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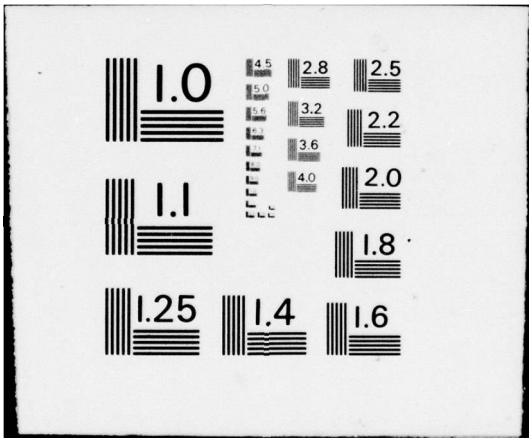
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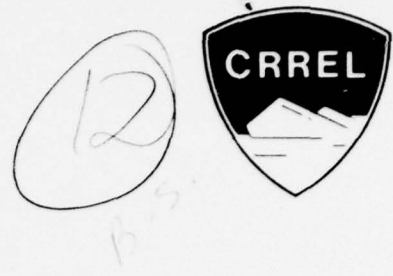
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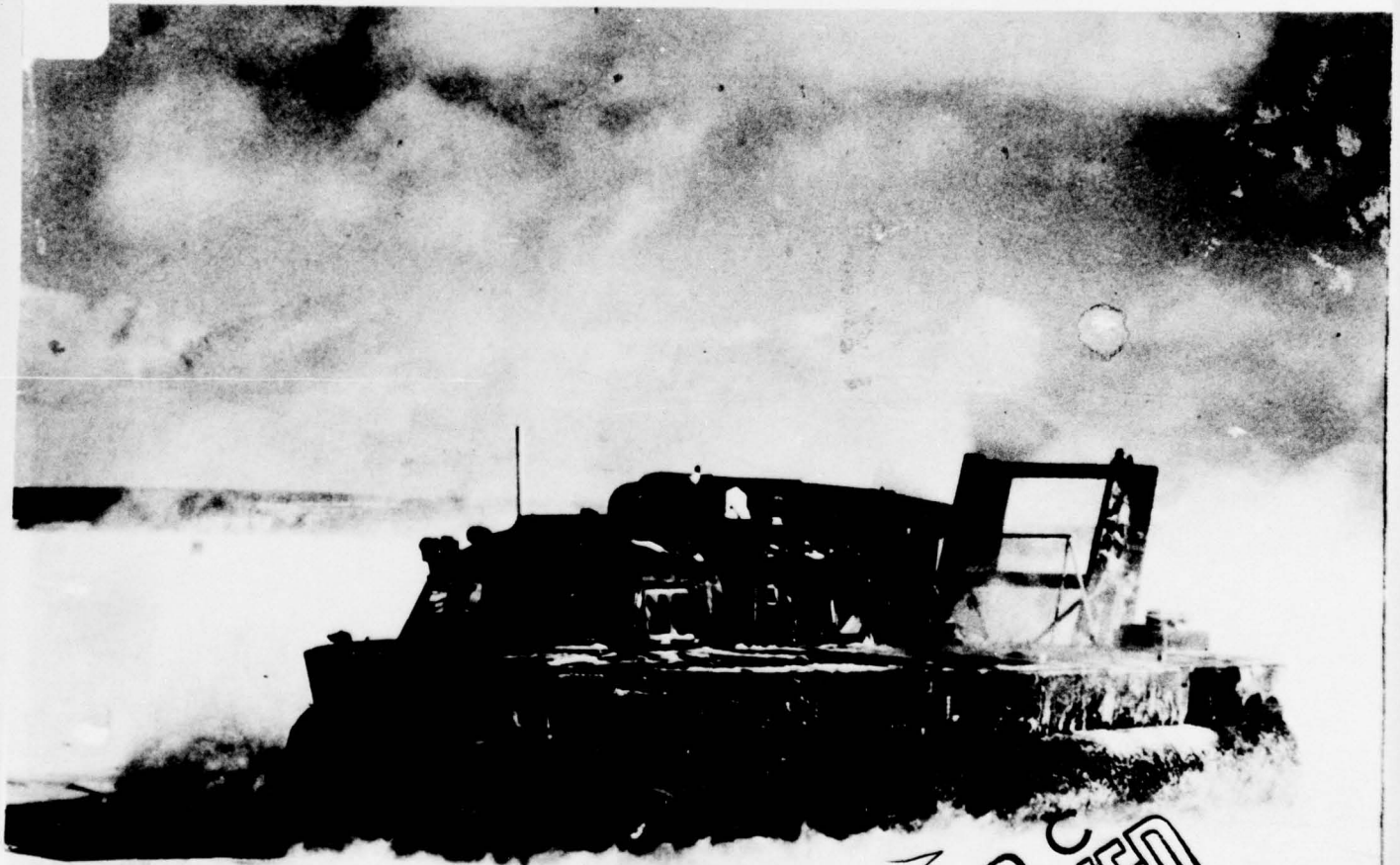
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REPORT 76-45



*Air cushion vehicle  
ground contact directional control devices*



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*Cover: SK-5 air cushion vehicle during over-snow  
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# CRREL Report 76-45

## *Air cushion vehicle ground contact directional control devices*

Gunars Abele and Ronald A. Liston

December 1976

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER Special Report 76-45	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) AIR CUSHION VEHICLE GROUND CONTACT DIRECTIONAL CONTROL DEVICES,		5. TYPE OF REPORT & PERIOD COVERED	
7. AUTHOR(s) Gunars Abele and Ronald A. Liston		6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		8. CONTRACT OR GRANT NUMBER(s)	
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, N.H. 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA Project 4A161101A91D Task 03 Work Unit 194	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE December 1976	
15. SECURITY CLASS. (of this report) Unclassified		13. NUMBER OF PAGES 22	
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. <b>14</b> CRREL-SR-76-45		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
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) Air cushion vehicles Ground effect machines Moments Skirts Wheels			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The maneuverability of air cushion vehicles can become a serious operational problem when the vehicle's travel route is restricted by obstacles, slopes or cross-wind conditions, or when close-quarter turns are required. While improvement and perfection of aerodynamic methods may be a more desirable approach, there is a practical limit to these methods, and the use of ground contact devices requires consideration for providing more positive directional control. Wheels deserve special attention, and therefore are analyzed in more detail because of their obvious application on a variety of land terrains. Brake rods and harrows are more suitable on water, ice and snow. The saucer-shaped ground contact device would cause the least ecological impact on fragile organic terrains such as tundra.			

## 20. Abstract (cont'd)

Relative directional stability is evaluated in terms of the total yawing moments produced by wheel arrangements (single, dual, tandem), location on the vehicle, and operational modes (free-rolling, braked, or a combination of the two). The available moments are plotted against the yaw angle of the vehicle to determine the most effective operational mode with a particular wheel arrangement for any yaw condition. The analysis is limited to retractable devices which act as moment producing brakes or rollers and do not serve as either propulsion or load support aids. Controlled ground contact with skirt sections having special wearing surfaces may provide a suitable control method and would require the least significant change to the basic design of the vehicle or its components. The concept involves the use of an air flow control mechanism for deflating specific skirt sections, thus causing skirt-ground contact at selected areas of the peripheral skirt.

## PREFACE

Section I of this study was prepared by Gunars Abele, Research Civil Engineer, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Section II was prepared by Dr. Ronald A. Liston, Chief, Applied Research Branch, Experimental Engineering Division, CRREL. The work was performed under DA Project 4A161101A91D/03 *In-House Laboratory Independent Research*, Work Unit 194.

