An Analysis of Desired Maneuvering Characteristics of Large Arctic SEV'S

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The following project was undertaken as part of the Advanced Research Projects Agency Arctic Surface Effect Vehicle (SEV) Program. A study of the effects of variation of control types, control rates, control size and placement on a large Arctic SEV, along with craft speeds and winds on the high-speed maneuvering characteristics of a large Arctic SEV has been conducted. The information obtained in this study has been related to the expected obstacle avoidance capabilities of the vehicle. The method of investigation included use of a three-degree-of-freedom digital computer simulation of the Arctic SEV. The results of this investigation indicate that swivelable shrouded propellers are the single control type which is best capable of turning a large SEV under Arctic conditions. At least four, 15-ft-diam shrouded props will be required for a 500-ton vehicle, or maneuvering must be done by using a combination of control types. Maneuvering at large yaw angles (at least to 25°) as well as operating control devices to the highest possible deflection without entering into stall regions is required to optimize turns.

Nomenclature

b = vehicle width, ft
C_{AXIAL} = axial force coefficient (body axes), n.d.
C_D = drag coefficient (wind axes), n.d.
C_N = yaw moment coefficient (wind or body axes), n.d.
C_{SIDE} = side force coefficient (body axes), n.d.
C_Y = side force coefficient (wind axes), n.d.
D = shrouded propeller diameter, ft
I_z = moment of inertia about vehicle vertical axis, ft lb sec^2
l = vehicle length, ft
q = freestream dynamic pressure = $1/2\ \rho V^2$, psf
s = reference area = $l \cdot b$, ft^2
SEV = abbreviation for surface effect vehicle
t = time (maneuvers begin at $t = 0$), sec
V = effective vehicle velocity magnitude = $|\mathbf{V}_{SEV}|^2 + V_W^2$, fps
$\mathbf{V}_{SEV}$ = velocity vector of vehicle relative to ground, fps
V_w = wind velocity vector magnitude, fps
$\mathbf{V}_{wind}$ = wind velocity vector, fps
W = vehicle weight, lb
$X_{c.g.}$ = distance center of gravity is behind nose of craft, ft
$X_{F(F)}$ = distance front fin is behind nose of craft, ft
$X_{F(R)}$ = distance rear fin is behind nose of craft, ft
X_I = craft position along X inertial axis, ft
$X_{T(F)}$ = distance front thrustors are behind nose of craft, ft
$X_{T(R)}$ = distance rear thrustors are behind nose of craft, ft
X_{turn} = maximum X_I achieved by vehicle during turning maneuver ≡ turnabout distance, ft
Y_I = craft position along Y inertial axis, ft
β = yaw angle of vehicle, deg
β_w = angle between X_I and $\mathbf{V}_{wind}$, deg
ρ = freestream air density, slugs/ft
ψ = angle between X_I and body longitudinal axis, deg
$\dot{\psi}$ = time rate of change of $\psi = d\psi/dt$, deg/sec
δ = fin control deflection angle, deg
$\dot{\delta}$ = time rate of change of $\delta = d\delta/dt$, deg/sec
τ = thrust control deflection angle, deg
$\dot{\tau}$ = time rate of change of $\tau = d\tau/dt$, deg/sec

Subscript

max = maximum value allowed or desired

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Introduction

INITIAL work by the Navy on the Arctic Surface Effect Vehicle (SEV) project, which is being sponsored by the Advanced Research Projects Agency (ARPA), indicated a need to develop an improved capability to evaluate the maneuverability of large SEV's. The largest Arctic SEV is envisioned as a craft whose gross weight will range from 500- to 1000-tons and as having a cruise speed up to 120 knots. Thus the craft will be three to five times heavier than the 180-ton SRN-4, the largest craft built to date. Previously, SEV's have operated primarily as water-borne vessels, generally as an over-water ferry, and the maneuverability or obstacle avoidance requirements have not been particularly stringent.

The Arctic SEV will operate over and adjacent to the pressure ridges, pack ice, and open leads of the Arctic region. This will place more stringent requirements upon its obstacle identification and maneuvering systems than for previous SEV's.

Because of the anticipated high cruise speeds, on the order of 120 knots, and the poor visibility situations (white-outs, long nights) occuring in the Arctic, a very sophisticated obstacle detection system is required. The predicted capabilities of the obstacle detection system are that obstacle height will be determined within ±2.5 ft at a maximum range of 3 miles.[1] It is hoped that skirt technology will be advanced to a level which would allow a 17-ft high skirt on a 500-ton Arctic SEV. Results of terrain studies of the Arctic (performed as part of the ARPA Arctic SEV program) have indicated that approximately 90% of all ice pack obstacles are 12-ft or less in height. Thus, if a 2.5-ft gap between top of obstacles and vehicle hard structure, and the +2.5-ft obstacle detection error at 3 miles are both added to the 12-ft obstacle, we have accounted for all 17-ft of skirt, and the 3 miles distance becomes a measuring stick against which maneuvers can be compared.

