6

Manœuvrability

6.1 Key ACV and SES manœuvrability factors

Basic concepts to be introduced in this chapter are vehicle directional stability on a straight course, including when wind and waves are not from the bow, the ability of a craft to turn in a controlled manner and the ability of craft to manœuvre at slow speed.

The various control surfaces and sources of turning moment available to the SES and ACV designer will be discussed, followed by the means to estimate the control forces and responses.

Features of ACV/SES

The manœuvrability of an SES and a high-speed catamaran or high-speed monohull are all similar, because there is no air leakage under the main part of SES sidewalls. Drifting does not occur during turning, except in the case of an SES with thin sidewalls and at a very high speed. We will therefore introduce the manœuvrability of this type of SES as a separate subject.

The manœuvrability of amphibious ACVs has some characteristics of each of conventional ships, wheeled vehicles and aeroplanes, as follows:

1. During turning (or holding a straight course in beam winds), the craft needs to maintain a yawed attitude, pointing into the centre of the turning circle or into the wind in order to maintain the intended track. This is because an ACV has very little contact with the water surface and so the drifting drag of the ACV is very small. The low righting moments at small angles of an ACV hovering over water result in heeling, pitching, yawing, drifting and surging motions all being significant.
2. The manœuvrability of an ACV is different from that of wheeled vehicles. During turning of wheeled vehicles, there is large sideways friction of wheels against the ground and large centripetal force acting on CG in the case of banked ground surface at the turn. These forces stop wheeled vehicles slipping sideways. In the case of an ACV turning, the craft will slip considerably unless special measures are taken by the driver. The desired craft trim is a bank into the turn. Some SES have canted rudders which create a rolling moment to achieve this effect. Amphibious ACVs

may be fitted with skirt lift or skirt shifting systems which move the cushion centre of pressure relative to the CG to roll the craft. Smaller craft may have elevators installed to achieve a similar effect.

3. ACV manœuvrability is also different from aeroplanes. When in flight, pilots can use the air rudder and wing elevators in co-ordination to make an inward banked turn and create a centripetal force in order to reduce the turning diameter and slipping distance. In addition, the aeroplane has less space restriction on its manœuvring should significant side-slip occur. An ACV on the other hand may be required to travel on narrow rivers, canals, under bridge spans, or to land in enclosed docks of landing ships, all of which represent limiting space for manœuvres.

Thus it can be seen that the manœuvrability of an ACV is rather different from conventional ships, vehicles and aeroplanes and so needs special features to provide adequate manœuvring power. The essentials are: the ACV is bound to flat surface; little drag in all horizontal directions; direct generation of control forces needed to provide centripetal forces to manœuvre the craft around corners. Meanwhile, the SES is very similar in behaviour to a slender hull catamaran.

Background to ACV manœuvrability

Manœuvrability has had a considerable impact on ACV development. Many ACV models and experimental manned craft exhibited at the first Conference on Air Cushion Technology in Beijing in August 1960 performed with unstable turns and manœvering capability.

At that time, in the era of peripheral jets and no flexible skirts, most craft had a considerable air gap above the ground. They had a tendency to make continuous small movements in all directions and the pilots found them very difficult to hold on a steady course due to lack of contact with the ground and the small propulsion units installed at that time. As the craft could not travel on a straight course, potential operators considered the ACV impractical to put into service at that time.

Considerable development efforts were consequently made by the pioneering designers, experimenting with all possible control surfaces which could be applied to the ACV, to improve its characteristics. This led to successful improvements in the manœuvrability of ACVs and assisted their development throughout the world at the end of the 1960s. The different means of control developed are reviewed through this chapter.

Following the widening of the range of ACV applications in the 1960s, military ACVs for amphibious assault were required to land in the stern well deck of a landing ship's dock (Fig. 6.1). These craft have been developed through the 1970s and 1980s. This requires very good manœuvrability at low craft speed in order to get onto the landing ship ramp in rough seas.

ACV or air cushion platforms have also been developed to manœuvre on the surface of swamps, marshy fields, rapids and narrow waterways. For these applications new challenges for manœuvrability and course stability have presented themselves to the designer.

Fig. 6.1 US LCAC-001 entering into the landing ship *Pensacola.*

Subjects covered in this chapter

Attention will be concentrated on the following:

1. The effectiveness of various control surfaces on ACV (or air cushion platform) manœuvrability in individual use or integrated application.
2. Experimental investigation of manœuvrability of ACVs at low speed with aid of radio controlled free-flying models.
3. Experimental investigation of manœuvrability of ACVs at high speed.
4. Theoretical study of ACV manœuvrability at low/high speed, including calculation and measurements of various hydrodynamic position derivatives and rotational derivatives, formation and solution of manœuvrability equations, etc. Electronic computers are applied widely in the solution of these equations, because designers can choose various control surfaces to assist the manœuvrability of craft according to the computer results in order to save a large amount of labour and expense to carry out model and full scale ship tests.

6.2 Introduction to ACV control surfaces

There are a lot of possible control surfaces that can be mounted on an ACV. They can be divided into three groups, i.e. rudder equipment, air propulsion systems and the control surfaces affecting the cushion force, as shown in Table 6.1.

Table 6.1 The equipment for controlling the course of ACV

Equipment for controlling the course of an ACV	Rudder Equipment	Vertical air rudders
		Swivelling air stabilizers
		Retractable water rudders
		Jetted rudders
		Horizontal air rudder
		Guided wheels on terrain
	Cushion air forces	Flexible skirt-lifting system
		Flexible skirt-shifting system
		Valves in air ducts
		Separately variable fan rpm or blade pitch from several fans
		Weight shifting using water ballast or shifting of crew to adjust trim or heel
	Air propellers	Separately variable propeller rpm or blade pitch from several units
		Swivelling pylons
		Controllable pitch of air or ducted propellers
		Swivelling jetted thrusters
		Puff ports

Rudders

Vertical rudder

A vertical rudder is shown in Figs 6.2–6.4. Due to the high position of a vertical air rudder over the CG, its action not only creates turning moments but also a drifting force and rolling moment, which leads to the craft performing an outward banked turn. Thus when the ACV is turning over water by means of an air rudder, in addition to turning, yawing, heeling and drifting will occur simultaneously and even lead to 'tiptoe' turn in the case of applying unsuitable control actions to the craft, such as excessive rudder angle or too long action of the rudder, especially for craft operating on ice and over ground.

Vertical fins for course stability (Fig. 6.2)

Vertical fins are used for improving course stability and efficiency of an air rudder. Their primary use is at high speed.

Jetted air rudder

This was a system developed at BHC in the 1960s to improve the manœuvrability of ACVs with a single air propeller. The jet was led from the air cusion into proximity to the rudder surface, so increasing the effectiveness of the rudders especially at lower craft speeds. After limited application on the SR.N6 craft, such equipment has not been applied to later designs, as other control systems with greater turning force for craft manœuvring have appeared.

Horizontal air rudders, or elevons

These are shown in Fig. 6.4. They are designed and installed on ACVs to regulate dynamic trim. Elevators are very effective and fast acting. Meanwhile, the craft

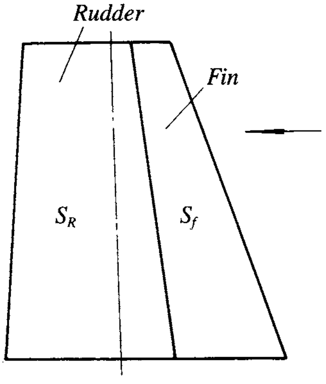


Fig. 6.2 Air rudder and fixed vertical stabilizer fin.