B. Hanamoto of CRREL technically reviewed the manuscript.

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## NOMENCLATURE

$W$	vertical load on one wheel
$W_T$	vehicle weight
$\mu$	coefficient of friction between wheel (tire) and hard ground
$F$	sideforce produced by one wheel = $W\mu$
$F_T$	turning force
$M$	yawing moment (for correcting sideslip)
$M_F$	moment produced by one wheel in a free-rolling mode
$M_B$	moment produced by one wheel in a braked and skidding mode
$M_{(i)}$	moment produced by the wheel on the leading side of the vehicle in yaw (referred to as the inside wheel)
$M_{(o)}$	moment produced by the wheel on the trailing side of the vehicle in yaw (referred to as the outside wheel)
$\beta$	yaw angle (angle between vehicle centerline and actual travel direction)
$\omega$	angular velocity
$m$	vehicle mass
$r$	turning radius
$x$	longitudinal distance from the center of gravity to the axis of the wheel
$y$	lateral distance from the center of gravity to the centerline of the wheel
$V$	travel speed

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI)  
UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

<i>Multiply</i>	<i>By</i>	<i>To obtain</i>
inch	25.4*	millimeter
foot	0.3048*	meter
mile/hour	1.609344*	kilometer/hour
pound-mass	0.4535924	kilogram
foot-pound-force	1.355818	joule

\* Exact.

## AIR CUSHION VEHICLE GROUND CONTACT DIRECTIONAL CONTROL DEVICES

Gunars Abele and Ronald A. Liston

### SECTION I: USE OF AUXILIARY DEVICES FOR ACV CONTROL

#### INTRODUCTION

One of the principal advantages of using an air cushion as the suspension system of a vehicle is the lack of contact between the vehicle and the terrain surface, thus making the vehicle's operational capabilities independent of the mechanical characteristics of the terrain surface material. The air cushion vehicle (ACV) is capable of traveling equally well on mineral and organic terrains, water, snow, ice, or a combination of any of these, its operation being constrained primarily by surface relief geometry and obstacles.

The advantage of not having contact between the vehicle and the terrain surface has to be regarded, however, as a disadvantage from a maneuverability point of view. Not only thrust but also control of an amphibian ACV has to be achieved primarily by aerodynamic means (rudders, puff ports, direction of propeller thrust by pylon rotation, etc.), which have a relatively slow response time and lack the directional control precision of a conventional ground contact vehicle. Consequently, maneuverability of an ACV can become a serious operational problem where the vehicle's travel route is restricted by obstacles and steep slopes or when close-quarter turns are required.

While experience has shown that improvement and perfection of aerodynamic methods would be the more desirable approach for improved directional control, there is a practical limit to these methods; therefore, the use of ground contact devices requires consideration for providing more positive results.

The concept of ground control for ACV's itself is by no means new. Retractable wheels were used on the Bell Carabao (Chaplin 1964), and were later converted to harrow disks for use on snow on the Greenland Ice Cap in 1964 (Abele 1966). For marine operations, hydraulically lowered tubes ("water rods") have been used by the Japanese on the MV-PP1 and MV-PP5 ACV's; on the MV-PP15 ACV, wheels with brakes were attached to the rods. The use of wheels, not only for directional control but also for propulsion and load support, has been discussed by Wong (1972). The use of ground contact aids for purposes other than directional control, and the relative merits of hybrid ACV's vs pure amphibian ACV's are not within the scope of this study. The discussion here is limited to retractable ground contact devices or implements which act as moment producing brakes or rollers and do not serve as either propulsion or load support aids.

To improve the directional control of an amphibious ACV, the wheel is naturally the first idea that comes to mind when considering over-land operations. For over-water and snow operations, some type of a brake in the form of a rod, a disk, or a skid would be the logical initial selection. The use of the flexible skirt itself, or some simple attachments to it, may be an idea which has not been fully investigated.

Usually the most critical maneuvering problems are encountered during over-land operations. Ordinary ACV operations on water, except for special tasks or travel on narrow streams, are not as frequently constrained by "elbow room" as are those on land. It therefore appears reasonable in considering ACV control improvements to consider first those ground contact devices which would be applicable to over-land maneuverability. It is reasonable to expect that a device

suitable on land may also be suitable in water, while the opposite may not necessarily be true (the "water rod" being a typical example). It is also necessary to keep in mind the potential damage that could result from such a device when used on certain types of organic terrains (tundra, for example). Therefore, the wheel deserves some attention because it is the most obvious ground control device, and the use of the flexible skirt should be considered because it may represent the least significant change to the basic design of the vehicle or its components.

## DISCUSSION OF WHEELS AS A CONTROL DEVICE

Analysis of the relative effectiveness of one or more wheels as a control device for the directional stability of an ACV is based in this discussion on the following conditions: 1) the wheels can be used in either a free-rolling or a braked and skidding mode, 2) the wheels are retractable, and 3) the wheels are not steerable. For the purpose of comparing the relative effectiveness of various wheel configurations and locations on the vehicle, only cases of contact with hard ground (no wheel sinkage) are considered here.

Five wheel arrangement configurations and accompanying operational modes (free-rolling, braked and skidding, or lifted) are analyzed and listed in Table I. Figure 1 gives the nomenclature of the terms used in the report.

### Dual wheels

Six operational modes are practicable for use with dual wheel arrangements.

*Mode A: Wheels free-rolling.* When the wheels are free to rotate on the axle, the only direction in which the side force can act is along the axle (refer to Fig. 1). Therefore, the yawing moment produced by each wheel is

$$M_F = Fx \quad (1)$$

and the total moment for both wheels (inside and outside) is

$$M_{F(i,o)} = 2Fx \quad (2)$$

where  $F$  is the sideforce produced by one wheel and  $x$  is the longitudinal distance from the ACV's center of gravity to the axis of the wheel.

In the case of free-rolling wheels, the yawing moment is independent of yaw angle  $\beta$ , distance  $y$ , and velocity  $V$ , except for any effect  $V$  may have on the coefficient of friction  $\mu$ . The yawing moment available for directional stability is a direct function of the longitudinal distance  $x$ . On a soft surface where wheel sinkage can occur, other force components, such as bulldozing and compaction resistance, and the lateral force on the sidewall of the wheel, would have to be considered. Here only the vertical load on each wheel  $W$  and  $\mu$  are considered; the rolling resistance is assumed to be minimal:

$$F = W\mu.$$

*Mode B: Wheels braked and skidding.* When dual wheels are in a non-rotating mode, the force will act along the direction of motion (refer to Fig. 1). Therefore, the moment arms are

Table I. Wheel arrangements and operational modes analyzed.

Mode	Arrangement*				
	Dual wheels		Single wheel	Tandem wheels	
	Inside	Outside	Rear	Front	Rear
A	Free	Free	Free	Free	Free
B	Braked	Braked	Braked	Braked	Braked
C	Braked	Free		Braked	Free
D	Free	Braked		Free	Braked
E	Free	Lifted			
F	Braked	Lifted			

\*Arrangements are illustrated in Figure 2.