This study addressed the problem of how to accomplish short radius turns. A three-degree-of-freedom digital computer program in the yaw plane of motion was used. The

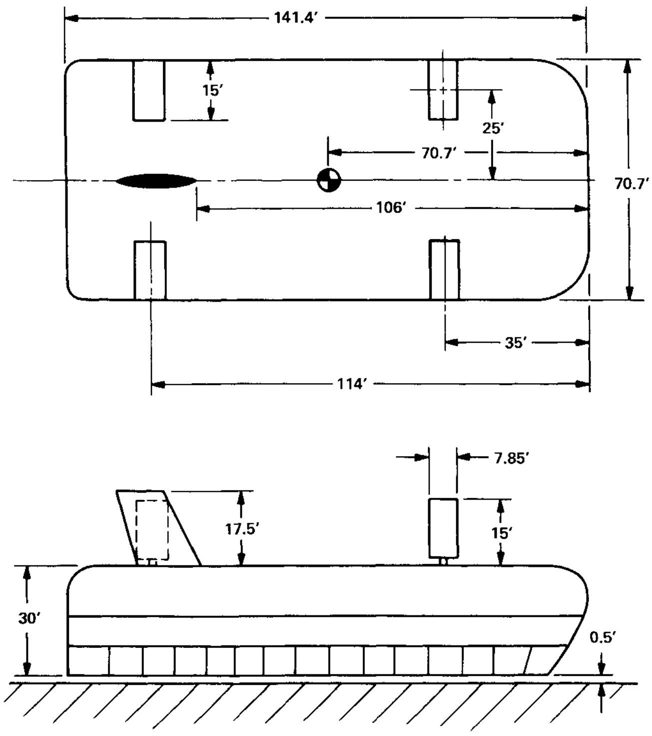

Fig. 1 Craft chosen for study.

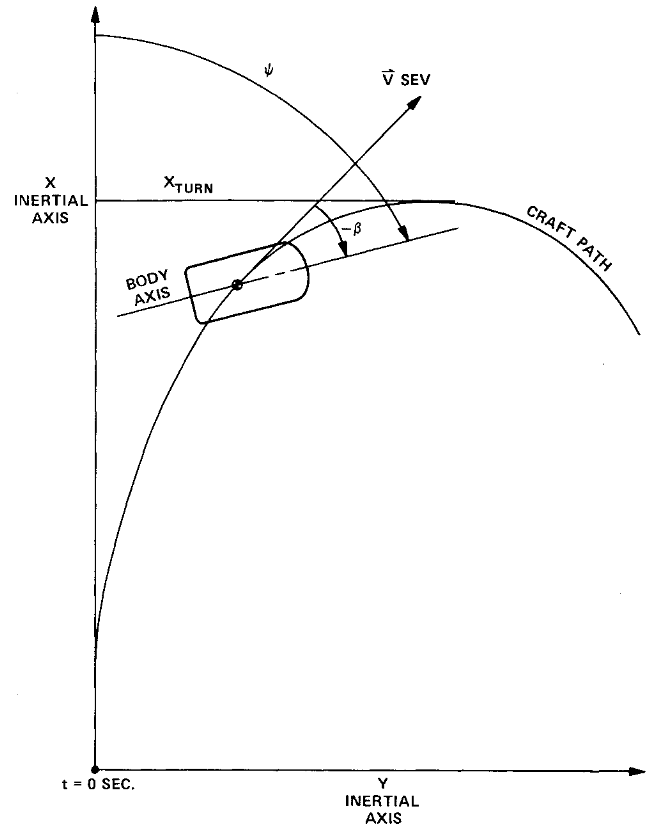

Fig. 2 Turning geometry, no wind.

variations considered in this study are presented primarily for an Arctic SEV with a gross weight of 500-tons (Fig. 1), and for turns initiated at 120-knot speeds. We would like to make it clear that the fixing of these two quantities was done primarily due to time limitations, and these numbers do not in any way reflect choices for the Arctic SEV. The results do include some maneuvering and control results for other size vehicles and for speeds other than 120-knots. These results show that the variations conducted on the 500-ton craft are applicable to the entire range of vehicle sizes studied (i.e., 200–1000-ton), and that the results for the 120-knot speed runs are indicative of results for other speeds.

Computer Program Description

A three-degree-of-freedom digital simulation was written specifically for the Arctic SEV program. The program consists of craft and control inputs, resultant craft lateral, longitudinal, and yaw motions and controls output at specified time steps during the maneuver. A drawing of the geometry of the maneuver and its nomenclature are shown in Fig. 2. Forces and moments acting on the vehicle during a maneuver were calculated both in the wind and body axes. The program is capable of imposing various wind magnitudes and directions on the craft.

The program inputs may be roughly divided into three groups: those dealing with craft itself, those dealing with the various craft controls, and those inputs which select various control options in the program. Figure 3 illustrates many of these inputs. The basic program outputs are listed in Table 1: craft motions, forces and moments on the craft, and control settings.

The program is very flexible in that craft of any size and geometry, and controls of various types used on present day craft can be input to the program. The program presently includes free prop and shrouded prop thrust control routines, puff port and aerodynamic fin control routines, ground contact controls, and combinations of the above. It does not include skirt lift controls.