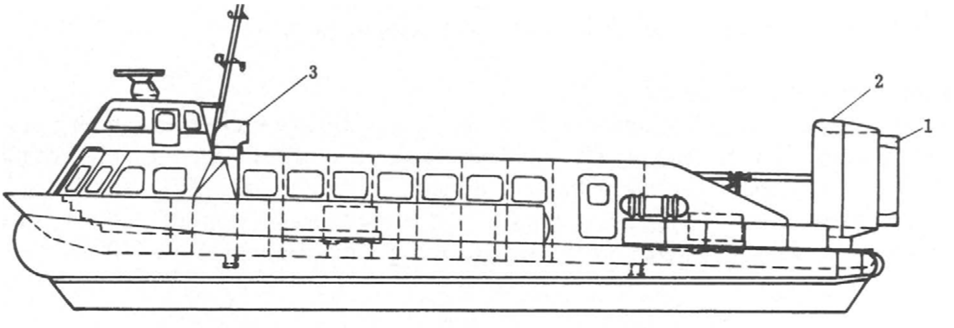


Fig. 6.3 The control surfaces of British ACV model AP.1-88. 1: vertical rudder; 2: propeller duct; 3: bow thruster.

Fig. 6.4 The ducted air propellers and rudder of AP.1-88. 1: rudders; 2: elevators; 3: propeller duct.

loading condition and operational environment will also affect the steady trim of an ACV, so it is very convenient to mount elevators for fast adjustment of craft trim in various conditions. Elevons are a variation on the basic elevator design. The control wires or rods are arranged in such a way that forward movement of a control stick causes pitch movement, while sideways movement causes the elevons to move differentially, causing a roll moment.

Retractable water rudder [57]

This device is shown in Fig. 6.5, which is suitable for handling the ACV at high speed. These control surfaces can be designed with smaller size due to the higher density of water than that of air. Moreover, this control surface may be mounted under the VCG of the craft and one of a pair can be put down during turning. This equipment will prevent drifting and outward banking motion during the turn, but it is less effective in the case of low speed on ACVs; in addition the equipment is more complicated.

Such rudders can cause severe rolling if deployed from a craft which is travelling with some drift, or even cause overturning. For this reason, the equipment was only installed on experimental ACVs in the early development period.

Guide wheels on land

In the case where an ACV operates over land with various conditions such as grassland, swamp, marsh, sand beaches and ice surfaces, etc. resistance for preventing drifting is very small, so it can be very difficult to handle an ACV precisely, preventing drifting and turning about the CG of the craft. Moreover, the speed of craft will be low in the case where an ACV travels over ground, leading to low effectiveness

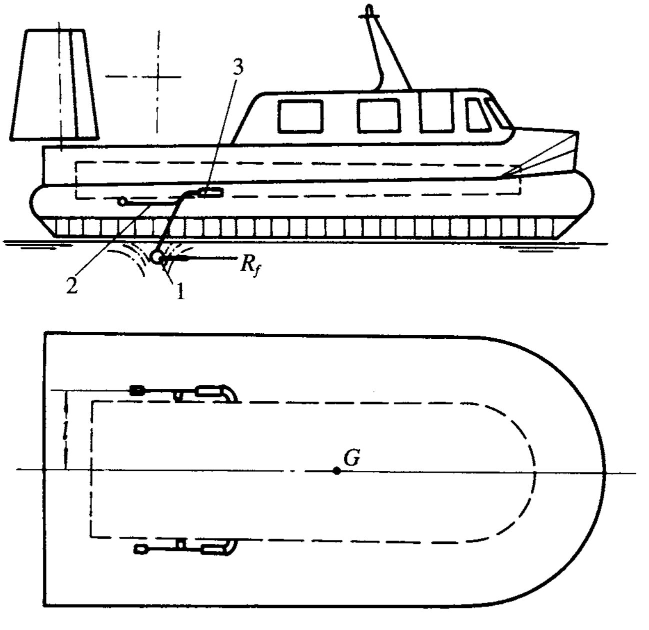


Fig. 6.5 Retractable water rudder. 1: retractable water rudder; 2: control bar; 3: actuator; *Rf* = addition drag due to rudder.

of rudders; so guide wheels can improve manœuvrability and course stability of ACVs and air cushion platforms considerably. Figure 6.6 shows guide wheels in operation on an ACV.

Air propulsors used for manœuvring

Steering by differential thrust from air propellers

The difference of rpm of two or more than two air propellers on both sides can be applied to ACVs to present a turning moment to make the ACV turn about the CG of the craft. This method is especially suitable for ACVs at low speed. Figures 6.3 and 6.4 show two sets of ducted air propellers at the stern. Owing to the high efficiency of ducted propellers, the effectiveness of this method for improving the manœuvrability of ACVs at low speed is very satisfactory.

Swivelling pylons

Figure 6.7 shows a sectional view of swivelling pylons with an integrated lift fan and air propeller system. It can be seen that the swivelling pylon can be rotated by means of a pair of hydraulic actuators. This apparatus can provide side forces as well as a turning moment, therefore various handling modes can be exploited with the aid of several swivelling pylons and their various force couples (moment). Figure 6.8 shows two modes of handling on British ACV model SR.N4: (a) shows the yoke handling, i.e. the thrust line of the propeller rotating in synchronism whereby the system can provide transverse force to prevent ACV drift, if the rotating angle of four swivelling pylons are same and the rudders are kept in neutral position; (b) shows the rudder bar control, i.e. the pilot moves not only the yoke but also the rudder bar and makes the fore and aft pair of pylons swivel with the same angle but inverse direction. Here the thrust of swivelling pylons will act as an additional rotation moment about the CG of the craft to accelerate the yawing angular velocity and reduce the turning diameter of the craft.

Controllable pitch air propellers (or ducted propellers)

Variable forward and reverse thrust and rotating moment (in the case of two or four air propellers) can be provided by means of controllable pitch air propellers. The available manœuvring forces from differential thrust are high, therefore pilots like it

Fig. 6.6 Ground wheels for the guidance of air cushion platform.

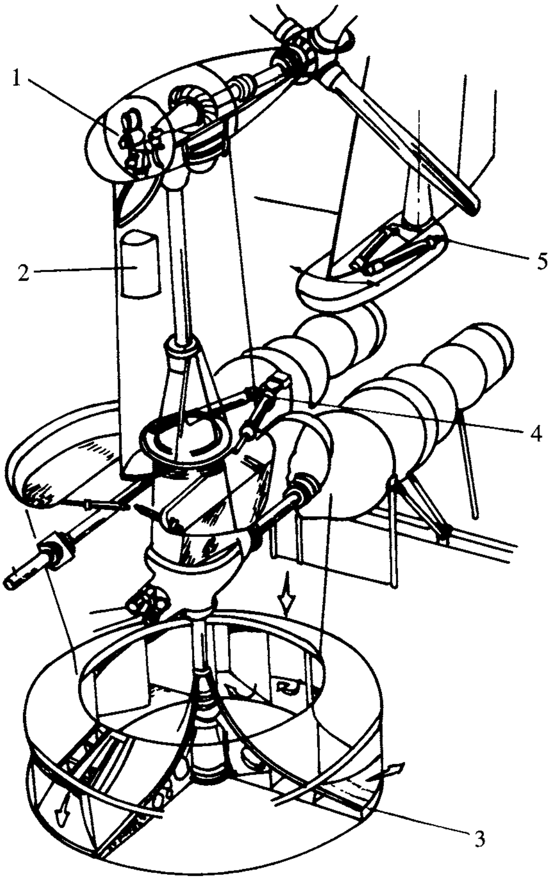


Fig. 6.7 Sectional view of SR.N4 swivelling air propeller pylon. 1: propeller; 2: pylon; 3: lift fan; 4: actuator for pylon; 5: actuator for rudder.

