}{U}$	Linear velocity of origin of body axes relative to fluid
u	$u' = \frac{u}{U}$	Component of U in direction of the x axis
$\dot{u}$	$\dot{u}' = \frac{\dot{u} L}{U^2}$	Time rate of change of u in direction of the x axis
u_c	$u_c' = \frac{u_c}{U}$	Command speed: steady value of ahead speed component u for a given propeller rpm for $\beta = \delta r = 0$; sign changes with propeller reversal
U_C		Linear velocity of current
u_C		Component of U_C in direction of x axis
U_R		Linear velocity of origin of body axis relative to fluid
u_R		Component of U_R in direction of x axis
U_p		Velocity at rudder due to motion and propeller race
U_A		Wind velocity

v_c		Component of U_c in direction of y axis
v_R		Component of U_R in direction of y axis
V		Absolute speed in knots
V_o		Steady approach speed in knots
V_{90}		Speed in knots at 90-degree heading change in a turn
V_{180}		Speed in knots at 180-degree heading change in a turn
v	$v' = \frac{v}{U}$	Component of U in direction of the y axis
$\dot{v}$	$\dot{v}' = \frac{\dot{v}L}{U^2}$	Time rate of change of v in direction of the y axis
x	$x' = \frac{x}{L}$	Longitudinal body axis; also the coordinate of a point relative to the origin of body axes
x_B	$x_B' = \frac{x_B}{L}$	The x coordinate of CB
x_G	$x_G' = \frac{x_G}{L}$	The x coordinate of CG
X_A	$X_A' = \frac{X_A}{\frac{1}{2}\rho_A L^2 U_A^2}$	Aerodynamic force component along X axis
x_o	$x_o' = \frac{x_o}{L}$	A coordinate of the displacement of CG relative to the origin of a set of fixed axes
X	$X' = \frac{X}{\frac{1}{2}\rho L^2 U^2}$	Hydrodynamic force component along x axis (longitudinal, or axial force)
X_{rr}	$X_{rr}' = \frac{X_{rr}}{\frac{1}{2}\rho L^4}$	Second order coefficient used in representing X as a function of r. First order coefficient is zero
$X_{\dot{u}}$	$X_{\dot{u}}' = \frac{X_{\dot{u}}}{\frac{1}{2}\rho L^3}$	Coefficient used in representing X as a function of $\dot{u}$
X_{uu}	$X_{uu}' = \frac{X_{uu}}{\frac{1}{2}\rho L^2}$	Second order coefficient used in representing X as a function of u in the non-propelled case. First order coefficient is zero
X_{vr}	$X_{vr}' = \frac{X_{vr}}{\frac{1}{2}\rho L^3}$	Coefficient used in representing X as a function of the product vr
X_{vv}	$X_{vv}' = \frac{X_{vv}}{\frac{1}{2}\rho L^2}$	Second order coefficient used in representing X as a function of v. First order coefficient is zero
$X_{vv\eta}$	$X_{vv\eta}' = \frac{X_{vv\eta}}{\frac{1}{2}\rho L^2}$	First order coefficient used in representing X_{vv} as a function of $(\eta-1)$
$X_{\delta r\delta r}$	$X_{\delta r\delta r}' = \frac{X_{\delta r\delta r}}{\frac{1}{2}\rho L^2 U^2}$	Second order coefficient used in representing X as a function of δr at $\eta = 0$. First order coefficient is zero