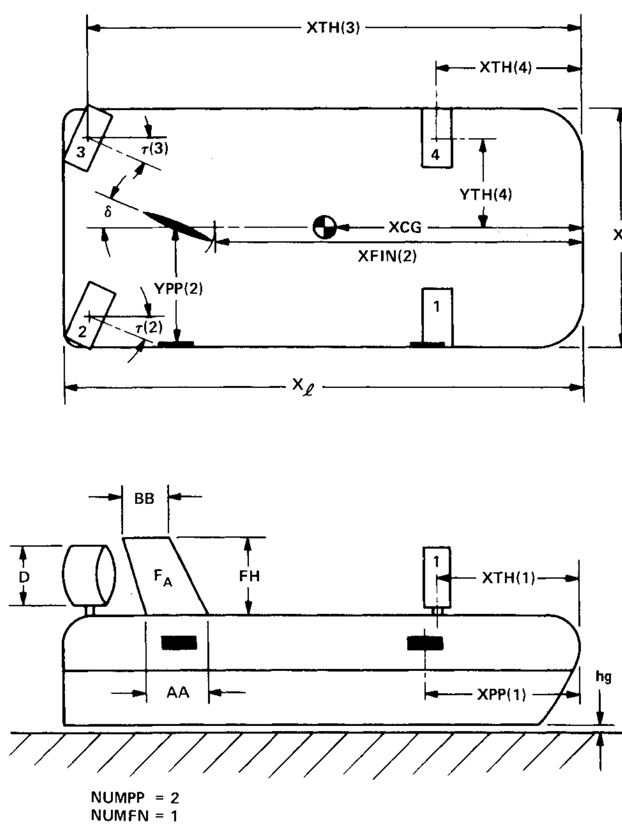

Fig. 3 Illustration of program inputs.

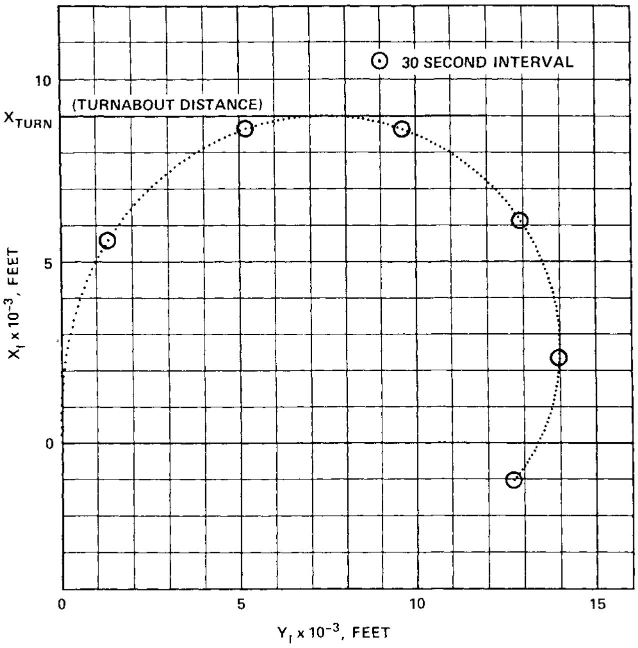

Fig. 4 Typical SEV maneuver results.

The external aerodynamic force and moment characteristics of the craft are input with an eighth order curve fit of these characteristics vs yaw angle, β. The curve fits used in this study resulted from the computer program described in Ref. 2. This aerodynamic prediction routine can be used for a variety of external SEV shapes.

Control Logic

The control logic used throughout this study is a logic which by trial and error has evolved as one workable for the craft and control types investigated in the study. It is not intended as an optimal control logic, but it has been found from experience that when the restrictions included in it are relaxed, the craft yaws uncontrollably resulting in a spin. The authors feel this logic can be improved to anticipate control reaction and reduce control and yaw angle oscillations. However, it was not within the scope of the present study to optimize the logic.

The control logic is outlined as follows for a turn to the right: The craft is allowed to yaw nose right until one of

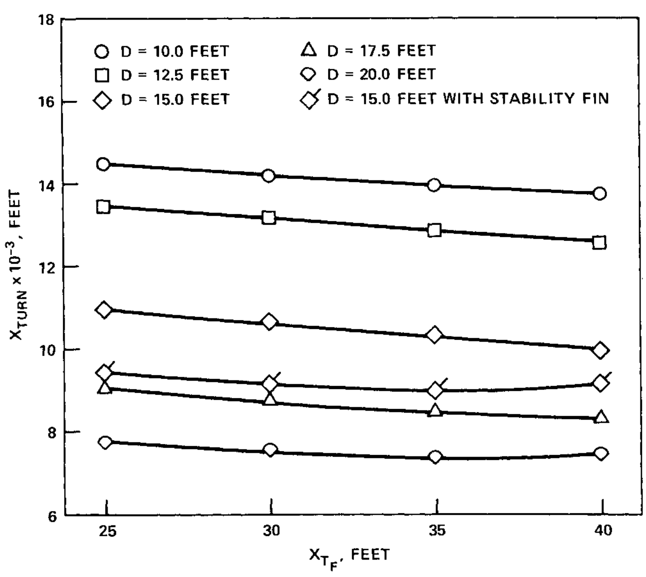

Fig. 5 Effects of variation 1 and 2 on turnabout distance.

Table 1 Program outputs

t	= time
u_B	= longitudinal velocity, body axis
v_B	= lateral velocity, body axis
$\dot{\psi}$	= ψ rate
ψ^a	= angle between X_I and longitudinal body axis
u_I	= longitudinal velocity, inertial axis
v_I	= lateral velocity, inertial axis
X_I^a	= X inertial axis
Y_I^a	= Y inertial axis
V	= total vehicle velocity relative to ground
g	= sideforce g's = side force/craft weight
β	= yaw angle
F_x, F_{xi}	= total axial force and its components in body axis system
F_y, F_{yi}	= total sideforce and its components in body axis system
M, M_i	= total moment and its components about vertical axis
δ_i, i	= $l, \ldots,$ NUMFN = fin deflection angles
τ_i, i	= $l, \ldots,$ NUMTH = thrustor deflection angles

[a]Illustrated in Fig. 2.

the maximums of Table 2 is exceeded. Controls are then actuated in the proper direction to decrease the parameter which has exceeded a maximum, but the craft is allowed to continue approaching β_{max}. When the yaw angle approaches to within a specified increment of β_{max}, the controls are reversed to anticipate overshoot. The resulting craft motion usually involves an oscillation of β within approximately $\pm 3°$ about β_{max} because of the large inertia and near zero damping characteristics of these large vehicles.