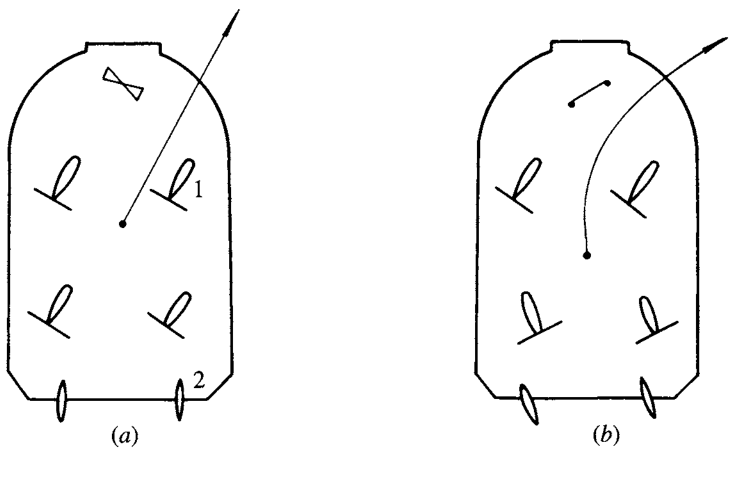


Fig. 6.8 Two control modes of SR.N4: (a) yoke control – pylons swivel together; (b) rudder bar control – pylons swivel in opposition. 1: pylons; 2: rudders.

very much. These pieces of equipment are complicated and expensive, and therefore are usually only installed on medium and large ACVs.

Rotating ducted thrusters

These are also called rotating jet nozzles, as applied to the British ACV model AP.1–88 shown in Fig. 6.3. A diagrammatic sketch of this apparatus is shown in Fig. 6.9. Using the pressurized air from centrifugal fans and ejected from a rotating nozzle, the ACV can obtain the jetted thrust. Fine manœuvrability of an ACV at low and high speed as well as in beam wind conditions can be obtained by means of co-ordinated operation of bow thrusters and stern rudders as well as stern air propeller pitch. The thrust efficiency of jet nozzles is low, but this is usually not important, since the power requirement is not high and may be less expensive than installing variable pitch propellers or fans for example.

Puff ports (Fig. 6.10) [57]

The working principle of this installation is the same as that of rotating thrusters, except that thrust is simply directed to port or starboard of the bow, so it is normally only used for increased rate of turn at low speed. The merit of puff ports is simplicity of structure and low cost. There are no separate fans for this installation. The lift fans have to be upgraded to account for the additional air flow.

The disadvantage of this installation is that a part of the cushion air will be consumed for this system, leading to a reduction of the cushion pressure at the side of the cushion on which the puff ports are in action. Thus the craft heels to one side and causes the air leakage at the other, consequently a drifting force is created in the inverse direction, which compensates for the jetted thrust provided by the puff port and reduces its effectiveness.

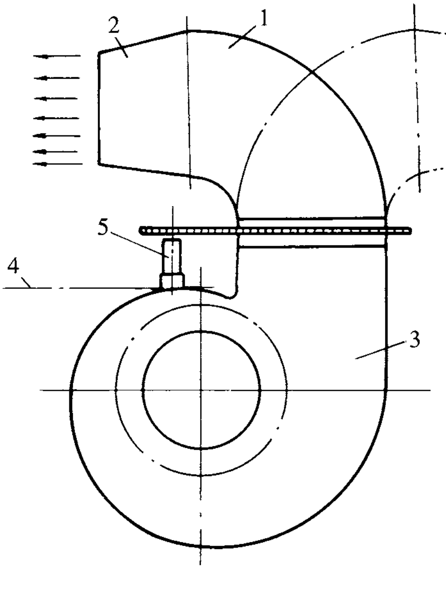


Fig. 6.9 Sketch of the arrangement of air thrusters. 1: rotating duct; 2: jet nozzle; 3: fan and duct; 4: ACV deck level; 5: rotation mechanism.

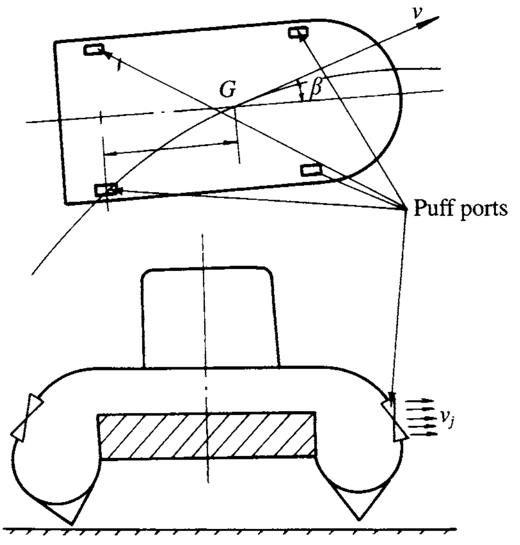


Fig. 6.10 Typical puff port installation.

This installation was mounted on SR.N6 in the 1960s and 1970s, but has not been developed since then. Such an installation was also tried on the Chinese ACV 711-II, but was not developed because of its low efficiency.

Cushion forces

Since the cushion force is equal to craft weight, it is very effective to use this force to control the craft for static (trim) adjustments. There are several methods in use.

Skirt lift apparatus

Figure 6.11 shows a diagrammatic sketch of a skirt lift apparatus: (a) shows the action of this apparatus to lift skirt bags, and (b) shows the action of this apparatus lifting the skirt fingers. The action of both causes lift to the skirt at one side of the craft, thus making this side heel down and presents not only a heeling moment but also a transverse force, which is useful in a turning manœuvre.

The effectiveness of lifting skirt fingers will be better than lifting skirt bags, because it may cause the change of jet direction and increase the transverse momentum of cross-flow. Nevertheless, in practice, type (a) will be more practical than type (b).

Owing to the inward heeling moment and centripetal force supplied by skirt lift, which can compensate for the centrifugal force of the craft during craft turning, the turning diameter will be reduced and also safety will be enhanced; so this apparatus has been applied widely in the industry.

The disadvantage of skirt lift is its complexity, since an extensive pulling system of wires and pulleys has to be installed and a set of hydraulic or mechanical operating systems has to be installed on the ACV. In addition, the large lift may shorten the life of the skirt; for this reason, it is not suitable to equip large ACVs with skirt lift.