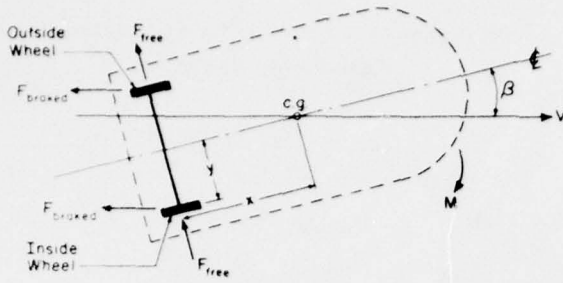


Figure 1. Schematic diagram of ACV.

inside wheel:  $y \cos \beta + x \sin \beta$

outside wheel:  $y \cos \beta - x \sin \beta$

and the corresponding moments are

$$M_{B(i)} = F(y \cos \beta + x \sin \beta) \quad (3)$$

$$M_{B(o)} = -F(y \cos \beta - x \sin \beta). \quad (4)$$

The total available yawing moment is

$$\begin{aligned} M_{B(i,o)} &= M_{B(i)} + M_{B(o)} = F(y \cos \beta + x \sin \beta) \\ &\quad + (-F)(y \cos \beta - x \sin \beta) = 2Fx \sin \beta. \end{aligned} \quad (5)$$

Equation 5 is still applicable when, as a result of a high  $\beta$ , both wheels are on the same side of the line of travel, the respective moments being

$$M_{B(i)} = F(y \cos \beta + x \sin \beta)$$

$$M_{B(o)} = F(-y \cos \beta + x \sin \beta)$$

resulting in the same total moment as eq 5:

$$M_{B(i,o)} = M_{B(i)} + M_{B(o)} = 2Fx \sin \beta.$$

Comparing eq 2 and 5:

$$2Fx > 2Fx \sin \beta$$

that is,

$$M_{F(i,o)} > M_{B(i,o)}$$

the relationship being

$$M_B/M_F = \sin \beta.$$

A higher yawing moment can be achieved with the wheels in the free-rolling mode than with the wheels braked.

*Mode C: Inside wheel braked and skidding, outside wheel free-rolling.* From eq 3 and 1 the respective moments are

$$M_{B(i)} = F(y \cos \beta + x \sin \beta)$$

$$M_{F(o)} = Fx.$$

The total available yawing moment is

$$\begin{aligned} M_{B(i)F(o)} &= M_{B(i)} + M_{F(o)} = F(y \cos \beta + x \sin \beta) + Fx \\ &= Fx(1 + y/x \cos \beta + \sin \beta). \end{aligned} \quad (6)$$

*Mode D: Inside wheel free-rolling, outside wheel braked and skidding.* From eq 1 and 4 the inside and outside wheel moments are

$$M_{F(i)} = Fx$$

$$M_{B(o)} = -F(y \cos \beta - x \sin \beta).$$

The total available yawing moment is

$$\begin{aligned} M_{F(i)B(o)} &= M_{F(i)} + M_{B(o)} = Fx + (-F)(y \cos \beta - x \sin \beta) \\ &= Fx(1 - y/x \cos \beta + \sin \beta). \end{aligned} \quad (7)$$

Since the wheels, of necessity, would have to be retractable, two more cases exist. With the outside wheel lifted, the inside wheel alone can be used for directional stability, either in a free-rolling or braked and skidding mode (refer to Fig. 1). Using the outside wheel, with the inside wheel lifted, is not practical, since a negative moment results.

Mode E: Inside wheel free-rolling, outside wheel lifted. The yawing moment equation for this case is the same as eq 1:

$$M_{F(i)} = Fx.$$

Mode F: Inside wheel braked and skidding, outside wheel lifted. From eq 3:

$$\begin{aligned} M_{B(i)} &= F(y \cos \beta + x \sin \beta) \\ &= Fx(y/x \cos \beta + \sin \beta). \end{aligned} \quad (8)$$

*Comparison.* The yawing moment equations for the six cases are compared in Table II. In any mode where braking of either one or both wheels is involved, the yawing moment is a function of the yaw angle  $\beta$ . When only one wheel is braked, the moment is also a function of the  $y/x$  ratio.

To compare the relative effectiveness of the six wheel mode cases on the directional stability of the ACV, some practical  $y/x$  ratios have to be selected. Since the center of gravity is usually somewhere near the geometric center of the vehicle, the maximum practical  $x$  distance would be limited to not more than approximately  $1/2$  of the vehicle's structural length. Since the length/beam ratios of ACV's are usually close to 2, the maximum practical  $y$  distance would be approximately  $1/2$  of the maximum  $x$  distance. For convenience,  $1/2$  of the vehicle length will be considered as a unit of measurement of  $x$  and  $y$ . Therefore, the value of  $x$  can vary from 0 to 1 and the value of  $y$  from 0 to  $1/2$ , the typical  $y/x$  ratios ranging from  $1/2$  to 1.

For the sake of comparison, the more likely wheel location arrangements were selected as shown in Figure 2. The moments, computed for various yaw angle  $\beta$  conditions and  $y/x$  ratios of 1 and  $1/2$ , are summarized in Table III and are plotted in Figures 3, 5 and 6.

For arrangement 2, where  $y/x = 1$  (Fig. 3b), it is evident that for any yaw angle, the highest yawing moment can be achieved by having the inside wheel braked and skidding and the outside wheel in a free-rolling mode (mode C). The next most effective procedure is to have both wheels in a free-rolling position (mode A), which produces the same moment regardless of the yaw angle. Mode B, both wheels in a braked position, is not an effective control method for small yaw angles; a higher moment can be achieved by using only the inside wheel in either a braked position (for  $\beta < 45^\circ$ ) or

Table II. Yawing moments for the six operational modes of a dual wheel arrangement.

Case	Total yawing moment
A	$M_{F(i,o)} = Fx$ (2)
B	$M_{B(i,o)} = Fx$ ( $2 \sin \beta$ )
C	$M_{B(i)F(o)} = Fx$ ( $\sin \beta + y/x \cos \beta + 1$ )
D	$M_{F(i)B(o)} = Fx$ ( $\sin \beta - y/x \cos \beta + 1$ )
E	$M_{F(i)} = Fx$
F	$M_{B(i)} = Fx$ ( $\sin \beta + y/x \cos \beta$ )

in a free-rolling position (for  $\beta < 30^\circ$ ) with the outside wheel lifted.

In arrangements 1 and 3 where  $y/x = 1/2$  (Fig. 3a and 3c) for yaw angles of less than approximately  $40^\circ$ , the highest yawing moment can be obtained by having both wheels in a free-rolling mode (mode A). For  $\beta > 40^\circ$ , a slightly higher moment is achieved with the inside wheel braked and skidding and the outside wheel free-rolling (mode C).

It should be noted that the numerical value of  $M$  for arrangement 3 is exactly twice that of arrangement 1, since the  $x$  value in arrangement 3 is twice the  $x$  value in arrangement 1. (The  $M_3 = 2M_1$  relationship is implied in the relative scale of the  $M$  axis in Figures 3a and 3c.) Everything else being equal, the value of  $M$  varies directly with the value of  $x$  for all wheel mode cases (refer to Table II).

For maximum directional stability with a dual wheel arrangement, the most effective wheel location is as close as possible to the rear corners of the vehicle, as shown in arrangement 3. For any  $y/x$  ratio, the available yawing moment is proportional to the longitudinal distance  $x$  for all braked and free-rolling wheel combinations. The influence of the lateral distance  $y$  is relatively less significant, since in the moment equations (Table II)  $y$  appears only in the  $y/x$  term. For free-rolling modes, the moment is independent of  $y$ .

Figure 4 shows the  $\beta$  vs  $y/x$  relationship at which the yawing moment for both wheels free-wheeling (mode A) equals the moment for inside wheel braked and skidding, and outside wheel free-rolling (mode C); i.e.

$$M_{F(i,o)} = M_{B(i)F(o)}.$$



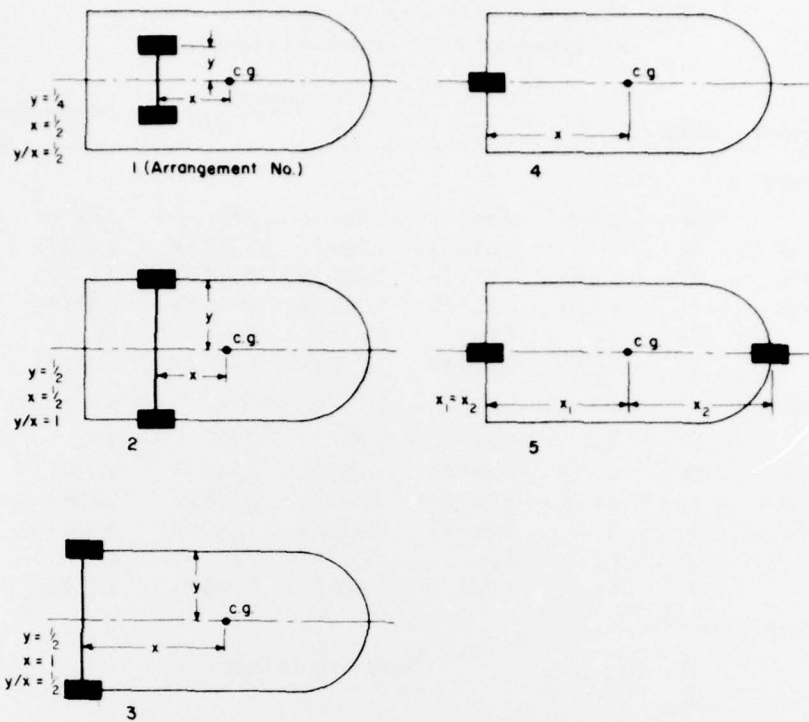


Figure 2. Wheel arrangements.