There are several maximums which are included in the control logic. These maximums can be varied, but typical values are shown in Table 2.

These preselected maximums may be exceeded (with the exception of τ, δ, $d\delta/dt$, and $d\tau/dt$); but as soon as they are exceeded during the maneuver, controls are activated to decrease their values.

One of the important aspects of this logic is that it is not meant to simulate a human pilot. The logic is probably much too complicated for a pilot to emulate in a real time situation.

Controls and Variations Investigated

There were two basic types of controls investigated in this study: thrust deflection control, and aerodynamic fin control. These are the only types of control considered adequate to develop enough side force to achieve the turnabout distance of 3 miles for a 500-ton SEV. Two types of thrust deflection controls were investigated; shrouded propellers—whose characteristics were obtained from wind-tunnel tests in Ref. 3 and digitally programed, and, free propellers—a method has been developed and programed from Ref. 4.

Two types of aerodynamic fin controls were considered[5]; controls in the freestream, and controls behind thrust devices.[4]

For the control, directional stability, and other variations investigated in this study, the craft illustrated in

Table 2 Typical maximum values

β_{max}	= 25 deg
τ_{max}	= 40 deg
δ_{max}	= 60 deg
$\left[\frac{d\tau}{dt} \text{ or } \frac{d\delta}{dt}\right]_{max}$	= 15 $\frac{\text{deg}}{\text{sec}}$
$\left[\frac{d\psi}{dt}\right]_{max}$	= 2 $\frac{\text{deg}}{\text{sec}}$
$\left[\frac{d^2\psi}{dt^2}\right]_{max}$	= 0.025 $\frac{\text{radians}}{\text{sec}^2} \simeq 1.43 \frac{\text{deg}}{\text{sec}^2}$

Fig. 1 was chosen. It is a 500-ton vehicle, 141.4 ft long and 70.7 ft wide (cushion pressure = 100 psf), and 30.0 ft high (on cushion). The c.g. was nominally chosen at half the vehicle length, though this was varied in one part of the study. Craft speed upon entering a turning maneuver was chosen as 120 knots (203 fps) but this, too, was the subject of variation in one part of the study. This speed represents a worst maneuvering case condition for the Arctic SEV. Table 3 presents the variations investigated.

Results

A typical plot of some of the results of one of the trajectories using shrouded propeller controls is presented in Fig. 4. The figure presents an X_I-Y_I plot, each point corresponding to a 1.0 sec time interval. In the Arctic SEV program, an important parameter is the maximum X_I distance travelled by the craft in a turn maneuver. This is because of the occurrence in the Arctic of long ice ridges which would necessitate either a 90° change of track of the craft to avoid collision or stopping the craft completely before hitting the obstacle. The thrust level in each of the variations following was set to equal total craft drag at zero yaw and all controls set at zero deflections. Thrust was vectored in thrust controlled turns, but thrust magnitude was never increased in order to try to maintain speed during the turn.

The effects of the variations presented in the previous section on the maximum X_I distance, which we will call turnabout distance or X_{turn}, are shown in Figs. 5–12. Figures 5–7 are all for shrouded propeller thrust controls. In each case there are four shrouded propellers, one in each quarter of the craft planform. Figure 5 presents the results of variations 1 and 2 of Table 3. For a given geometrical positioning of four shrouded propellers on the craft, it can be seen that increasing shroud diameter from 10 to 20 ft decreases X_{turn} by over 6000-ft (or about 40%). This is directly attributable to the increased side forces of the larger shrouds which not only adds directly to the turning side forces generated, but also to the control yaw moments available. This increased yaw moment allows the craft to be yawed to greater yaw angles, which increases body aerodynamic side forces, and, decreases turnabout distance.

Table 3 Variations investigated

Variation	Range of Parameters	
1. Shrouded prop size and longitudinal position of forward shrouded props	D $X_{T(F)}$	= 10′ to 20′ = −25′ to −40′
2. Shrouded prop longitudinal position of forward shrouded props with single stability fin	$X_{T(F)}$	= −25′ to −40′
3. Stability fin size (shrouded propeller size and positions are fixed)	Fin Ht	= 17.5′ to 27.5′
4. Stability fin location	$X_{F(R)}$	= −92′ to −120′
5. Stability level of craft by moving $X_{c.g.}$, $X_{T(F)}$, $X_{T(R)}$ forward on craft simultaneously	$X_{c.g.}$ $X_{T(F)}$ $X_{T(R)}$	= −70.7′ to −55.7′ = −35′ to −20′ = −114′ to −99′
6. τ_{max} and $\dot{\tau}_{max}$	$\dot{\tau}_{max}$ τ_{max}	= 25° to 40° = 10 to 25 deg/sec
7. β_{max} with thrust controlled turns-free props	β_{max}	= 10° to 25°
8. β_{max} with fin controlled turns out of thrustor slipstream-free props	β_{max}	= 10° to 25°
9. Same as 8 with shrouded props	β_{max}	= 10° to 25°
10. Same as 8 with fins in thrustor slipstream	β_{max}	= 10° to 25°
11. Same as 10 with shrouded props	β_{max}	= 10° to 25°