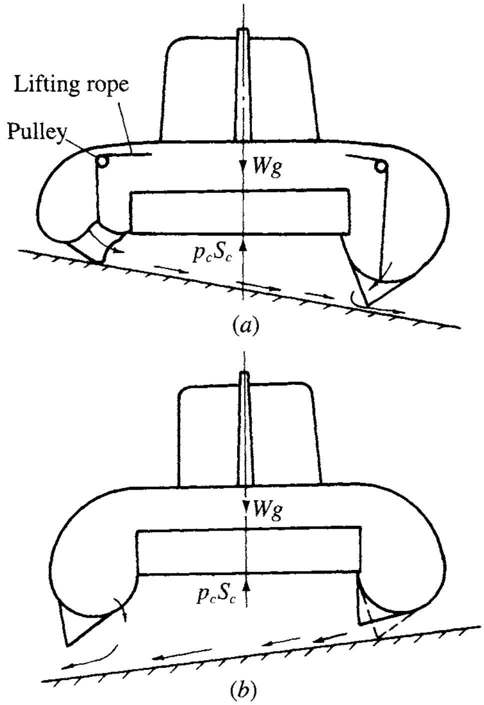


Fig. 6.11 Skirt lifting installation: (a) action of lifting bag; (b) action of lifting fingers.

Skirt-shifting installation

This apparatus is shown in Fig. 4.30, which can provide transverse force and heeling moment. It has been used on relatively few craft (HD.2, VT.1) mainly because it suits the open loop and segment skirt rather than the bag and skirt. On larger craft (VT.1) it was found that the system was not really needed for satisfactory manœuvring and it was simply ignored. The possible large shifts of craft CP could actually be dangerous in a high-speed turn for a craft of the size of VT.1 and so on the later amphibious VT.2 the skirt shift system was decommissioned. Utility craft such as the Griffon series are well suited to this installation.

Using the weight of persons and water (oil) ballast to regulate the trim and heel

On small ACVs, the weight of people can be used for regulating the running attitude and obtain an excellent effect just as riding a bicycle. But it is impractical for large commercial ACVs. However, the water (oil) ballast can replace the weight of people as the mass for regulating the trim or heel, but it cannot be regulated dynamically in regard to the operational environment, such as the action of beam wind, the shift of CG, etc., because the shift of ballast water (oil) needs enough time. For this reason this method cannot be used as handling apparatus, just for static trim.

Air duct valves

The centre of pressure of an air cushion can be changed with the aid of air duct valves to produce the heel/trim forces (moment). This is not used except in experimental conditions, as it is not efficient in use of cushion air.

Using the difference of rate of revolution or regulation of fan blades

The principle of this is the same as air duct valves. It is used experimentally.

The state of the art and control surface features on Chinese and European ACVs

This is shown in Table 6.2, and the application of air rudders and fins are shown in Table 6.3. The features of control surfaces on various ACVs can be seen as follows:

1. Because of the many control surfaces mounted on the ACV 711-IID, its manœuvrability is most satisfactory, however the installation is too complicated.
2. The control surfaces mounted on ACV version 7210 are simple and cheap, with the penalty of poor handling performance, particularly if the craft is running with a single propeller.
3. The manœuvrability of craft version 722-I is satisfactory because of relatively large control surface areas, even if the craft is of medium size.
4. Owing to the single non-swivelling propulsor and fan of SR.N6, the manœuvrabil-

Table 6.2 A selection of control surfaces mounted on Chinese and Western ACVs

Craft identification	711-IID	7210	716-II	722-I	SR.N6	SR.N4	AP.1-88
Nationality	China	China	China	China	UK	UK	UK
Craft type	ACV	ACV	ACV	ACV	ACV	ACV	ACV
Rudder installation							
Vertical	✓	✓	✓	✓	✓	✓	✓
Jetted					✓		
Vertical fin(s)	✓			✓	✓		
Retractable water rudder							
Horizontal air rudder	✓			✓	✓		✓
Guide wheels on terrain							
Air propulsor							
Air propeller	2	1 Ducted	2 Ducted	4	1	4	2 Ducted
Swivelling pylon(s)	–	–	–	2	–	4	–
Propeller + thrusters	✓			✓	✓	✓	
Swivelling jet nozzle							✓
Puff ports					✓		
Cushion Air Controls							
Skirt lifting	✓			✓	✓		
Skirt shifting							
Air duct valves				✓			
Ballast water or oil tanks					✓	✓	✓
Differential fan speed				✓		✓	✓

Table 6.3 Application of air rudders and fins on Chinese and European ACV

Craft identification	SR.N5	SR.N6	N.300	SR.N4	711-IID
Nationality	UK	UK	France	UK	China
No. of vertical fins + rudders	2 + 2	2 + 2	–	2 + 2	2 + 2
No. of inclined fins + rudders	–	–	2 + 0	–	–
No. of horizontal fins + rudders	0 + 2	0 + 2	–	–	1
Total area of vertical fins and rudders (m^2)	2.2	2.2	?	14.8	3.96
Total area of horizontal fins and rudders (m^2)	0.1	0.1	–	–	2
Total fin area/craft side area (%)	6	4.5	?	5	7.3
Total rudder area/craft side area (%)	23.2	18	?	?	18
Fin/rudder inclination from horizontal (°)	90	90	87	90	90
Distance fin to propeller disc/prop. dia. (m)	0.5	0.5	?	0.5	2.3

ity had to be improved by installing many additional devices such as jetted air rudder, lifting skirt and puff port.

5. Two sets of bow-swivelling thrusters together with two set of propulsors make the manœuvrability of ACV AP.1–88 most satisfactory, even though the adjustable pitch air propeller is replaced by a fixed pitch propeller.

6.3 Differential equations of motion for ACV manœuvrability

To identify the necessary forces which a control surface may have to apply, we need to solve the equations of motion for a given ACV design, the relevant manœuvre and environmental condition.

The manœuvrability of an ACV is different from that of conventional ships in that the cushion air blows from the side skirt to provide the transverse force during manœuvring. Therefore from the point of view of hydrodynamics, we should not investigate the manœuvrability by means of forming differential equations of motion with three degrees of freedom as usually used on conventional ships, such as yawing, swaying and surging.

One or two additional degrees of freedom have to be considered such as rolling, caused by transverse forces and its coupled motion, pitching. In the strict sense, the last degree of freedom, heaving, also should not be neglected.

Because of the longitudinal asymmetry of the cushion, pitch will couple with the rolling motion, and consequently the differential equation of motion with six degrees of freedom has to be investigated, which will cause a lot of difficulty for solving the differential equations. Furthermore, the solution of the position derivatives and rotation derivatives will be hard and complicated work, expending a great deal of labour and money, However, designers often pay great attention to this, particularly where an ACV will probably operate on land and ice.

The differential equations of motion are the basis for studying the manœuvrability of ACVs; once obtained, designers will find it simple to analyse the manœuvrability, course stability and handling characteristics of ACVs operating on ice, land and other complicated support surfaces with the aid of a computer. References 55 and 58 have described some methods in this respect.

These methods can also be applied to analyse the effect of principal dimensions, parameters and control surfaces on the manœuvrability of ACVs, in order to choose reasonable design criteria and save a great deal of time and labour on radio-controlled free-flying models and full-scale ship tests.

Basic assumptions and nomenclature

1. The ACV is running on calm water or flat land and we neglect the effect of spray and its added mass on the manœuvrability of craft.
2. The differential equations of motion for manœuvrability of an ACV are based on four degrees of freedom, i.e. the motions of craft in a horizontal plane (sea surface or ground surface) and the drifting motion of ACVs on this plane as well as the roll motion during turning of craft.