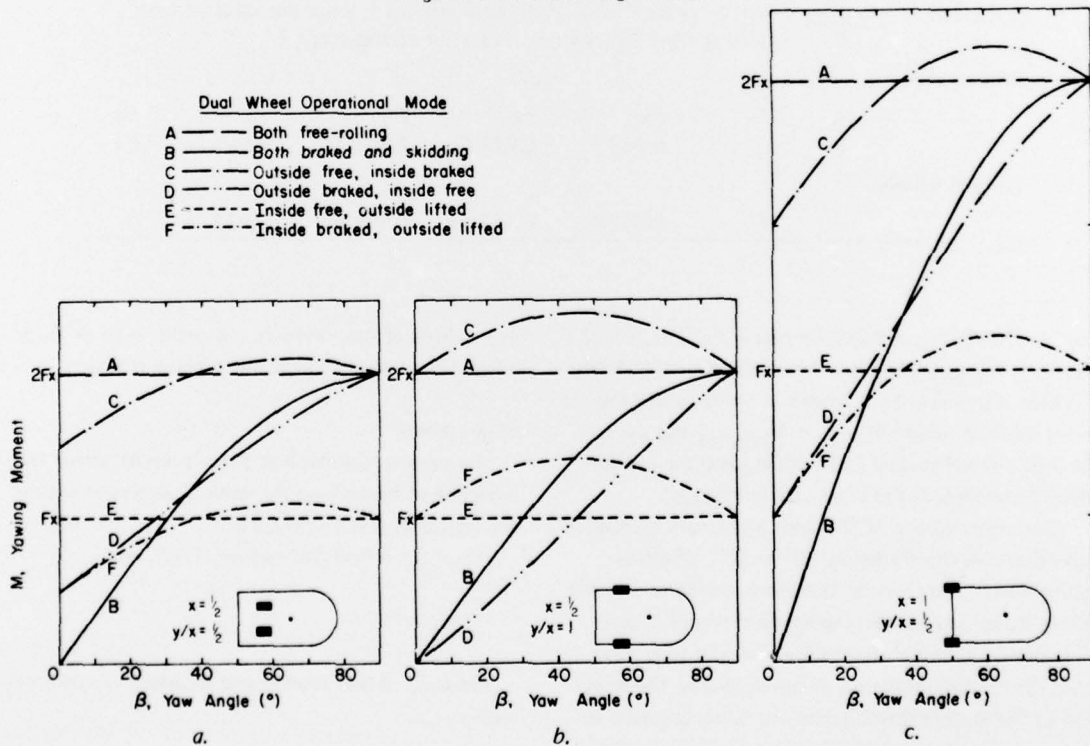


Figure 3. Yawing moment vs yaw angle for wheel arrangements 1-3.

Table III. Moments, in terms of  $F_x$ , of various wheel arrangements and operational modes for various yaw angles.

Arrangement	Mode	Yaw angle, $\beta$					
		$0^\circ$	$20^\circ$	$40^\circ$	$60^\circ$	$80^\circ$	$90^\circ$
<b>Dual wheels</b>							
1	A	$2 F_x$	$2 F_x$	$2 F_x$	$2 F_x$	$2 F_x$	$2 F_x$
	B	0	$0.684 F_x$	$1.286 F_x$	$1.732 F_x$	$1.970 F_x$	$2 F_x$
	C	$1.5 F_x$	$1.812 F_x$	$2.026 F_x$	$2.116 F_x$	$2.072 F_x$	$2 F_x$
	D	$0.5 F_x$	$0.872 F_x$	$1.260 F_x$	$1.616 F_x$	$1.898 F_x$	$2 F_x$
	E	$F_x$	$F_x$	$F_x$	$F_x$	$F_x$	$F_x$
	F	$0.5 F_x$	$0.812 F_x$	$1.026 F_x$	$1.116 F_x$	$1.072 F_x$	$F_x$
<b>Dual wheels</b>							
2	A	$2 F_x$	$2 F_x$	$2 F_x$	$2 F_x$	$2 F_x$	$2 F_x$
	B	0	$0.684 F_x$	$1.286 F_x$	$1.732 F_x$	$1.970 F_x$	$2 F_x$
	C	$2 F_x$	$2.282 F_x$	$2.409 F_x$	$2.366 F_x$	$2.159 F_x$	$2 F_x$
	D	0	$0.402 F_x$	$0.877 F_x$	$1.366 F_x$	$1.811 F_x$	$2 F_x$
	E	$F_x$	$F_x$	$F_x$	$F_x$	$F_x$	$F_x$
	F	$F_x$	$1.282 F_x$	$1.409 F_x$	$1.366 F_x$	$1.159 F_x$	$F_x$
<b>Dual wheels</b>							
3	A	Same as for arrangement 1					
	B	Same as for arrangement 1					
	C	Same as for arrangement 1					
	D	(Note that the absolute numerical value of $M$ for arrangement 3 will be twice that of $M$ for arrangement 1, since the value of $x$ for arrangement 3 is twice that of $x$ for arrangement 1.)					
	E	Same as for arrangement 1					
	F	Same as for arrangement 1					
<b>Single wheel</b>							
4	A	$F_x$	$F_x$	$F_x$	$F_x$	$F_x$	$F_x$
	B	0	$0.342 F_x$	$0.643 F_x$	$0.866 F_x$	$0.985 F_x$	$F_x$
<b>Tandem wheels</b>							
5	C	$F_x$	$0.658 F_x$	$0.357 F_x$	$0.134 F_x$	$0.015 F_x$	0

For any  $\beta$  and  $y/x$  combination below this line, where  $M_{F(i,o)} > M_{B(i)F(o)}$ , the maximum directional stability is achieved by using both wheels in a free-rolling mode; above this line, where  $M_{F(i,o)} < M_{B(i)F(o)}$ , the use of the inside wheel braked and skidding and the outside wheel free-rolling is the more efficient mode.

Yaw angles during ACV travel in ordinary crosswind conditions are usually below  $30^\circ$  or  $40^\circ$ . The free-rolling wheel mode would, therefore, be the usual method for directional stability with  $y/x$  ratios of  $1/2$  or less.

It should be noted that in the case of a turn away from the existing direction of travel, that is, the direction of the desired turning moment being opposite to that required for counteracting yaw (in this discussion referred to as the yawing moment), appropriate changes

in the signs of the sideforce vectors have to be made when computing the available turning moments.

#### Single wheel

Arrangement 4 involves a single wheel, either free-wheeling or braked, on the vehicle centerline behind the center of gravity (Fig. 2).