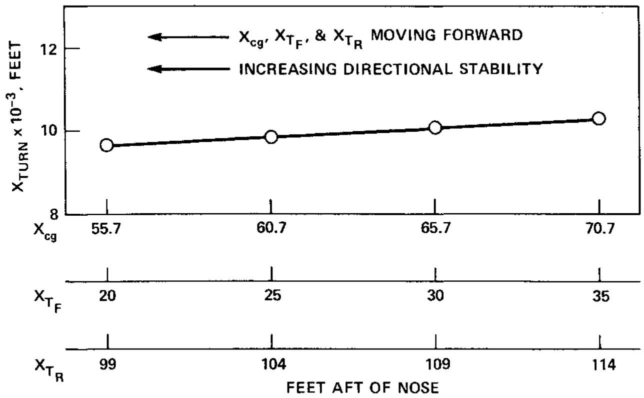

Fig. 6 Effects of variation 5 on turnabout distance.

In addition, Fig. 5 presents the effects of forward thruster positioning on the turnabout distance. Moving the front two thrusters from 25-ft aft of the nose to 40-ft aft of the nose, decreases the turnabout distance approximately 1000-ft (or about 9%) for the 15-ft-diam shrouded props. This can be explained as follows: Moving the forward thrustors rearward on the craft allows greater deflection angles, τ's, for a given amount of control (yaw moment)–thus, the average side force generated by the thrustors during the turn is increased.

Also presented in Fig. 5 is the effect of adding a stability fin to the configuration with four 15-ft-diam shrouded props. It can be seen that the addition of a fin 17.5-ft high, 106-ft rearward of the nose, decreases X_{turn} between 1000- to 1500-ft (8% to 13% decrease), depending on forward thrustor position $X_{T(F)}$.

Variations in stability fin size and location (variations 3 and 4 of Table 3) were made to determine the effect of varying craft directional stability. There is little effect on the turnabout distance for either of these variations. Increasing the fin size (aft of the c.g.) or distance from the nose increases the directional stability of the craft. Also, fin size increases the amount of generated side force at a given β. However, the gains in side force and directional stability are offset by a reduction in the rear propulsor deflections and, thus, their side force contribution. This is because of the limited amount of control moment that can be generated by the forward thrustors. Therefore, there is no net gain in side force during the maneuver and turnabout distance is not affected.

In Fig. 6 the effects of moving $X_{c.g.}$ forward on the craft (i.e., increased aerodynamic directional stability on X_{turn}) are presented. $X_{T(F)}$ and $X_{T(R)}$ are moved forward with the c.g. to maintain control moments. It appears that increasing craft stability in this manner decreases the turnabout distance (about 500-ft or 5% in the case shown here). This effect is explained by the fact that increased stability requires higher average propulsor de-

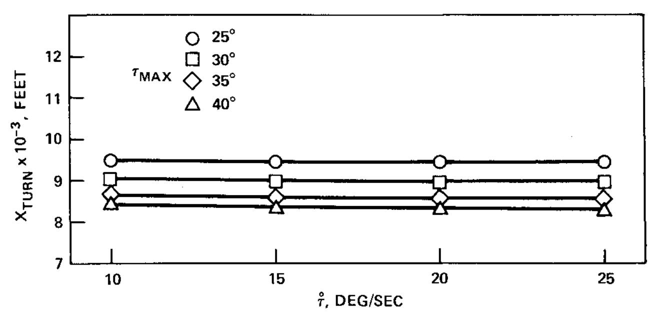

Fig. 7 Effects of variation 6 on turnabout distance.

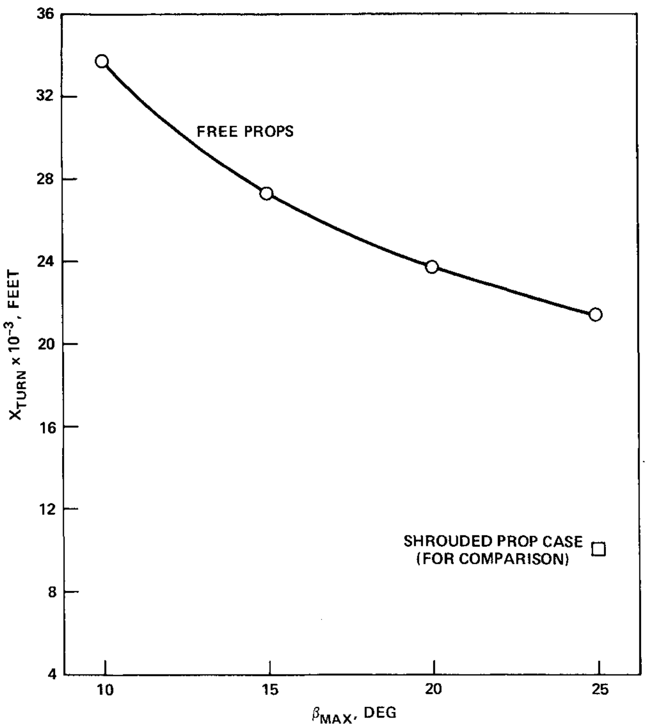

Fig. 8 Effects of variation 7 on turnabout distance.