$X_{\delta r\delta r\eta\eta}$	$X_{\delta r\delta r\eta\eta}' = \frac{X_{\delta r\delta r\eta\eta}}{\frac{1}{2}\rho L^2 U^2}$	Second order coefficient used in representing $X_{\delta r\delta r}$ as a function of η
y	$y' = \frac{y}{L}$	Lateral body axis; also the coordinate of a point relative to the origin of body axes
y_B	$y_B' = \frac{y_B}{L}$	The y coordinate of CB
y_G	$y_G' = \frac{y_G}{L}$	The y coordinate of CG
y_o	$y_o' = \frac{y_o}{L}$	A coordinate of the displacement of CG relative to the origin of a set of fixed axes
Y	$Y' = \frac{Y}{\frac{1}{2}\rho L^2 U^2}$	Hydrodynamic force component along y axis (lateral force)
Y_A	$Y_A' = \frac{Y_A}{\frac{1}{2}\rho_A L^2 U_A^2}$	Aerodynamic force component along Y axis
Y_*	$Y_*' = \frac{Y_*}{\frac{1}{2}\rho L^2 U^2}$	Lateral force when $\beta = \delta r = 0$
Y_p		Distance of port propeller from centerline
Y_s		Distance of starboard propeller from centerline
Y_r	$Y_r' = \frac{Y_r}{\frac{1}{2}\rho L^3 U}$	First order coefficient used in representing Y as a function of r
$Y_{r\eta}$	$Y_{r\eta}' = \frac{Y_{r\eta}}{\frac{1}{2}\rho L^3 U}$	First order coefficient used in representing Y_r as a function of $(\eta-1)$
$Y_{\dot r}$	$Y_{\dot r}' = \frac{Y_{\dot r}}{\frac{1}{2}\rho L^4}$	Coefficient used in representing Y as a function of $\dot r$
$Y_{r\lvert r\rvert}$	$Y_{r\lvert r\rvert}' = \frac{Y_{r\lvert r\rvert}}{\frac{1}{2}\rho L^4}$	Second order coefficient in representing Y as a function of r
$Y_{\lvert r\rvert\delta r}$	$Y_{\lvert r\rvert\delta r}' = \frac{Y_{\lvert r\rvert\delta r}}{\frac{1}{2}\rho L^3 U}$	Coefficient used in representing $Y_{\delta r}$ as a function of r
Y_v	$Y_v' = \frac{Y_v}{\frac{1}{2}\rho L^2 U}$	First order coefficient used in representing Y as a function of v
$Y_{v\eta}$	$Y_{v\eta}' = \frac{Y_{v\eta}}{\frac{1}{2}\rho L^2 U}$	First order coefficient used in representing Y_v as a function of $(\eta-1)$
$Y_{\dot v}$	$Y_{\dot v}' = \frac{Y_{\dot v}}{\frac{1}{2}\rho L^3}$	Coefficient used in representing Y as a function of $\dot v$
$Y_{v\lvert r\rvert}$	$Y_{v\lvert r\rvert}' = \frac{Y_{v\lvert r\rvert}}{\frac{1}{2}\rho L^3}$	Coefficient used in representing Y_v as a function of r
$Y_{v\lvert v\rvert}$	$Y_{v\lvert v\rvert}' = \frac{Y_{v\lvert v\rvert}}{\frac{1}{2}\rho L^2}$	Second order coefficient used in representing Y as a function of v

$Y_{v\|v\|\eta}$	$Y_{v\|v\|\eta}' = \frac{Y_{v\|v\|\eta}}{\frac{1}{2}\rho L^2}$	First order coefficient used in representing $Y_{v\|v\|}$ as a function of $(\eta-1)$
$Y_{\delta r}$	$Y_{\delta r}' = \frac{Y_{\delta r}}{\frac{1}{2}\rho L^2 U^2}$	First order coefficient used in representing Y as a function of δr
$Y_{\delta r\eta}$	$Y_{\delta r\eta}' = \frac{Y_{\delta r\eta}}{\frac{1}{2}\rho L^2 U^2}$	First order coefficient used in representing $Y_{\delta r}$ as a function of $(\eta-1)$
β		Angle of drift
β_r		Angle of drift relative to fluid
δ_F		Deflection of flanking rudder
δ_S		Deflection of steering rudder
δr_i		Steady rudder angle at i^{th} execute in an overshoot or zigzag maneuver; $i = 1,2,3.....$
$\dot{\delta}_F$	$\dot{\delta}_F' = \frac{\dot{\delta}_F L}{U}$	Flanking rudder deflection rate
$\dot{\delta}_s$	$\dot{\delta}_s' = \frac{\dot{\delta}_s L}{U}$	Steering rudder deflection rate
		Ship propulsion ratio; $\frac{u_c}{u} \cdot \frac{n}{n_c}$
σ_{ih}	$\sigma_{ih}' = \sigma_{ih}\frac{L}{U}$ $\sigma_{ih}'' = \sigma_{ih}'\sqrt[3]{\frac{\eta}{2}}$	Roots of characteristic stability equation for horizontal plane motions, $i = 1$ or 2
ψ		Heading or yaw angle
ψ_i		Heading angle at i^{th} execute in an overshoot or zigzag maneuver, measured from value at first execute; $i = 2,3....$
$\dot{\psi}$	$\dot{\psi}' = \dot{\psi}\frac{L}{U}$	Rate of change of heading
$\dot{\psi}_h$	$\dot{\psi}_h' = \dot{\psi}_h\frac{L}{U}$	Height of loop at neutral rudder angle from spiral maneuver
$\dot{\psi}_i$	$\dot{\psi}_i' = \dot{\psi}_i\frac{L}{U}$	Rate of change of heading at i^{th} execute in an overshoot or zigzag maneuver; $i = 2,3.....$
ω	$\omega' = \frac{\omega L}{U}$	Frequency of oscillation