   In a strict sense, there are some problems with this basis which affects the accuracy of the solution of the differential equations, because the turning of an ACV will also lead to a heeling motion of the ACV and air leakage of cushion air from the side skirts, as well as drifting motion due to the strong coupling of heeling with heaving motion. However, for reasons of simplification, we neglect the heaving and pitching motions. It may be useful to consider the heeling motion as a separate consequence of a turn, to assess the effect on stability.
3. The body coordinate system on ACVs is $GXYZ$ and the fixed coordinate system is shown in Figs 6.12 and 6.13. Here

   V = linear velocity of craft on CG
   β = yawing angle of track of CG of craft (i.e. the angle between the X axis and velocity vector of craft motion)
   ω = yawing angular velocity of craft at CG
   φ = angle between the 0ξ axis and velocity vector of the craft at CG

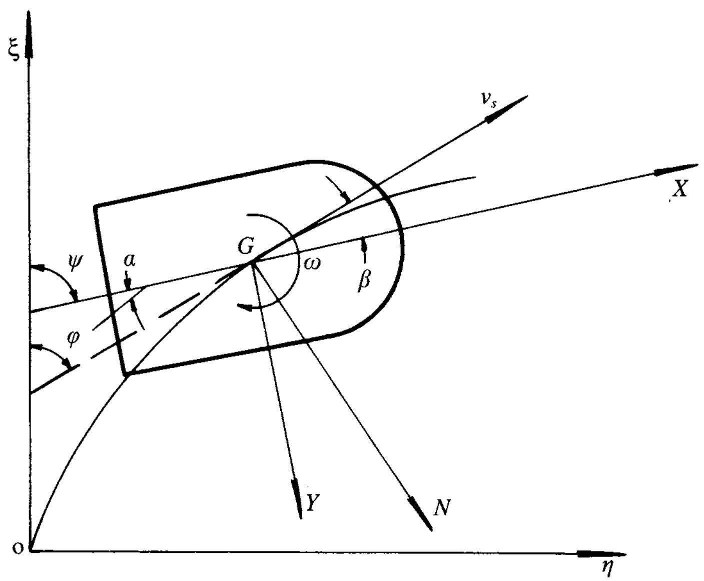


Fig. 6.12 Operation track nomenclature for ACV in turning manœuvres.

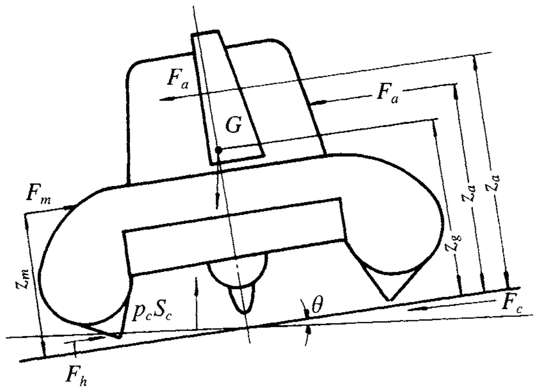


Fig. 6.13 Forces acting on an ACV when turning.

ψ = course direction of the craft
a = rudder angle
R = turning radius
m = craft mass
W = craft weight
θ = heeling angle of craft
F_a = force acting on rudder
z_g = VCG
z_a = arm of force exerting on rudder (distance from ground to the centre of force acting on rudder)
F_s = resistance due to air cushion and skirt
F_c = jetted thrust due to air leakage from cushion during turning manœuvre
F_m = air momentum force
z_m = distance from ground to the centre of air momentum force
F_a = aerodynamic profile drag
x_a = distance from ground to the centre of aerodynamic profile drag

Formation of the equations of motion

The differential equations of motion concerning the manœuvrability with four degrees of freedom can be written as

$$\begin{aligned}
\text{Surging:}\quad F_x &= m(\ddot{x} - \dot{\beta}\dot{y})\\
\text{Yawing:}\quad F_y &= m(\ddot{y} - \dot{\beta}\dot{x})\\
\text{Swaying:}\quad M_z &= I_z\ddot{\beta}\\
\text{Rolling:}\quad M_x &= I_x\ddot{\theta}
\end{aligned}$$

where F_x, F_y, M_z, M_x are the forces and moments acting on the craft with respect to the x and y axes, I_z the moment of inertia of the craft about the z axis, I_x the moment of inertia of the craft about the x axis.

Since the air gap of a modern ACV is very small, in the case where craft are manœuvring over water, the craft will be in yawing and heeling motion, to be exerted by various forces, such as external aerodynamic force, hydrodynamic force, cushion force, air momentum force and propeller thrust and the moments due to these forces. Meanwhile the ACV is basically hovering over the water surface, and so the added water mass can be neglected.

If the forces (moments) (i.e. corresponding static force derivatives and rotary moment derivatives) can be obtained, then the differential equations of motion can be solved with the aid of computers, and the track of motion such as $x(t)$, $y(t)$, $\beta(t)$ [or $\psi(t)$], $\theta(t)$, can also be obtained.

The yawing angle β but not course angle ψ is applied to equation (6.1) and the time history of the track can be obtained by computer as shown in Fig. 6.20. The results of one point can be used as the initial data of the next point; the time interval for two points should be less 10 seconds and the calculation results can then be obtained as the time history of the motion track.

Determination of position and rotation derivatives

There is a very large volume of work on this subject. M. Murao, W. Zeifuss Jr, and E. J. Brook Jr investigated the formation and solution of differential equations of motion on the feasibility of navigation of ACVs on ice surfaces in Arctic regions.

The various forces and moments acting on ACVs such as F_x, F_y, M_x, M_z can be written as:

$$\begin{aligned}
F_x &= F_{xa} + F_{xh} + F_{xc} + F_{xm} + F_{xp} \\
F_y &= F_{ya} + F_{yh} + F_{yc} + F_{ym} + F_{yp} \\
M_z &= M_{za} + M_{zh} + M_{zc} + M_{zm} + M_{zp} \\
M_x &= M_{xa} + M_{xh} + M_{xc} + M_{xm} + M_{xp} + M_{x\theta} \qquad (6.2)
\end{aligned}$$

in which the suffix a is the aerodynamic force, h the hydrodynamic force, c the cushion force, m the air momentum force and p the thrust.

The manœuvrability of an ACV in wind with various directions and force can be included in the equations above, as long as the wind vector can be included in these equations. However, this can be neglected temporarily in order to simplify the equations, thus we in general assume:

$F_{yp} = 0$ (no swivelling pylon taken into account on the ACV)
$M_{zp} = 0$ (no difference on rpm of propellers to be taken into account)
$F_{xc} = 0$ (no trim, thus no longitudinal cushion force)
$M_{xp} = 0$

and $M_{x\theta}$ is the moment of the craft during the heeling angle of θ and M_{xc} the heeling moment from the force of the jet blown under the side skirts during heeling angle of θ.

Thus the equations (6.2) can be written as

$$\begin{aligned}
F_x &= F_{xa} + \mathrm{F}_{xh} + F_{xm} + F_{xp} \\
F_y &= F_{ya} + F_{yh} + F_{ym} + F_{yc} \\
M_z &= M_{za} + M_{zh} + M_{zc} + M_{zm} \\
M_x &= M_{xa} + M_{xh} + M_{xc} + M_{xm} + M_{x\theta} \qquad (6.3)
\end{aligned}$$

The forces and moments can be obtained respectively as follows.