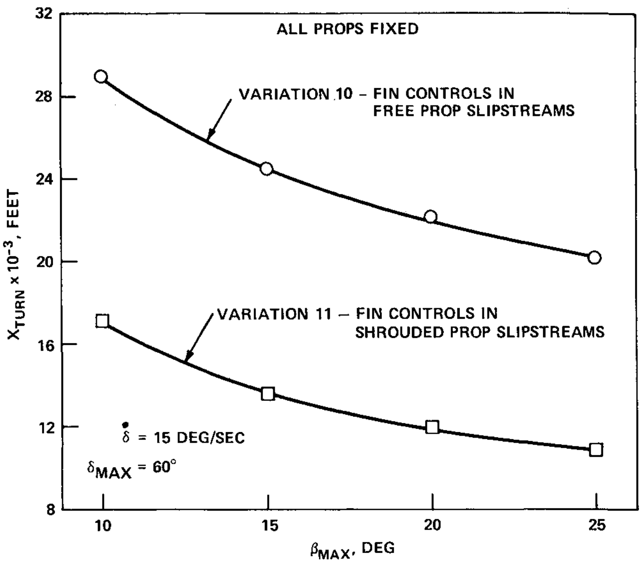

Fig. 10 Effects of variations 10 and 11 on turnabout distance.

flection angles to maintain the craft at a fixed yaw angle. This means higher average side forces generated by the thrust controls.

Figure 7 presents the effects of increasing the maximum thrust control deflection angle allowable, τ_{max}, and the deflection rate, $\dot{\tau}$. $\dot{\tau}$ appears to have little effect, but increasing τ_{max} from 25° to 40° has the effect of decreasing X_{turn} by about 1000-ft or 11%. This is due simply to the higher operating τ's and, thus, higher side forces generated by the thrustors. At τ's greater than 40°, stall problems are incurred, and this is why higher τ angle results are omitted.

Figure 8 presents some results for a craft using four free propellers as control devices. The variation is β_{max}, i.e., the maximum allowable yaw angle of the craft. It can be seen that allowing the craft to yaw to 25° β instead of 10° β reduces the X_{turn} by 12,000-ft or 35%. This is a direct result of the higher side forces generated. Thus, an extremely good case can be made for flying the craft at high yaw angles during turning; however, allowable yaw angles of much greater than 25° results in the craft becoming uncontrollable due to high unstable yaw moments developed by body aerodynamics and the inability of the free propellers to counteract these yawing moments. However, body generated side force increases with β up to 45°, so that if the craft could be controlled, it is possible that even higher yaw angles would be desirable, and this might well be the case with craft having body aerodynamic characteristics which are more directionally stable than this vehicle. Also shown in Fig. 8 is a shrouded prop case (all four located at the same positions as the four free props) to show the relative turnabout distances of free and shrouded props. The results of the much higher side forces generated by shrouded props is evident.

Variations 8 and 9 are shown in Fig. 9 for fin controlled turns. (The props are locked at $\tau = 0$.) The fins are not in thrustor slipstreams. Variation 8 shows the results of β_{max}

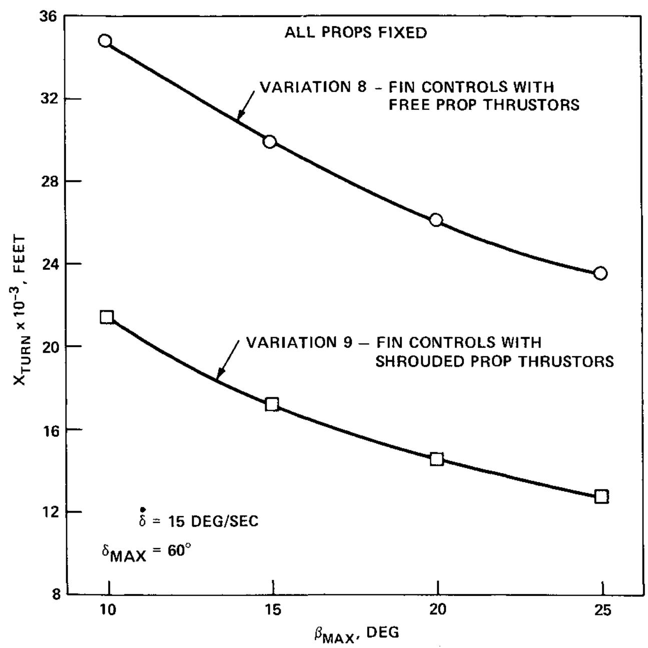

Fig. 9 Effects of variations 8 and 9 on turnabout distance.

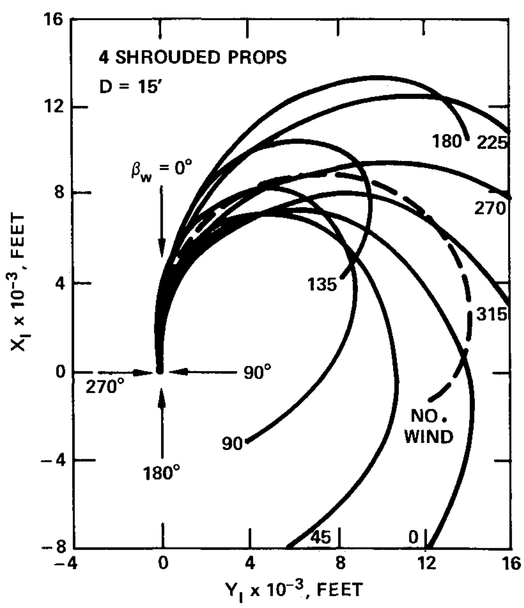

Fig. 11 Effects of 25 knot wind direction on turning of a 500-ton SEV.