1.0 INTRODUCTION

The towboat manuevering simulator is based on the integration in time of the differential equations which describe the motions of the towboat and barge string in three degrees of freedom, i.e., yaw, sway and surge. The theoretical background for these equations are presented in Reference 1, "The Prediction of River Tow Maneuvering Performance," U.S. Coast Guard Report No. CG-D-32-78. This reference presents the basic equations and a complete set of hydrodynamic coefficients for a representative towboat and barge train. These coefficients were obtained by model tests.

This section of the simulator documentation provides a description of the basic equations of motion included in the simulator and the relationships used to determine external forces and moments due to a bow thruster and wind. These equations are completely general in nature and could be used, with the proper hydrodynamic coefficients, to describe the maneuvering of vessels other than towboats.

2.0 MATHEMATICAL MODEL

The mathematical model for the maneuvering of a river tow consists of the coupled differential equations in three degrees of freedom (yaw, sway and surge) which describe the motions in the X, Y plane and the complete set of hydrodynamic coefficients and external forces which are required in order to numerically integrate these equations. There are also auxiliary equations which describe the response of the steering and propulsion system to external inputs.

A complete set of three coupled differential equations with all of the terms necessary to simulate normal maneuvers of surface ships are presented in Reference 2. These equations have been used by HYDRONAUTICS, Incorporated to calculate the maneuver trajectories for a wide range of surface ship types in deep and shallow water. These equations are based on a more complete set of equations developed by the U.S. Navy for the simulation of submarine motions in six degrees of freedom. The equations in Reference 2 differ from other sets of equations, such as those of Reference 3 used to describe surface ship maneuvers primarily in the way higher order terms are introduced. The equations of Reference 3 use a Taylor expansion which results in odd functions being represented by linear and cubic terms. The equations of Reference 2 are a square absolute representation for higher order terms so that odd functions are represented by linear and square terms. At large drift angles, which is a likely operating condition for a river tow, the forces and moments are dominated by cross flow drag which is proportional to velocity squared. Thus, it is better to use equations in which forces and moments are proportional to velocity squared rather than cubed. As a result , the equations presented in Reference 2 were selected to form the basis for the equations which describe the maneuvering of a river tow. There are a number of modifications which must be made to these equations. These modifications and the resulting set of equations are described in the following paragraphs.

The following equations in three degrees of freedom are referred to a right-hand orthogonal system of moving axes, fixed in the body, with its origin normally located at the center of mass of the body. The positive direction of the axes, angles, linear velocity components, angular velocity components, forces and moments are given in Figure 1. Unless otherwise indicated in the Notation, the numerical values for the hydrodynamic coefficients used with the equations are for the ship propulsion point ($\eta = 1.0$). The equations are written in terms of the complete barge flotillia towboat configuration. Thus the values of the coefficients embrace the interaction effects between rudder and hull, propeller and hull, and propeller and rudder as determined from the model tests of the complete configuration.