Aerodynamic force and moment

Taking the hull, superstructure, rudder, fin, duct, etc. as a single body, which can also then be related to functions of rudder angle α, yaw angle β and yawing velocity $\dot{\beta}$, then the aerodynamic forces and moments can be written as

$$
\begin{aligned}
F_{xa} &= 0.5\rho_a V_s^2 C_{xa} S_a \\
F_{ya} &= 0.5\rho_a V_s^2 C_{ya} S_a \\
M_{za} &= 0.5\rho_a V_s^2 C_{mza} S_a l_a \\
M_{xa} &= F_{ya} z_a
\end{aligned}
\tag{6.4}
$$

where S_a is the lateral area of hull, superstructure, fins rudders and air ducts, l_a the average height of the craft, z_a the vertical distance of the centre of lateral area over the lower tip of skirts; since the air gap is very small, the vertical distance of the centre of lateral area over the ground can be taken as $l_a/2$. *Cxa, Cya, Cmza* are the coefficients of aerodynamic force and moment. Thus they can be written as

$$
\begin{aligned}
C_{xa} &= C_{xa0} + C_{xa1}\alpha + C_{xa2}\beta + C_{xa3}\dot{\beta} \\
C_{ya} &= C_{ya0} + C_{ya1}\alpha + C_{ya2}\beta + C_{ya3}\dot{\beta} \\
C_{mza} &= C_{mza0} + C_{mza1}\alpha + C_{mza2}\beta + C_{mza3}\dot{\beta}
\end{aligned}
\tag{6.5}
$$

where

$$
\begin{aligned}
C_{xa1} &= (\partial C_{xa}/\partial \alpha)\alpha = \beta = \dot{\beta} = 0 \\
C_{ya1} &= (\partial C_{ya}/\partial \alpha)\alpha = \beta = \dot{\beta} = 0 \\
C_{mza1} &= (\partial C_{mza}/\partial \alpha)\alpha = \beta = \dot{\beta} = 0
\end{aligned}
\tag{6.6}
$$

$$
\begin{aligned}
C_{xa2} &= (\partial C_{xa}/\partial \beta)\alpha = \beta = \dot{\beta} = 0 \\
C_{ya2} &= (\partial C_{ya}/\partial \beta)\alpha = \beta = \dot{\beta} = 0 \\
C_{mza2} &= (\partial C_{mza}/\partial \beta)\alpha = \beta = \dot{\beta} = 0
\end{aligned}
\tag{6.7}
$$

$$
\begin{aligned}
C_{xa3} &= (\partial C_{xa}/\ \dot{\beta})\alpha = \beta = \dot{\beta} = 0 \\
C_{ya3} &= (\partial C_{ya}/\partial \dot{\beta})\alpha = \beta = \dot{\beta} = 0 \\
C_{mza3} &= (\partial C_{mza}/\partial \dot{\beta})\alpha = \beta = \dot{\beta} = 0
\end{aligned}
\tag{6.8}
$$

The expressions in equations (6.6) and (6.7) are the position derivatives, which can be obtained by wind tunnel experiments. Equation (6.8) gives the rotation derivatives, which can be obtained by tests on rotating arm facilities or a planar motion mechanism in a wind tunnel.

Hydrodynamic forces and moments

These are due to the slipping and heeling motion of craft. The hydrodynamic forces and moments are a function of β, θ and F_{xb}, F_{yb}, M_{zh}, M_{xh} and thus the equations can be written as

$$F_{xh} = 0.5\rho_w V_s^2 C_{xh} S(\theta,\beta)$$
$$F_{yh} = 0.5\rho_w V_s^2 C_{yh} S(\theta,\beta)$$
$$M_{xh} = F_{yh} z_g$$
$$M_{zh} = 0.5\rho_a V_s^2 C_{mzh} S(\theta,\beta) l_c \tag{6.9}$$

where C_{xh}, C_{yh} are the hydrodynamic coefficients of the cushion and skirt, which can be written as

$$C_{xh} = C_{xh0} + C_{xh1}\theta + C_{xh2}\beta$$
$$C_{yh} = C_{yh0} + C_{yh1}\theta + C_{yh2}\beta \tag{6.10}$$

$S(\theta,\beta)$ is the lateral area of skirts in contact with the water surface in the case of heeling angle θ and yawing angle β of the craft.

C_{xh1}, C_{xh2}, C_{yh1}, C_{yh2} are the position derivatives of skirt and cushion; these can be written as

$$C_{xh1} = (\partial C_{xh}/\partial\theta)\theta = \beta = 0$$
$$C_{xh2} = (\partial C_{xh}/\partial\beta)\theta = \beta = 0$$
$$C_{yh1} = (\partial C_{yh}/\partial\theta)\theta = \beta = 0$$
$$C_{yh2} = (\partial C_{yh}/\partial\beta)\theta = \beta = 0 \tag{6.11}$$

C_{xh1}, C_{xh2}, C_{yh1}, C_{yh2} can all be measured in model tests in a towing tank or circulating water tunnel.

M_{xh} = hydrodynamic moments of cushion and skirts about the x axis
M_{zh} = hydrodynamic moment of cushion and skirt about the z axis
l_c = cushion length
C_{mzh} = corresponding hydrodynamic coefficient

$$C_{mzh} = C_{mzh1}\theta + C_{mzh2}\beta \tag{6.12}$$

where

$$C_{mzh1} = (\partial C_{mzh}/\partial\theta)\theta = \beta = 0$$
$$C_{mzh2} = (\partial C_{mzh}/\partial\beta)\theta = \beta = 0$$

Cushion force and moment

Cushion force and moment F_{yc}, M_{zc}, M_{xc} can be written as

$$F_{yc} = \rho_a Q_c V_j = \rho_a Q_c (2p_c/\rho_a)^{0.5} \tag{6.13}$$

where V_j is the jet velocity under the side skirt, p_c the cushion pressure, Q_c the jetted flow rate under the side skirt

$$Q_c = l_c h_c V_j \phi$$

where ϕ is the flow coefficient, h_c the craft hover height at heeling-up side

$$h_c = h_0 + 0.5B_c \tan\theta$$

h_0 the initial hover height and B_c the cushion beam.

Thus equation (6.13) can also be written as

$$F_{yc} = \rho_a l_c (h_0 + 0.5B_c \tan\theta)(2p_c/\rho_a)\phi$$
$$= 2l_c\phi p_c(h_0 + 0.5B_c \tan\theta) \quad (6.14)$$
$$M_{zc} = F_{yc} l_{Gc} \quad (6.15)$$
$$M_{xc} = F_{yc} z_g \quad (6.16)$$

where l_{Gc} is the longitudinal distance between the LCG and midship, z_g the height of the VCG.

Aerodynamic force and moment

Aerodynamic forces and moments F_{xm}, F_{ym}, M_{zm}, M_{ym} can be written as

$$F_{xm} = \rho_a V_s Q \cos\beta$$
$$F_{ym} = \rho_a V_s Q \sin\beta$$
$$M_{zm} = F_{ym} z_m = \rho_a V_s Q \sin\beta\,(z_m - z_g)$$
$$M_{xm} = F_{ym} z_m = \rho_a V_s Q \sin\beta\,(l_{Gm}) \quad (6.17)$$

where Q is the fan flow rate (m^3/s), l_{Gm} the distance between the LCG and centre-line of the fan air inlet (m) and z_e the height of centre-line of the fan air inlet over ground (m).

Restoring moment ($M_{x\theta}$) during heeling (rolling) of craft

$$M_{x\theta} = Wh \tan\theta \quad (6.18)$$

where h is the metacentric height of the craft on cushion (m) and W the craft weight (N).