*Mode A: Wheel free-rolling.* From eq 1:

$$M_F = F_x.$$

*Mode B: Wheel braked and skidding.* From eq 3, with  $y = 0$ :

$$M_B = F_x \sin \beta. \quad (9)$$

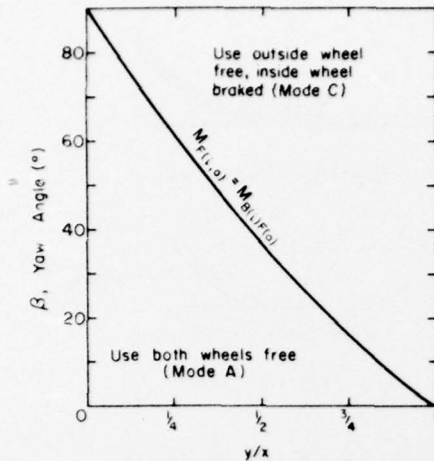


Figure 4. The most effective dual wheel operational modes for various yaw angle and  $y/x$  ratio combinations.

As in the dual wheel case:

$$M_B/M_F = \sin \beta.$$

Since for the same  $F$  and  $x$  the single wheel arrangement provides only  $1/2$  of the moment available with the dual wheels, the single wheel would have no practical advantage, unless it can be installed farther back (increased  $x$  distance) and designed for a higher load  $W$  than the dual wheel arrangement. The  $M$  values for various  $\beta$  angles are compared in Table III and plotted in Figure 5.

#### Tandem wheels

Arrangement 5 involves two wheels at the vehicle centerline, one ahead, the other behind the center of gravity (Fig. 2).

*Modes A and B: Both wheels free-rolling or both wheels braked and skidding.* In both free-rolling and braked modes the total yawing moment is 0, when  $x_1 = x_2$ , and only a relatively small moment could be obtained at  $x_1 > x_2$  (Fig. 2). Thus, these modes are impractical.

*Mode C: Rear wheel free-rolling, front wheel braked and skidding.* From eq 1 and 9, for  $x_1 = x_2 = x$ :

$$M_{F(\text{rear})} = Fx$$

$$M_{B(\text{front})} = -Fx \sin \beta.$$

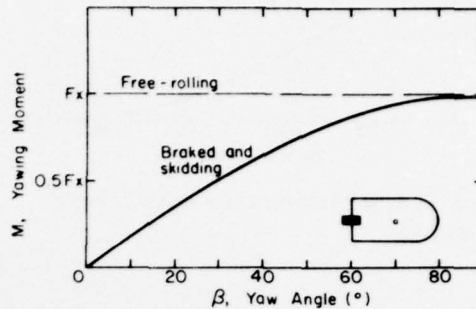


Figure 5. Yawing moment vs yaw angle for wheel arrangement 4.

The  $M_{B(\text{front})}$  is negative because the direction of  $F_{(\text{front})}$  at any  $\beta$  is opposite that of  $F_{(\text{rear})}$ . The total yawing moment is

$$\begin{aligned} M_{F(\text{rear})B(\text{front})} &= M_{F(\text{rear})} + M_{B(\text{front})} \\ &= Fx + (-Fx \sin \beta) = Fx (1 - \sin \beta). \quad (10) \end{aligned}$$

The opposite arrangement, rear wheel braked and skidding, front wheel free-rolling, results in a negative moment. The front wheel in this arrangement serves no useful purpose as long as it is not steerable. The  $M$  values for mode C are shown in Table III and plotted in Figure 6.

#### Application to existing ACV's

For a vehicle the size of the relatively large Bell Voyager, for example, the directional stability in terms of the total yawing moment provided by the most effective dual wheel arrangement (arrangement 3) would be as follows:

Assume: Gross weight = 80,000 lb  
 $x$  distance = 25 ft  
 $y$  distance = 12.5 ft  
 $y/x = 1/2$

Load on each wheel  $w = 5\%$  of gross = 4000 lb  
 Coefficient of friction  $\mu = 0.5$ .

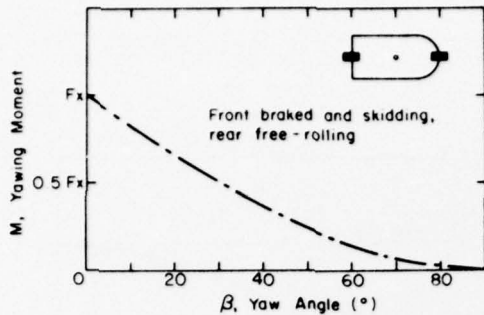


Figure 6. Yawing moment vs yaw angle for wheel arrangement 5.

For wheels in a free-rolling mode (mode C) on a hard surface:

$$F = W\mu = 2000 \text{ lb/wheel}$$

$$M_{F(i,o)} = 2Fx = 100,000 \text{ ft-lb.}$$

For a vehicle the size of the Bell Viking, using dual wheels in a free-rolling mode (arrangement 3, mode C), the available moment on a hard surface would be:

Assume: Gross weight = 40,000 lb

$$x = 15 \text{ ft}$$

$$y = 7.5 \text{ ft}$$

$$y/x = 1/2$$

$$\text{Load/wheel} = 5\% \text{ of gross} = 2000 \text{ lb}$$

$$\mu = 0.5.$$

$$F = W\mu = 1000 \text{ lb/wheel}$$

$$M_{F(i,o)} = 2Fx = 30,000 \text{ ft-lb.}$$

Structural constraints and the location of the center of gravity may require placement of the wheels at a location other than assumed here; however, the values shown above give an idea of the order of magnitude of the yawing moments that would be provided for directional stability by this type of a ground contact control aid.

### OTHER CONTROL DEVICES

Although retractable wheels are the more obvious ground contact devices for the directional stability and



Figure 7. "Hockey stick."

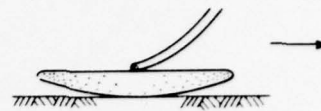


Figure 8. Saucer.



Figure 9. Finger rollers.

control of ACV's several other concepts could be considered.

Any retractable rod, in contact with the terrain surface, would act as a brake on the same principle as that of a handbrake used on a toboggan to correct for side-slip or to produce a turning moment. A curved, rounded bar, resembling a field hockey stick (Fig. 7) or a skid in the form of a saucer (Fig. 8), could be used as a brake for directional control. The applicable moment equations would be the same as those for a braked and skidding wheel discussed previously. Since in many situations the braked wheel is not as effective as the free-rolling wheel, other forms of non-rolling ground contact brakes may not be the best solution in terms of control efficiency or durability, but they may be easier to install with minimum structural alteration and may result in more convenient maintenance. Because of its shape, the saucer-type device would have the least damaging effect on organic terrain surfaces, an important consideration when operating on tundra.

Utilization of the flexible skirt itself as a control device warrants serious consideration. The use of retractable rollers or rolling disks, installed in the skirt fingers (Fig. 9), may provide a very effective, yet simple, directional control method. Another method of utilizing the skirt as a ground contact control device is discussed in Section II.

The most serious disadvantage of using any non-rolling ground contact device would be the potential of

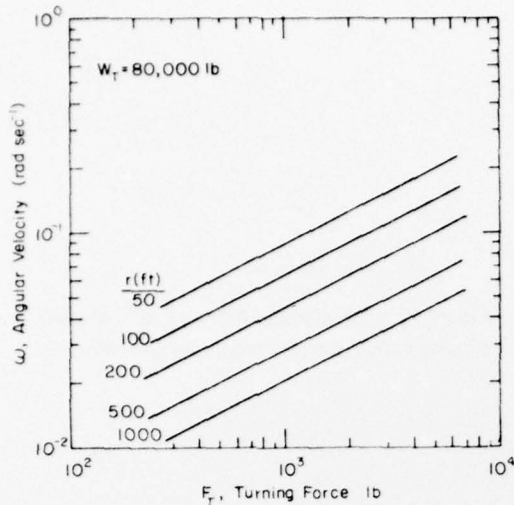


Figure 10. Angular velocity vs turning force for various turning radii.