An important consideration in the maneuvering of a river tow is the effect of current which can vary significantly along the length of the tow. As a result, it is necessary to introduce the effect of the current velocity into the mathematical model. The approach adopted was to define the hydrodynamic terms in the equations based on the relative velocities and yaw rate between the hull and the fluid rather than the inertial velocities and yaw rate. The relative velocities and relative yaw rate can be calculated by the vector addition of the inertial velocity and inertial yaw rate and the current velocities and current yaw rate. In the numerical integration the procedure is to define a matrix of current speeds (U_{cij}) and directions (Ψ_{cij}) at points on the X, Y plane. Based on the location of the bow (X_B, Y_B) midships

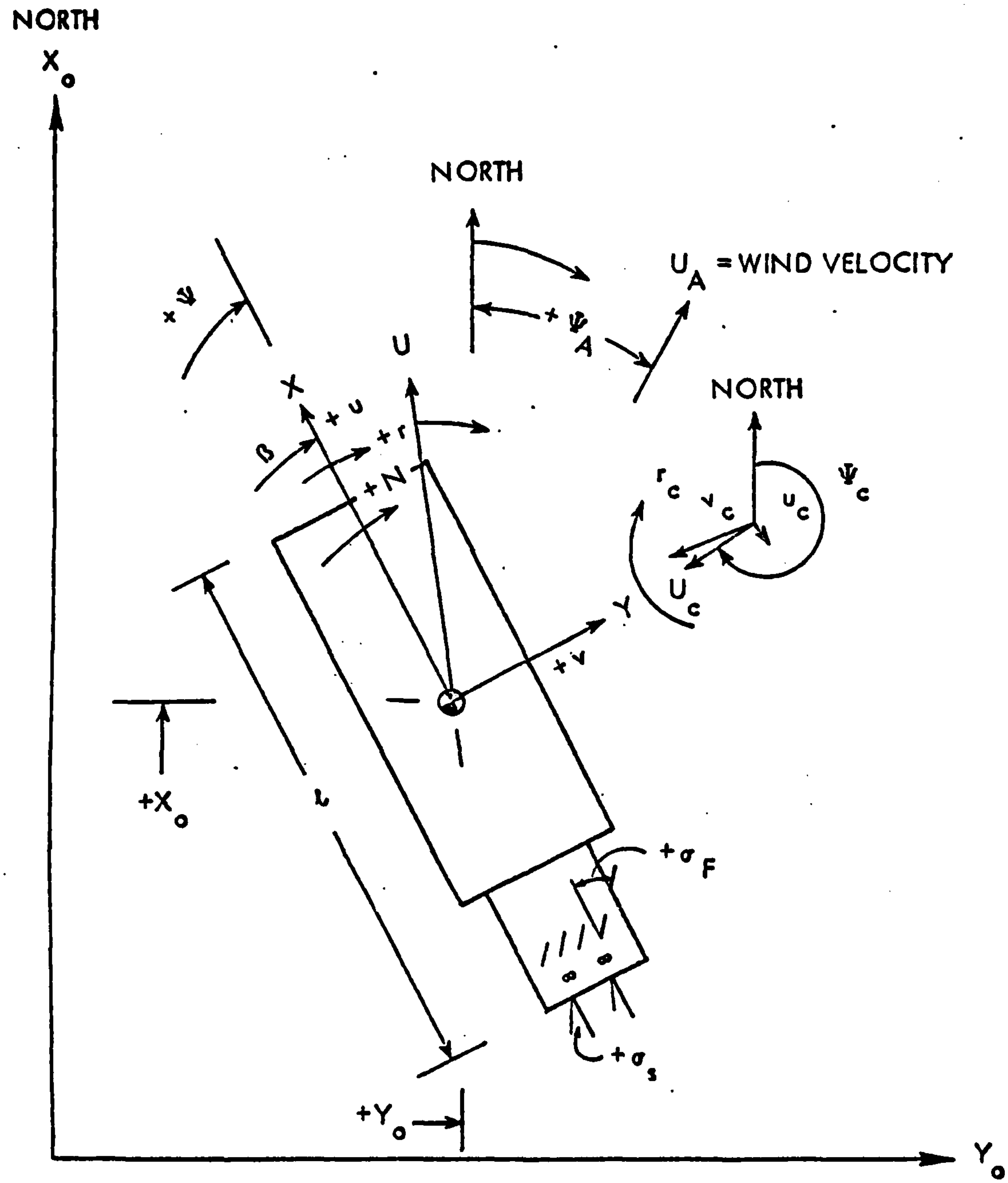

FIGURE 1 - SIGN CONVENTION FOR RIVER TOW MANEUVERING SIMULATION

(X_m, Y_m) and stern (X_s, Y_s) of the tow, an interpolation in the current speed and direction matrix is carried out to obtain the current speed and direction at the bow (U_{CB}, ψ_{CB}), midships (U_{CM}, ψ_{CM}) and stern (U_{CS}, ψ_{CS}). The following relationships then apply:

$$\left.\begin{array}{ll}
u_{CB} = U_{CB} \cos(\psi_{CB}-\psi) & v_{CB} = U_{CB} \sin(\psi_{CB}-\psi) \\
u_{CM} = U_{CM} \cos(\psi_{CB}-\psi) & v_{CM} = U_{CM} \sin(\psi_{CM}-\psi) \\
u_{CS} = U_{CS} \cos(\psi_{CS}-\psi) & v_{CS} = U_{CS} \sin(\psi_{CS}-\psi) \\
u_C = \dfrac{u_{CB} + u_{CM} + u_{CS}}{3} & v_c = \dfrac{v_{CB} + v_{CM} + v_{CS}}{3} \\
r_C = \dfrac{v_{CB} - v_{CS}}{\ell} & \\
u_R = u - u_C \quad v_R = v - v_C \quad r_R = r - r_C &
\end{array}\right\} \quad (1)$$

In this procedure the mean longitudinal and lateral current velocity in the body axis system is obtained from the average of the values at the bow, midships and stern. The variation of the lateral velocity along the tow is accounted for by the apparent current yaw rate defined by the difference in the lateral velocities at the bow and stern divided by length. This assumes the lateral velocity varies linearly from bow to stern. If this is not the case a more complex relationship would have to be introduced.

The equations of motion formulated for a river tow are as follows:

$$U_R = \sqrt{u_R^2+v_R^2} \qquad v_R = -U_R \sin \beta_R \qquad u_R = U_R \cos \beta_R$$

$$\beta_R = \arctan \left(- \frac{v_R}{u_R}\right)$$

AXIAL FORCE

$$
\begin{aligned}
m(\dot{u}-vr-x_G r^2) = {} & \frac{\rho}{2}\ell^3\left(X_{\dot{u}}'\dot{u}_R + X_{vr}'\,v_R r_R\right) \\
& + \frac{\rho}{2}\ell^2\left(X_{vv}'v_R^2\right) + \frac{\rho}{2}\ell^2 u_R^2\left(a_1 + \frac{b_1}{2}\eta_s + \frac{c_1}{2}\eta_s^2 + \frac{b_1}{2}\eta_p + \frac{c_1}{2}\eta_p^2\right) \\
& + \frac{\rho}{2}\ell^2\left[\frac{X_{vv\eta}'}{2}(\eta_s-1) + \frac{X_{vv\eta}'}{2}(\eta_p-1)\right]v_R^2 \\
& + \frac{\rho_A}{2}\ell^2 X_A'u_A^2 + \frac{\rho}{2}\ell^2\left[u_{p_p}^2\left(\frac{X_{\delta_S\delta_S}'\delta_S^2 + X_{\delta_F\delta_F}'\delta_F^2}{2}\right) + u_{p_s}^2\left(\frac{X_{\delta_S\delta_S}'\delta_S^2 + X_{\delta_F\delta_F}'\delta_F^2}{2}\right)\right] \quad (2)
\end{aligned}
$$