The differential equations of motion

Substituting equations (6.2)–(6.18) into equation (6.1), the coupled differential equations in four degrees of freedom (surge, sway, yaw and roll) can be obtained as

$$F_x = m\ddot{x} - \dot{\beta}\dot{y} = -0.5\rho_a V_s^2 S_a (C_{xa0} + C_{xa\alpha}\alpha + C_{xa\beta}\beta + C_{xa\dot{\beta}}\dot{\beta})$$
$$- 0.5\rho_w V_s^2 S(\theta, \beta)(C_{xh\theta}\theta + C_{xh\beta}\beta)$$
$$- \rho_a V_s Q \sin\beta + F_{xp}$$
$$F_y = m\ddot{y} - \dot{\beta}\dot{x} = -0.5\rho_a V_s^2 S_a (C_{ya0} + C_{ya\alpha}\alpha + C_{ya\beta}\beta + C_{ya\dot{\beta}}\dot{\beta})$$
$$- 0.5\rho_w V_s^2 S(\theta, \beta)(C_{yh\theta}\theta + C_{yh\beta}\beta)$$
$$- \rho_a V_s Q \sin\beta - 2l_c p_c \phi(0.5B_c \tan\theta + h_0)$$
$$M_z = I_z\ddot{\beta} = -0.5\rho_a V_s^2 S_a l_a (C_{mza0} + C_{mza\alpha}\alpha + C_{mza\beta}\beta + C_{mza\alpha\dot{\beta}}\dot{\beta})$$
$$- 0.5\rho_w V_s^2 S(\theta, \beta)(C_{mzh\theta}\theta + C_{mzh\beta}\beta) l_c$$
$$- \rho_a V_s Q \cos\beta\, l_{Gm} - 0.5 l_c p_c \phi(0.5p_c \tan\theta + h_0) l_{Gc}$$

$$\begin{aligned} M_x = I_z\ddot{\theta} \quad &= -0.5\rho_a V_s^2 S_a (C_{ya0} + C_{ya\alpha}\alpha + C_{ya\beta}\alpha + C_{ya\dot{\beta}}\dot{\beta}) z_a \\ &\quad - 0.5\rho_w V_s^2 S(\theta, \beta)(C_{yh\theta}\theta + C_{yh\beta}\beta) z_g \\ &\quad - \rho_a V_s Q \sin\beta (z_m - z_g) \\ &\quad - 2 l_c p_c \phi (0.5 p_c \tan\theta + h_0) z_g - Wh \tan\theta \end{aligned} \tag{6.19}$$

These nonlinear differential equations of motion in four degrees of freedom (6.19) can be solved as a type of time history-response solution by the Runge–Kutta method, in which we neglect the damping moment due to rolling motion because of the small value of rolling velocity $\dot{\theta}$.

Some assumptions have been made in these equations and it is difficult to determine the various derivatives analytically, so they are normally solved by iteration using a computer.

6.4 Course stability

Amphibious ACVs generally have only a small hydrodynamic component of drag over water. When operating over relatively smooth ground, or ice, such craft are totally dependent on their aerodynamic control forces to maintain track, or make manœuvres. The ability to maintain a desired track (course stability) therefore requires effective aerodynamic control forces to be available.

Effective yawing control forces via the rudder(s) and stable aerodynamic directional stability via adequate vertical fins are important. If a craft has low rotational stability, the pilot will be obliged to turn rudders frequently to correct course and large yawing angles will be required for most turning manœuvres. High yawing angle and associated sideslip is particularly unfavourable in a seaway, as it leads to rolling motions which are uncomfortable for passengers. For this reason, course stability is a very important design criterion.

The course stability of an ACV can be divided into two, i.e. static and dynamic course stability. The static course stability can be understood as the ability of a craft to keep a given course at a yawing angle of β, and the dynamic course stability is the ability of a craft to keep a given course at a yawing angle β, heeling angle θ and yawing angular velocity ω_z.

The yawing angular velocity mentioned above does not represent the drifting angular velocity $\dot{\beta}$, but $\omega_z = \dot{\psi}_0$ which not only includes the self-rotation of the ACV, but also the revolution of ACV.

Static course stability

The condition for static course stability of an ACV can be written as

$$C_z^\beta < 0$$

where C_z^β is the coefficient of static course stability. From equation (6.19), we have

$$m_z^\beta = 0.5\rho_a V_s^2 S_a l_a C_{mz}^\beta \beta + 0.5\rho_w V_s^2 S(\beta) l_a C_{mz}^\beta \beta + \rho_a V_s Q \sin\beta\, l_{Gm}$$

where m_z^β is the rotating moment of an ACV about the z axis caused by the yawing angle β. The rotation moment m_z^β as defined above does not consider the effect of other parameters, such as heeling angle θ, on the rotating moment, therefore the coefficient of rotating moment of an ACV at the yawing angle of β about the z axis can be written as

$$
\begin{aligned}
C_z^\beta &= 1/[0.5\rho_a V_s^2 S_a l_a](\partial m_z/\partial\beta)\beta = 0 \\
&= C_{mza}^\beta + (\rho_w l_c/\rho_a l_a)C_{mzh}^\beta + Q l_{Gm}\cos\ \beta/[0.5\rho_a V_s^2 S_a l_a] \qquad (6.20)
\end{aligned}
$$

in which we assume that $S(\beta) = S_a$ = constant and we can also neglect the item of momentum force, considering the moment due to this momentum force as a small value and the items of hydrodynamic force (moment) in the case of small yawing angle. Thus the foregoing expressions can be simplified to

$$C_z^\beta = C_{mza}^\beta < 0 \qquad (6.21)$$

In order to maintain high course stability for an ACV, the yawing moment has to be negative to present a restoring moment. In other words, the centre of lateral area of the craft hull, the centre of forces acting on the air inlets and skirts have to be located to the stern of the craft LCG. Typically the lateral centre of area should be approximately 5% behind the LCG (see Table 6.3).

Dynamic course stability

The criterion for predicting the dynamic course stability can be written as

$$C_{mz}^\beta/C_y^\beta - C_{mz}^{\omega z}/C_y^{\omega z} > 0 \qquad (6.22)$$

where C_{mz}^β is the derivative of rotating moment about the z axis with respect to yawing angle, C_y^β the derivative of transverse force coefficient with respect to yawing angle, $C_{mz}^{\omega z}$ the derivative of yaw moment coefficient with respect to non dimensional yawing angular velocity and $C_y^{\omega z}$ the derivative of transverse force coefficient with respect to non-dimensional yawing angular velocity. These derivatives can be obtained from equation (6.19).

The criteria for the course stability of Soviet ACV from [52] can be written as follows:

$$
\begin{aligned}
C_z^\beta &< -0.5 \quad (\textit{see}\ \text{equation (6.21)}) \\
C_{mz}^\beta/C_y^\beta - C_{mz}^{\omega z}/C_y^{\omega z} &> +1.7 \quad (\textit{see}\ \text{equation (6.22)}) \qquad (6.23)
\end{aligned}
$$

Analysis of the course stability of some ACV models

Figure 6.14 shows experimental results of a BHC ACV with single propeller and lift fan in a wind tunnel by R. L.Wheeler [59]. In the figure, C_N can be considered as C_{mza}^β in equation (6.19), because of the effect of cushion force and aerodynamic momentum on course stability was not considered in [59].