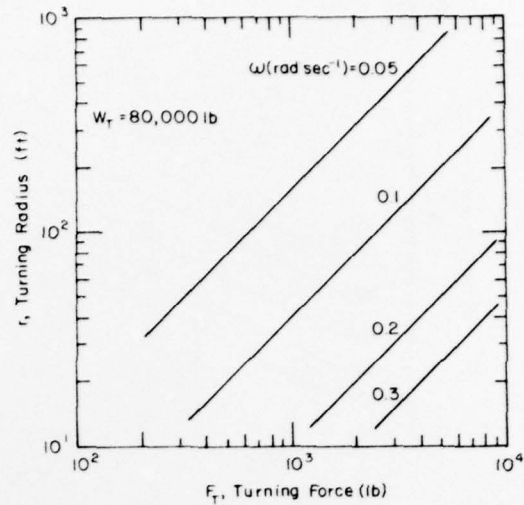


Figure 11. Turning radius vs turning force for various angular velocities.

excessive wear when operating on mineral terrains or other hard surfaces.

It may very well be that the selection of a ground contact device would be dictated to a considerable degree by the terrain type on which the vehicle will operate. A harrow disk type of device may be perfectly suitable for operations on permanently snow-covered areas such as Greenland or Antarctica, but would be unacceptable on tundra where soft wheels or saucers may be the only suitable implements.

#### TURNING FORCE

While the yaw moment is a source of directional stability, the turning force contributes to the maneuverability of the ACV. An optimum control configuration should consider both factors.

There is not a direct relationship between the turning radius of an ACV and its yaw angle. Just as in the case of a conventional aircraft, an ACV can operate at a large yaw angle while moving in a straight line. It is reasonable to state that the longitudinal axis of either an aircraft or an ACV is seldom oriented coincidentally with the direction of motion. The turning force on an aircraft is developed by banking or rolling the craft so that a horizontal component of wing lift can act radially, directed toward the point about which the craft is rotating.

In the case of an ACV, the turning force is generated by yawing the craft relative to its direction of motion so that a component of the propulsive force becomes available for turning. This can be done by an aerodynamic force with the puff ports, by rotating the pylons on which the propellers are mounted, or in the present case, by generating a side force with the wheels.

If the craft is assumed to follow a steady-state circular path about a point, the turning force  $F_T$  that must be generated is

$$F_T = m r \omega^2 \quad (11)$$

where  $m$  is the vehicle mass,  $r$  the turning radius, and  $\omega$  the angular velocity.

The relationship between angular velocity and turning force for an 80,000-lb vehicle for various turning radii is shown in Figure 10. The same data are replotted in Figure 11 showing turning radius vs turning force for various angular velocities. (The turning force that can be developed by an ACV will usually be a characteristic of each particular vehicle; therefore, it has been treated here as the independent variable.)

Figure 12 shows, in a nomograph form, the relationships between vehicle weight, turning force, turning radius and vehicle speed. An example (dashed line) is shown for an 80,000-lb vehicle capable of producing a turning force of 1000 lb; to make a 200-ft radius turn, the vehicle speed has to be kept to 6 mph or less.

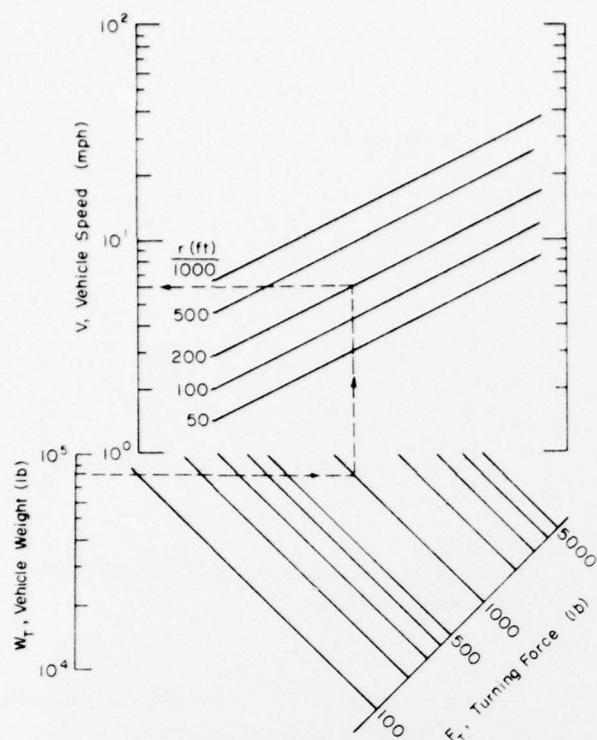


Figure 12. Relationship between vehicle speed, turning radius, turning force and vehicle weight.

A higher speed would result in a higher turning radius, unless the turning force can be increased.

## CONCLUSIONS

A comparison of the relative directional stability in terms of the total yawing moments produced by the sample wheel arrangements is shown in Figure 13. The sample wheel arrangements and operational modes used in the comparison are

Dual wheel arrangement ( $y/x = 1/2$ ):

- 1) Both wheels free-rolling
- 2) Inside wheel braked and skidding, outside wheel free-rolling
- 3) Both wheels braked and skidding.

Single wheel arrangement:

- 1) Wheel free-rolling
- 2) Wheel braked and skidding.

The yawing moments in Figure 13 are expressed in general terms of  $Fx$  and assume no wheel sinkage.

With the dual wheel arrangement for yaw angles of less than approximately  $40^\circ$ , the highest yawing moment is achieved by having both wheels in a free-rolling mode. (The moment produced by a free-rolling wheel is independent of the yaw angle.) For yaw angles above  $40^\circ$ , a slightly higher moment can be achieved by braking and skidding the inside wheel and leaving the outside wheel free-rolling. Braking both wheels is not an effective method; it becomes comparable to the other two only when the yaw angle approaches  $90^\circ$ .

With the single wheel arrangement, the free-rolling wheel mode is more advantageous for directional stability than the braked mode, especially at small yaw angles.

Suitable ground contact devices are by no means limited to wheels, and their selection would be dictated to a considerable degree by the terrain type on which the vehicle was to operate. Nonrolling brake type implements may be more practical in certain applications, such as operations on snow, and smooth, rounded saucer type devices appear suitable for use on tundra. The evaluation of the effectiveness of these devices for directional stability would involve the same approach as that for braked wheels.

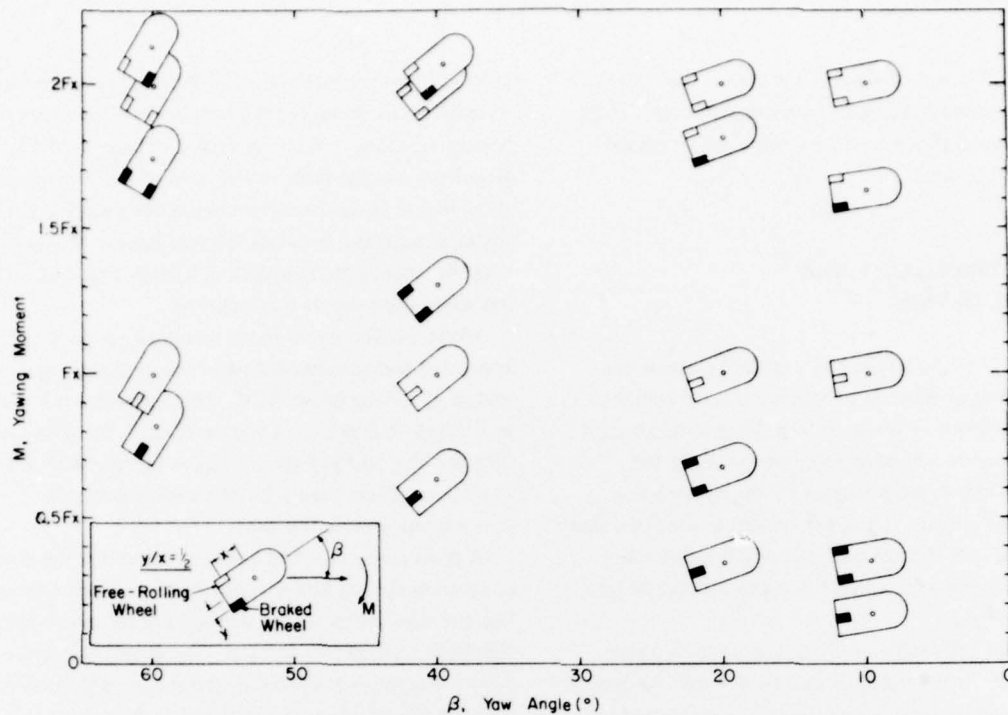


Figure 13. Relative directional stability of various dual and single wheel operational modes.