LATERAL FORCE

$$
\begin{aligned}
m(\dot{v}+ur+\bar{x}_G\dot{r}) = {} & \frac{\rho}{2}\,\ell^4 \left(Y_{\dot{r}}{}'\dot{r} + Y_{r|r|}r_R|r_R|\right) + \frac{\rho}{2}\,\ell^3\left(Y_{\dot{v}}{}'\dot{v}\right) \\
& + \frac{\rho}{2}\,\ell^3 \left(Y_r{}'u_R r_R + Y_{v|r|}{}'v_r|r_R|\right) + \frac{\rho_A}{2}\,\ell^2 v_A{}^2 Y_A{}' \\
& + \frac{\rho}{2}\,\ell^2 \left(Y_v{}'u_R v_R + Y_{v|v|}{}'v_R|v_R| + Y_{v\eta}{}'u_R\dot{v}_R\left(\frac{\eta_s+\eta_p}{2} - 1\right)\right) \\
& + \frac{\rho}{2}\,\ell^2 \left[Y_{v|v|\eta}{}' \cdot v_R|v_R|\left(\frac{\eta_s+\eta_p}{2} - 1\right)\right] + \frac{\rho}{2}\,\ell^3 Y_{r\eta}{}'u_R r_R\left(\frac{\eta_s+\eta_p}{2} - 1\right) \qquad (3) \\
& + \frac{\rho}{2}\,\ell^2 \left[u_{p_p}{}^2\left(\frac{Y_*{}'+Y_{\delta_S}{}'\delta_S+Y_{\delta_F}{}'\delta_F}{2}\right) + u_{p_s}{}^2\left(\frac{Y_*{}'+Y_{\delta_S}{}'\delta_S+Y_{\delta_F}{}'\delta_F}{2}\right)\right]
\end{aligned}
$$

YAWING MOMENT

$$
\begin{aligned}
I_z\dot{r} + mx_G(\dot{v}-ur) = {} & \frac{\rho}{2}\ell^5\left(N_{\dot{r}}'\dot{r} + N_{r|r|}'r_R|r_R|\right) + \frac{\rho}{2}\ell^4 N_{\dot{v}}'\dot{v} \\
& + \frac{\rho}{2}\ell^4\left(N_r'u_Rr_R + N_{|v|r}'|v_R|r_R\right) \\
& + \frac{\rho}{2}\ell^4\left(N_{r\eta}'u_Rr_R\right)\left(\frac{\eta_s+\eta_p}{2} - 1\right) \\
& + \frac{\rho}{2}\ell^3\left(N_{v\eta}'u_Rv_R + N_{v|v|}'v_R|v_R|\right)\left(\frac{\eta_s+\eta_p}{2} - 1\right) \\
& + \frac{\rho}{2}\ell^3\left[u_{p_p}^2\left(\frac{N_{\delta_S}'\delta_S+N_{\delta_F}\delta_F+N_*'}{2}\right) + u_{p_s}^2\left(\frac{N_{\delta_S}'\delta_S+N_{\delta_F}'\delta_F+N_*'}{2}\right)\right] \\
& + \frac{\rho}{2}\ell^3\left(N_v'u_Rv_R + N_{v|v|}'v_R|v_R|\right) + \frac{\rho_A}{2}\ell^3N_A'u_A^2 \\
& + \frac{\rho}{2}\ell^2u_R^2\left[-Y_s\left(\frac{b_1}{2}\eta_s + \frac{c_1}{2}\eta_s^2\right) + Y_p\left(\frac{b_1}{2}\eta_p + \frac{c_1}{2}\eta_p^2\right)\right]
\end{aligned}
\tag{4}
$$

$u_p^2 = (du_R^2 + eDnu_R + fD^2n^2)$ where n = Prop RPM

η = Propulsion Ratio = $(n/u_R)/(n_c/u_c)$

The foregoing equations of motion, as noted previously, are patterned after the quasi-steady state equations of Reference 2. The non-dimensional hydrodynamic coefficients which comprise the basic equations are considered to be independent of speed (Froude number). This assumption is valid since river tows always operate at low Froude number.

These equations differ from the equations of Reference 2 in the following details:

a. They are written in terms of the relative velocities and yaw rate to allow the introduction of varying current as discussed above.

b. Terms are included for steering rudders (steering rudder angle = δ_S) and flanking rudder (flanking rudder angle = δ_F).

c. Terms are included for twin propellers which may operate at different RPM's and different directions of rotation. The turning moment due to differential thrust is included in the yawing moment, Equation (4).

d. The forces and moments generated by the rudders are based on a velocity defined by

$$U_p^2 = (du_R^2 + eDnu_R + fD^2n^2)$$

which is a function of the relative axial velocity, u_R, and propeller RPM, n. The constants d, e and f depend on the sign of u_R and n. This allows a proper representation of the rudder forces and moments at zero speed and finite propeller RPM.