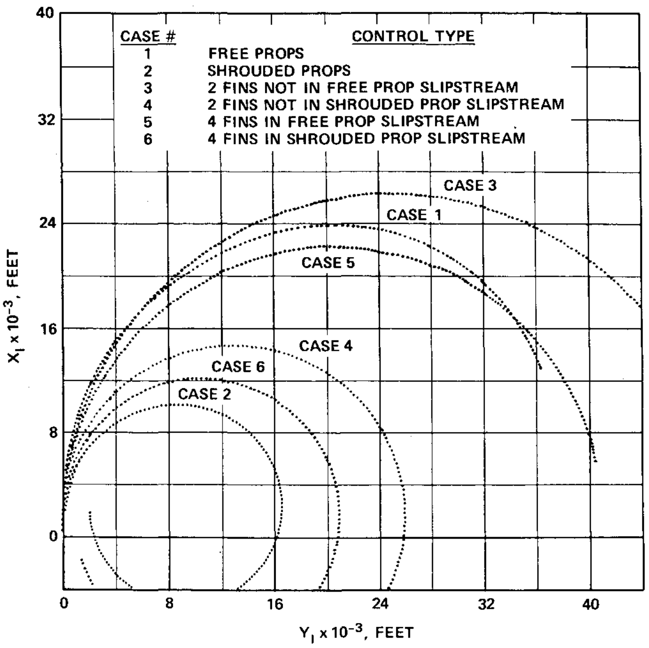

Fig. 12 Effects of control type on vehicle maneuvers.

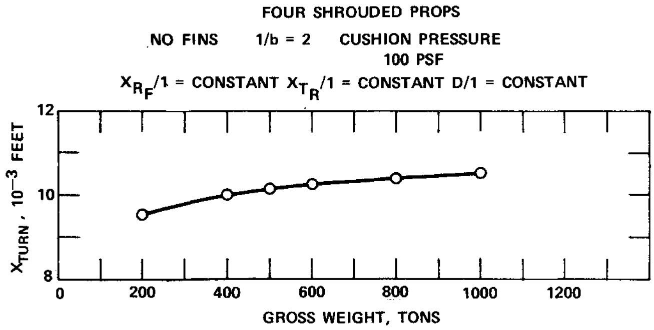

Fig. 14 Effect of gross weight on turnabout distance.

on a fin controlled, free prop propelled craft, and variation 9, the results of β_{max} on a fin controlled, shrouded prop propelled craft. For both variations, the craft was controlled by two 27.5-ft high fins located at 30 and 106-ft aft of the nose on the craft's longitudinal centerline. Again, the desirability of maneuvering at high yaw angles is pointed out.

Variations 10 and 11 are presented in Fig. 10 again for fin controls and the props locked. However, in this case there are four 17.5-ft high fins mounted in the slipstream of both free props and shrouded props. Large β_{max}'s are again proved desirable, and the advantage of using shrouded props over free props, even when the props are not used as the active control devices, is shown.

Also investigated in the present study is the effect of environmental winds at various headings to the craft. These winds are important to the maneuvering. Shown in Fig. 11 is the effect of a 25 knot wind at various headings to the craft on the X_I-Y_I plot of a turning maneuver. For reference, the basic case with no wind is presented. All the cases are for the 500-ton vehicle with four 15-ft-diam ducted props as control devices. β_{max} was kept at 25° for all these wind cases. As expected, tail winds (β_w = 135°, 180°, 225°) have a rather deleterious effect on turnabout distance, increasing this distance as much as 46%. This degradation can be expected to be even more dramatic at craft initial speeds lower than 120 knots, especially where wind speeds approach or exceed craft initial velocity.

Figure 12 summarizes the turning maneuvers resulting from the various types of control devices used in this study. An X_I vs Y_I plot for 6 cases is presented. These cases are not entirely dependent on just the control type. For example, the difference between cases 1 and 5 is not only free prop controls and fin controls, but also total fin areas and the fin positions are different. However β_{max} = 20° for each case, and each case was chosen to represent a good turn of those investigated for each control type. Each dot presents a data point at 2-sec intervals and each turn has been arbitrarily terminated at 360 sec.

It is evident from this figure that the shrouded props produce the best turns (cases 2, 6, and 4). Also, it is advantageous to use fin controls mounted such that they take advantage of thrustor slipstream effects. If a three mile turnabout distance requirement indeed results from the obstacle avoidance system and skirt designs, only the shrouded prop controls are capable of producing the required turns.

It is hoped that the preceeding results give an indication of the kinds of controls required for maneuvering large SEV's in the Arctic and the magnitudes of the turning capabilities of these large craft. From strictly the maneuvering standpoint, it appears highly desirable to use shrouded propellers as propulsion and maneuvering devices. However, at least four 15-ft-diam shrouded props will be required to achieve the desired maneuvering forces considering winds. Another approach to the maneuvering problem is the use of combinations of several types of controls to produce the required side force. The use of shrouded propellers in combination with aerodynamic fins in the prop slipstream appears particularly attractive.