## SECTION II: USE OF FLEXIBLE SKIRTS FOR ACV CONTROL

### INTRODUCTION

One of the admitted problems of operating amphibian air cushion vehicles on land is the limited maneuverability available from aerodynamic controls. Most ACV's use a combination of aerodynamic controls that may include rudders, puff ports, asymmetric thrust from multiple propellers, control of thrust by rotation of pylons on which propellers are mounted, and skirt lift devices that cause a rotation about the longitudinal axis. With the exception of puff ports, all of the devices or techniques described are obvious from their descriptions. Puff ports, which demand definition, are located either at both the bow and stern or at the bow of a craft, and they consist of ports with controllable doors that can be opened to allow a blast of air to escape perpendicularly to the longitudinal axis of the vehicle. The escaping air produces several hundred pounds of force, which when coupled with a relatively long moment arm, provides a significant torque to turn the craft.

However, even if a craft utilizes all of the aerodynamic controls available, maneuverability remains marginal. Operation in terrain having many obstacles must be conducted at a slow speed, and terrain with steep slopes is impassable. In brief, it can be stated that the amphibian ACV which depends on aerodynamic control and propulsion is restricted to a rather limited set of terrain conditions.

To resolve the operational problems of ACV's and increase the area in which they can be successfully operated, many proposals have been made to produce hybrid vehicles that can use either the air cushion mode or ground contacting mode of operation, dependent upon terrain conditions. The approach that was taken in the brief study reported herein was to attempt to introduce control by a ground contacting device with minimum change to the basic mechanisms of the vehicle. The component closest to being ground contacting is the flexible skirt which is fundamental to the amphibian ACV concept. Therefore, the objective of the study was to selectively convert the flexible skirt into a ground contact device without modifying its basic function. One of the advantages sought by proponents of hybrid ACV's is the use of a ground contact device that not only improves control but also is a source of

propulsion. It was obvious at the outset that the skirt is a most unlikely source of a propulsive force. Thus, interest was confined to the examination of means to improve control.

### THE FLEXIBLE SKIRT AS A CONTROL DEVICE

If the skirt is to be used as a ground contact device, the first problem is to achieve ground contact. The only previous uses of the skirt in ground contact were to provide a braking force or to reduce the amount of debris blown about by the air escaping through the air gap. Thus, the complete skirt periphery was forced into contact with the ground, but other than developing a retarding force, no directional control was involved.

The skirt lift device resulted in a rotation of the craft about the longitudinal axis, which may have produced a modest turning moment. However, the fact that the device has been abandoned on more recent ACV designs leads one to conclude that it was not effective.

The approach taken in this study was to determine methods of forcing the skirt into contact with the ground surface with some degree of selectivity. A contact surface which would result in minimal damage to and from the terrain was seen as necessary. The resulting concept is shown in Figure 14. The departures from conventional ACV technology consist of an additional duct between the skirt bags and the lift fan, the use of a flow control to direct air flow by one or another of the ducts, a membrane valve to prevent debris from being ingested by the lift fan, and surfaces molded into the flexible fingers that would serve as ground contacting devices. The operation of the system is clearly shown in Figure 14. The flow control can direct air either into the air bag as shown on the left or out of the bag as shown on the right. However, the membrane valve is actuated by very modest vacuum levels so that once the valves are closed, there is little or no flow out of the bag and into the fan. Thus, a long delay between deflation and inflation would not occur.

Several experiments were conducted to establish the effectiveness of the membrane valve. The first apparatus is shown in Figure 15. The valve consisted of two

layers of flexible material. The inner layer had a series of small holes along its periphery and the outer layer had a single large hole in its center. The area of the large hole was the same as the total of the areas of the small holes. A narrow annulus was cemented around the large hole and between the two layers. It was found that the valve responded to much lower levels of vacuum when the annulus was installed.

When the first experiment was positive, a second apparatus was constructed which more closely approximated an air bag on an ACV. This apparatus is shown in Figures 16 and 17. In Figure 16 air is being pumped into the bag, and in Figure 17 air is being evacuated. A vacuum of less than 1 in. of mercury was sufficient to completely close the valve.

A great many schemes were examined for the ground contacting devices but almost all had to be discarded because they either would damage the terrain or were themselves subject to damage. The device selected is hardly elegant; it is simply a hard rubber disk molded into the flexible fingers which would drag along the surface upon deflation of the bag. The disk appears innocuous to the environment and unlikely to be easily damaged. The drag produced by the disks when the skirt is fully deflated appears significant, although computations were not made to estimate its magnitude.

It is likely that control of air flow would have to be selective so that only parts of the skirt could be placed in ground contact, and when more drag was required, greater and greater proportions of the bag could be deflated. Thus, internal baffling of the bags might be found necessary.

### MODEL TESTS

It is evident that the scheme proposed can best be investigated by means of a model. A small scale model incorporating the flow control, membrane valves, and attachments to the flexible fingers could be constructed at a modest cost to establish the potential of the proposed system. There seem to be enough questions concerning the practicality of the device to make detailed computation of the skirt behavior and resulting drag forces of less significance than determining whether the idea can be made to work at all.



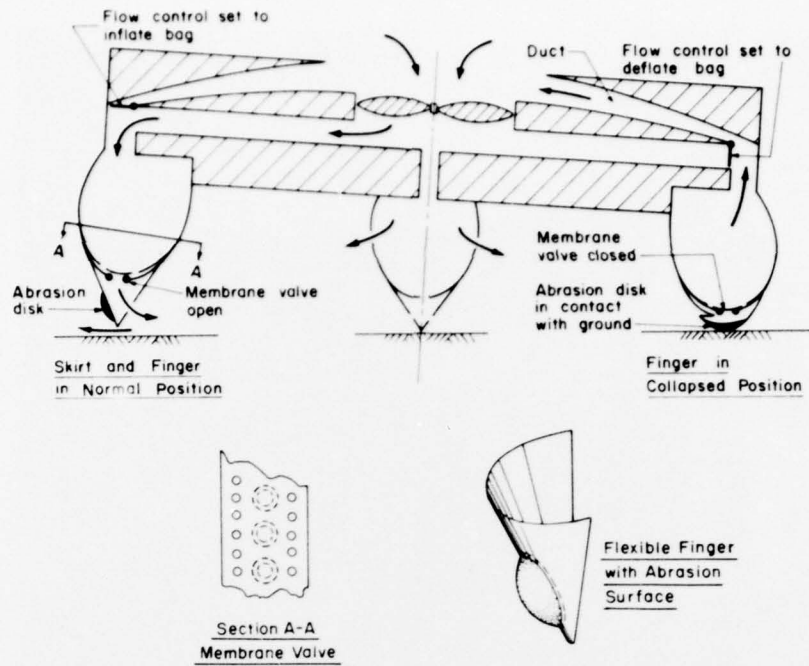


Figure 14. Concept of flexible finger with abrasion surface.