In realistic maneuvers, river tows operate both ahead and astern and in some cases at large drift angles. In order to properly represent the hydrodynamic forces and moments which act in such conditions, different sets of hydrodynamic coefficients are used depending on the relative drift angle β_R. As will be noted in Reference 1 in which the hydrodynamic coefficients from the model tests are presented, most coefficients depend on the direction of motion, i.e., ahead $270° \leq \beta_R \leq 90°$ or astern $90° \leq \beta_R \leq 270°$. In order to obtain a better representation of the steady sideforce and yaw moment at drift angles near 90 and 270 degrees certain coefficients have an additional value when $30° \leq \beta_R \leq 150°$ or $210° \leq \beta_R \leq 330°$.

As noted in the introduction to this section, a complete set of hydrodynamic coefficients for Equations 2, 3 and 4 for a towboat and barge string are presented in Reference 1. The simulator as presently configured has the hydrodynamic coefficients as constants independent of water depth. Thus, if operations in shallow water are to be simulated, hydrodynamic coefficients applicable to the appropriate depth should be used. As a general rule, the water can be considered as deep if it exceeds the draft of the tow by a factor of 2.5 or 3.

The equations of motion (i.e., equations 2, 3 and 4) are solved stepwise in time in the computer program. In the program the time step, DT is set equal to 1.0 seconds. For a long, relatively slow-moving river tow, a longer time step (2 to 4 seconds) could be used without significantly affecting the results of most maneuvers. The 1.0 second time step was chosen more on the basis of the updating rate for the control display. It was considered desirable to minimize the time delay between a control input and the display response. A 1.0 second time step was considered reasonable on this basis.

At each time step in the solution of the equations of motion, the current velocity at the low, midship and stern of the tow is determined. This calculation is carried out by subroutine CURT.

In the input to the program, the current speed and direction is specified at up to 30 lines or stations across the river. These may be arbitrarily spaced along the river. The river bank is defined in the visual display by lines joining the end points of consecutive stations. As a result, stations should be concentrated in the area of bends or rapid changes in river width. The current speed and direction are also likely to change rapidly in such areas.

At each station, the current speed and direction is specified at 8 evenly spaced points (see Figure 13 of Volume I). Subroutine CURT determines the current speed and direction at bow, midship and stern by searching the stations in sequence. At each station, the smallest distance between the vessel point and one of the 8 station points is determined. Initially this process is repeated until the minimum distance point is found. The current defined at the closest point is then used in calculations. After the initial time step the search is carried out locally around the station point found to have the minimum distance during the previous time step. This local search technique saves significant computer time.

3.0 EXTERNAL FORCES

3.1 Bow Thruster

The towboat maneuvering simulator contains the provision for a bow thruster. The forces and moments generated by the bow thruster are represented by the following relationships:

Thruster Lateral Force -

$F_{Yo} = (T_{MAX}) * (\text{Percent Output}) = \text{THMAX} * \text{TRPM}$

F_{Yo} = Y force at zero forward speed

Percent output ranges from -1.0 to 1.0

The lateral forces of a tunnel type bow thruster decreases with forward speed. Thus, the lateral force introduced into the lateral force Equation (3) is given by:

$$\text{FXP}(3) = F_Y = F_{Y_o} \left(\text{TRC}(1) + \text{TRC}(2) * \text{Cos}\ (2\pi\ u/v_j)\right) \qquad (5)$$

$$\text{for } u/V_J \leq 0.5$$

$$= F_{Y_o} \left((\text{TRC}(1) - \text{TRC}(2)) + \text{TRC}(3) * (U/V_J - 0.5)\right)$$

$$\text{for } u/V_J > 0.5$$

where

u = axial speed of vessel

V_J = thruster jet or exit velocity

$V_J = (F_{Y_o}/\rho A)^{\frac{1}{2}}$

ρ = mean density of water

A = thruster Disc Area

Typical constants for a tunnel bow thruster based on Reference 5 would be:

THMAX = 10,000 lbs

TRC(1) = 0.65

TRC(3) = 0.18

CTHV = $1/\rho A$ = 0.025

Thruster Yawing Moment

Because of interaction forces with the hull the yawing moment due to the thruster does not change with forward speed in the same way as the lateral force. The yawing moment due to the thruster which is introduced into the yawing moment equation is given by:

$$N = F_Y X_t \left(1 - (1 - 0.67\ u/VJ)\left(1 - \frac{F_Y}{F_{Y_o}}\right)\right) \qquad (6)$$

N = Yawing Moment due to thruster

X_t = Longitudinal location of thruster = YCSP(3)

3.2 Wind Forces and Moments

The forces and moments acting on the towboat and barges due to wind were calculated using methods and data given in Reference 4. The forces and moment at a given time are calculated using the instantaneous relative wind velocity.