The results of this study also indicate that maneuvering at large yaw angles is not only desirable, but may be necessary in order to take advantage of the high aerodynamic side forces generated by the body in achieving the necessary turns. In this study β_{max} was limited to 25° as a re-

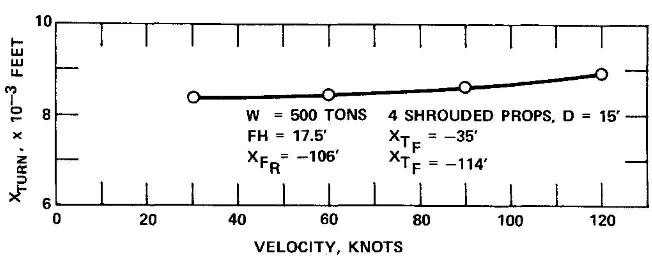

Fig. 13 Effects of initial velocity on turnabout distance.

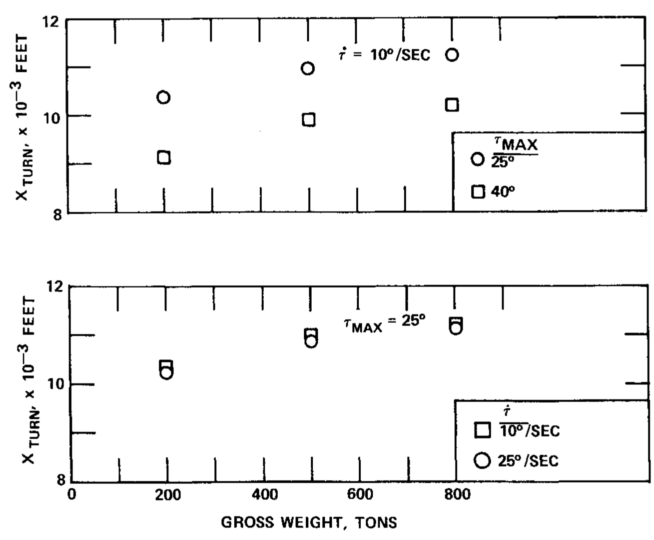

Fig. 15 Effects of gross weight on variation 6.

sult of the lack of control moment required to offset the yaw moment at angles greater than 25°. Operating control devices to the highest possible deflection angles without entering into stall regions is required to minimize turnabout distance. Though investigations of craft aerodynamic directional stability variations were limited, preliminary indications are that craft configurations approaching neutral static stability combine the best of the two worlds of controllability and quick response to control inputs.

All data presented have been for a 500-ton vehicle at a speed of 120 knots. This speed was chosen as being the upper limit of cruise velocity for this size of SEV's. Figure 13 presents the effects of varying the initial velocity on the turnabout distance for a 500-ton SEV. The 120 knot case represents the greatest distance required to turn, but initial velocity has little effect of X_{turn} for this vehicle. This can be explained by the fact that the aerodynamic forces decrease as the square of the velocity decreases. Therefore, although the craft has a longer period of time to maneuver, the available forces, both body aerodynamic side force and thrust, have decreased significantly.

The 500-ton SEV was chosen as being a representative vehicle size for the Arctic SEV. The effect of gross weight on the turnabout distance, X_{turn} is presented in Fig. 14. X_{turn} increases 1000-ft from a 200-ton craft to a 1000-ton craft.

To illustrate that the variations presented for a 500-ton SEV would be applicable to the entire range of vehicle sizes, Fig. 15 is presented. Two variations are shown, the effects of varying maximum propulsor deflection angles (τ_{max}) and varying propulsor deflection rate ($\dot{\tau}$). It is shown that varying the size of the vehicle does not significantly affect the results of the variation.

It is felt that the information presented in this paper is applicable to the entire weight range of craft that are being considered for operation in the Arctic (i.e., 200- to 1000-tons).

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Ram Wing Surface Effect Boat

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The development of an efficient, stable, self-trimming ram wing vehicle for operation over water is described. It has long been recognized that low aspect ratio (and, therefore, structurally efficient) wings have very high lift over drag ratios when operated in close proximity of a surface. An apparent static pitch and heave instability has prevented the design of practical ram wing vehicles until recently. This paper describes the design, wind-tunnel testing and radio controlled model testing of a two-man ram-wing boat, which (at full scale) would have a gross weight of 1500 lb and cruise at 70 mph over 1-ft waves.

Nomenclature

c = chord
$C_D = 2D/\rho V^2 sc$ = drag coefficient
$C_L = 2L/\rho V^2 sc$ = lift coefficient
$C_M = 2M/\rho V^2 sc^2$ = pitching moment coefficient
$C_p = 2p/\rho V^2$ = pressure coefficient
D = drag
g = acceleration of gravity
$H = 20h/s$ = nondimensional ground clearance parameter
h = height of gap under side plates
L = lift
M = pitching moment
p = gage pressure
s = span between side plates, or width of channel
V = freestream velocity
γ = angle-of-attack with respect to bottom edge of side plate
ρ = air density

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Introduction

KARRIO[1,2] was the first (1932–1949) to operate a ram wing vehicle and comment on a static pitch and heave instability which has prevented the development of the ram wing until quite recently. In Karrio's words—"It was noted with the scale model that when the speed was considerably in excess of the takeoff speed, the wing tended to lose its stability and rise too high from the surface." Karrio's tailess vehicles were statically unstable far from the surface representing a severe hazard should they bounce into the air after striking the surface.

The Kawasaki[3,4] ram wing exhibited a similar instability and several stabilizers were tried. They eventually settled on a large stabilizer at the rear of each float extending outboard of the main span and with considerable dihedral. Even this tail did not result in static pitch stability near the ground, and could only be used because the vehicle was intended to always touch the water thus providing the required stability.