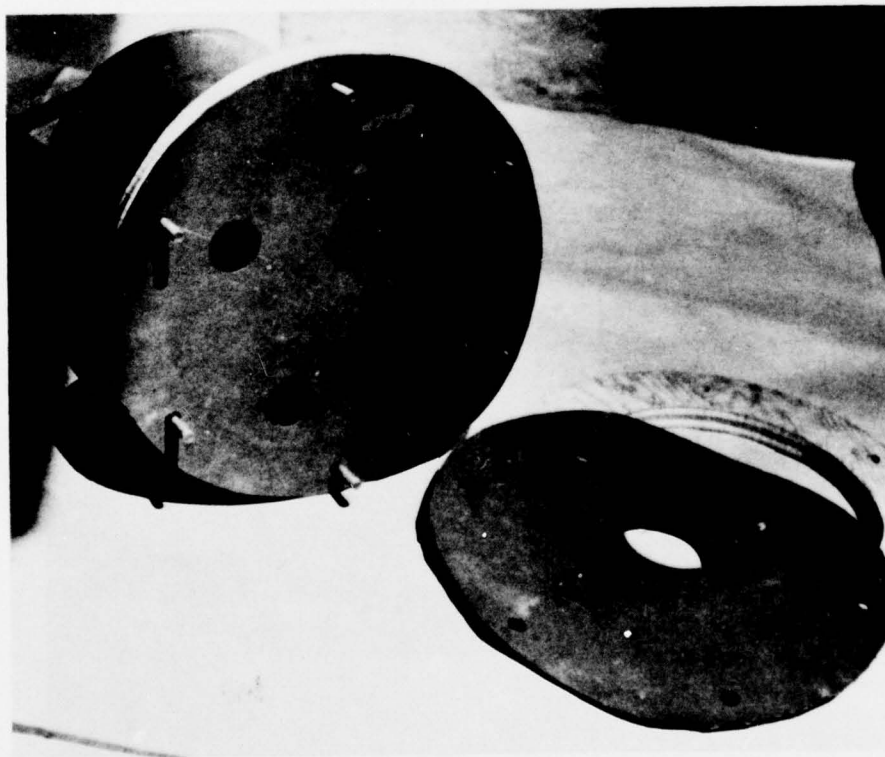
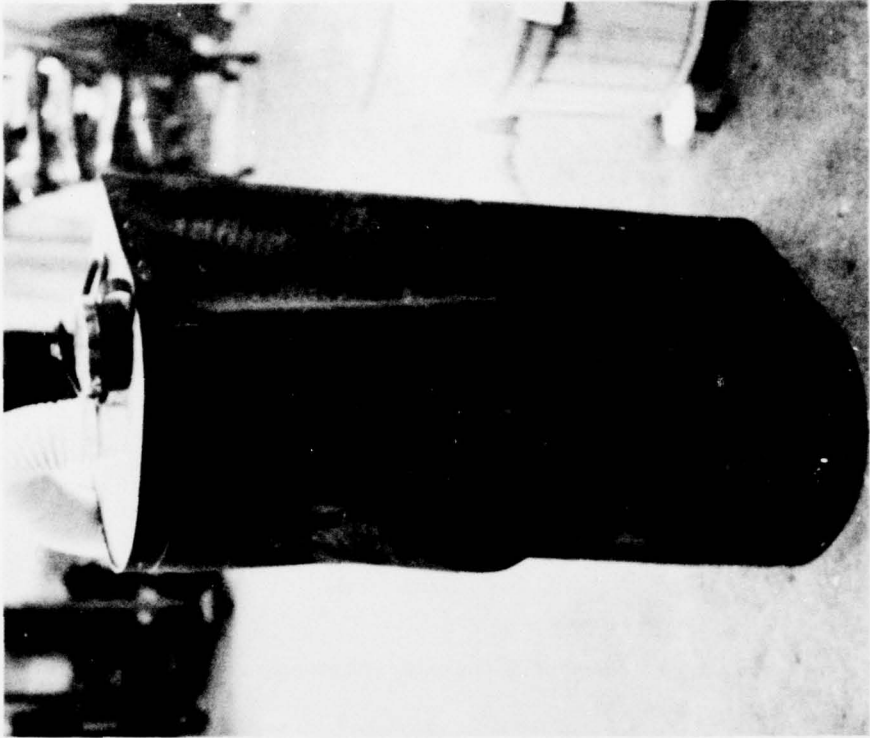
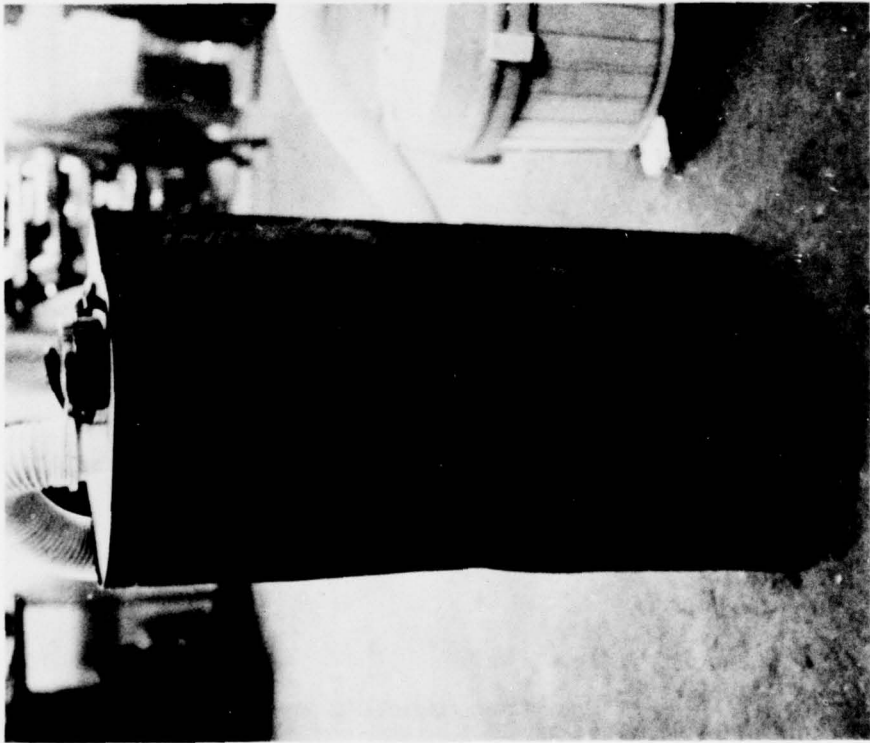


Figure 15. Original membrane valve test apparatus.



*Figure 17. Model air bag in deflation mode.*



*Figure 16. Model air bag with membrane valve in inflation mode.*

## CONCLUSIONS

Previous attempts at producing hybrid ACV devices have had results ranging from disaster to clear failure. It may be that ill-fated earlier attempts were doomed by an infant technology, but it is the writer's opinion that they failed for the same reason that almost all hybrid mechanisms fail: when an attempt is made to design a mechanism to operate in two distinctly different environments, the compromises demanded are so great that the hybrid becomes good in no environment at all. The goal of the proponents of hybrid ACV's is to develop a machine that operates well both in conditions suitable for ACV's and in conditions suitable for land vehicles. I suggest that since we have yet to produce a completely suitable land vehicle or a completely suitable water vehicle, it is almost hopeless to assume that we can produce a vehicle that is good in both regimes. It is recognized that this is an unpopular opinion to hold, and that the proponents for hybrid machines argue, with very good reason, that if we can improve the control on land a little without damaging performance in other regimes we should do so. To this argument I answer: "Agreed, if and when we have exploited the aerodynamically controlled ACV to its fullest, and this we have not." Of course, this last statement is in the realm of opinion and subject to dispute. Perhaps further tests on skirts as control devices will disprove it.

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