The axial and lateral forces and yawing moment due to wind are given by:

$$X_w = -\tfrac{1}{2}\rho_a C_{xw} V_{we}{}^2 A_{px} \cos^2 \beta_{we} = FX(2) \qquad (7)$$

$$Y_w = \tfrac{1}{2}\rho_a C_{yw} V_{we}{}^2 A_{py} \sin^2 \beta_{we} = FY(2) \qquad (8)$$

$$N_w = Y_w x_{\ell cp} = FN(2) \qquad (9)$$

where

X_w and Y_w are longitudinal and lateral forces (in ship coordinates) due to wind

N_w is yawing moment about the c.g. due to wind

ρ_a is air mass density

C_{xw} and C_{yw} are longitudinal and lateral drag coefficients

A_{px} and A_{py} are longitudinal and lateral projections of above water hull and deckhouses

V_{we} is effective wind velocity = VwR

β_{we} is angle measured from the ship x-axis to the effective wind velocity vector = BW

$x_{\ell cp}$ is longitudinal position of the center of pressure of the wind force

The effective wind velocity, including the effect of the boundary layer at the water surface, deduced empirically in Reference 4. is:

$$V_{we} = \left(\frac{z_{ca}}{32.81}\right)^{0.15} (V_{wx}^2 + V_{wy}^2)^{\frac{1}{2}}$$

$$= \left(\frac{z_{ca}}{32.81}\right)^{0.15} \left[(u + V_w \cos \beta_w)^2 + (v + V_w \sin \beta_w)^2\right]^{\frac{1}{2}} \quad (10)$$

where

z_{ca} is vertical center of area of the ship

V_{wx} and V_{wy} are longitudinal and lateral components of the effective wind velocity

u and v are components of ship velocity

V_w is actual wind velocity

B_w is wind heading angle measured from ship x-axis to actual wind velocity vector

The angle β_{we} is given by

$$\beta_{we} = \tan^{-1}\left(\frac{u + V_w \cos \beta_w}{v + V_w \sin \beta_w}\right)$$

The center of pressure is determined from the longitudinal center of area, using empirical methods and data from Reference 4 and is:

$$x_{\ell cp} = L_{BP}\left[3\,\frac{x_{ca}}{L_{BP}} - (0.001 + 0.01\ AR)\ (|\beta_w'| - 90)\right]$$

where

L_{BP}	is ship LBP
x_{ca}	is longitudinal position of the center of lateral area = XLCA
β_w'	is the value of β_{we} in degrees = BW
AR	is hull aspect ratio, $AR = 2A_{py}/L_{BP}^2$ = AS

Based on the data given in Reference 4 and estimated above water hull and deckhouse shapes, the following wind force coefficients would apply to the towboat and barges configuration for which hydrodynamic data are reported in Reference 1.

L_{BP} = 745 ft

X_{ca} = 58.8 ft

AR = 0.0167

C_{xw} = 1.0

C_{yw} = 1.0

A_{px} = 1520 ft^2

A_{py} = 4635 ft^2

Z_{ca} = 6.2 ft

3.3 Other External Forces

At this time no other external forces are included in the simulator. In the future, other external forces such as bank suction, interaction with passing vessels and the effects of mooring lines could be included.

4.0 CONTROL SYSTEMS

The control systems included in the towboat maneuvering simulator include steering control for the steering and flanking rudders, RPM control for the port and starboard propellers and the bow thruster output control. The command inputs for all of these controls are provided thru the computer A to D input from the control station. In the simulator, the response to the control inputs is at a constant rate. The rates used based on Reference 6 are as follows:

Steering and Flanking Rudders	5 deg/sec
Propeller RPM	20 RPM/sec
Thruster Output	10 percent thrust change/sec

The response to the control system inputs is considered representative of a typical towboat. If required in the future, a more complex representation of the response to control inputs could be modeled in the simulator.

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