Figure 6.14(a) shows yaw stability where only the lateral area of the hull/skirt, superstructure and fins had been taken into account. Thus it is seen that the ACV is not positively stable on courses with yawing angle $\beta > 18°$. The craft will be stable on courses with worse yawing angles when the effect of not only the hull, but also the air propellers and fins affect the course stability, which can be seen in Fig. 6.14(b).

Based on using the differential equations of motion for manœuvrability (6.19) as the mathematic model, computer analysis can be carried out to analyse the course stability of an ACV with control surfaces and lateral profile as well as various operational environments, particularly when the ACV is operating on an ice surface.

Professor Murao has taken advantage of the differential equations of motion to investigate the feasibility of handling the Japanese ACV model MV PP05A on an ice surface. Figure 6.15 shows the calculation results for this ACV at three different

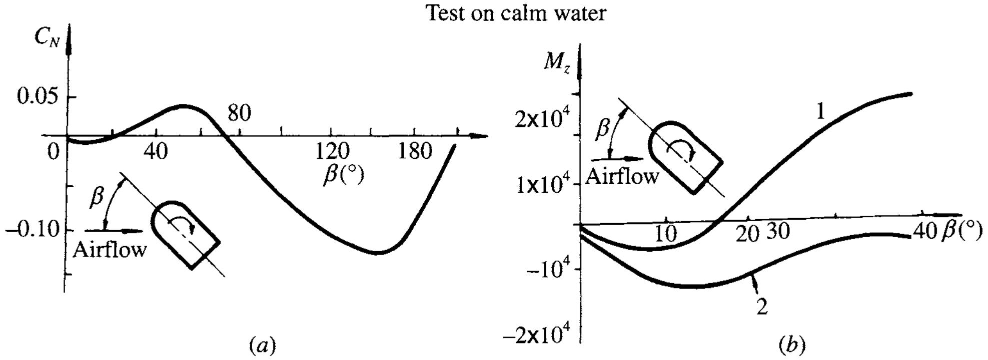


Fig. 6.14 Aerodynamic yawing moment acting on BH.7 at 50 knots: (a) hull, superstructure and stabilizers only; (b) hull, superstructure, stabilizers and air propellers. 1: yawing moment, hull only; 2: yawing moment, hull, props, fins.

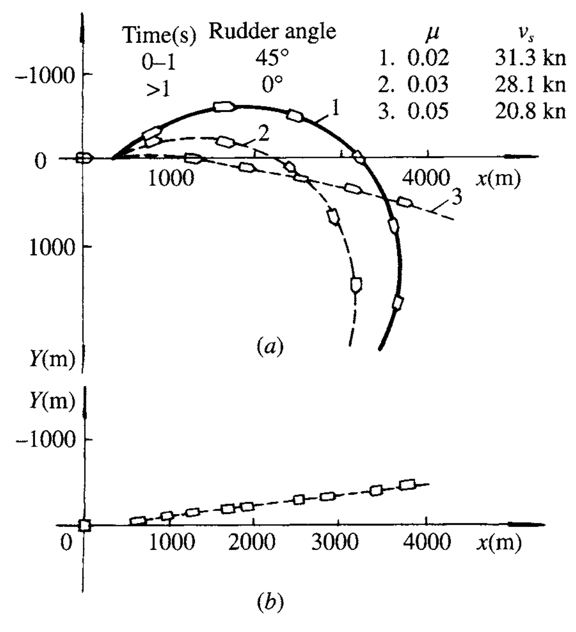


Fig. 6.15 Simulation of Japanese ACV model MV.PP5 turning manœuvre: (a) no rudder control; (b) rudder control.

speeds, 31.3, 28.1 and 20.8 knots, running on an ice surface. Three friction coefficients such as $\mu = 0.02, 0.03, 0.05$ were taken into account. Figure 6.15(a) shows the turning track of the craft with no rudder control, which means that the pilot took a step of rudder with an angle of 45° in a time interval of 0–1 s, then kept the rudders in neutral condition (rudder angle $\alpha = 0°$).

Calculation results show that the craft would not keep a straight course in the case of high craft speed and small frictional coefficient ($v = 31.3$, 28.1 knots; $\mu = 0.02$–0.05). Too high speed and too small friction coefficient would allow the rudder action to lead to continued turning of craft when the rudder is returned to zero. In the case of small craft speed ($v = 20.8$ knots) and large frictional coefficient ($\mu = 0.05$) continued turning would not occur and the ACV course would deviate, which would be the normal intent of a short application of the rudder. It is clear, therefore, that craft to be operated at high speeds in conditions of low surface interface drag need higher aerodynamic stability.

Figure 6.15(b) shows that the ACV running on an ice surface could be kept on the required course and straight course line at various craft speeds and frictional coefficients with the aid of automatic handling equipment of rudders.

6.5 ACV turning performance

The turning track of an ACV can be obtained by means of solving the differential equations of motion. The position derivatives as well as the rotation derivatives, can be obtained in water tunnel, wind tunnel and towing tank tests. Some parameters can be considered based on the computer analysis in [60], [55] and [58]:

1. Figure 6.16 presents the effect of wind directions with a wind speed of 10 knots on the turning track of an amphibious hovercraft model landing craft LCAC weighing 150 t, at an initial craft speed of 45 knots. Owing to its rotatable ducted air propellers, the ACV could be in steady turning even operating in wind.

   The longitudinal turning distance (on the x axis) would be maximum in quartering winds (angle of wind direction $\theta = 135°$) and the turning diameter would be maximum in the case of beam wind ($\theta = 90°$) and minimum in the case of head wind ($\theta = 0°$). This agrees well with experience in practice. It demonstrates that the craft can be turned quickly in a head wind because of large yawing angular velocity.
2. Figure 6.17 also shows the effect of wind directions with the wind speed of 25 knots on the turning track of the 150 t LCAC at the initial speed of 45 knots. It can be seen that the craft could be turned in the case of a head wind, while it could not be turned in the case of a tail wind ($\theta = 180°$).

   Based on practical experience ACVs travelling at high speed downwind can be very difficult to turn. The normal approach to this problem is to slow down and possibly increase skirt friction by reducing cushion power, to reduce side-slip and then begin the manœuvre.

   Rotating the craft into 'reverse' is an option for high powered craft, either military or small craft, but would be disconcerting for a passenger ferry. Based upon such computer analyses it is possible to evaluate the optimum profile of the craft

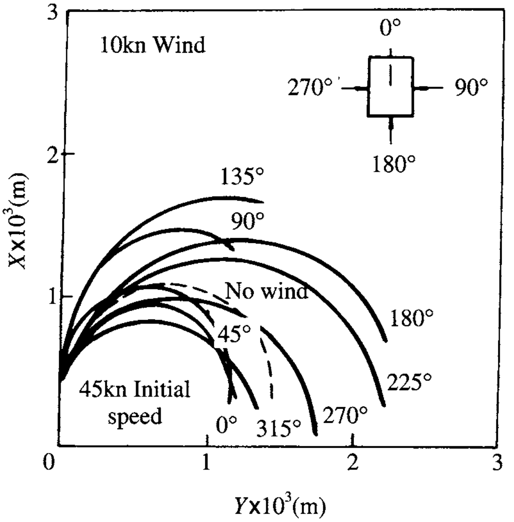


Fig. 6.16 Influence of wind direction with speed of 10 knots on the turning track of US ACV weighing 150 t at the initial speed of 45 knots.

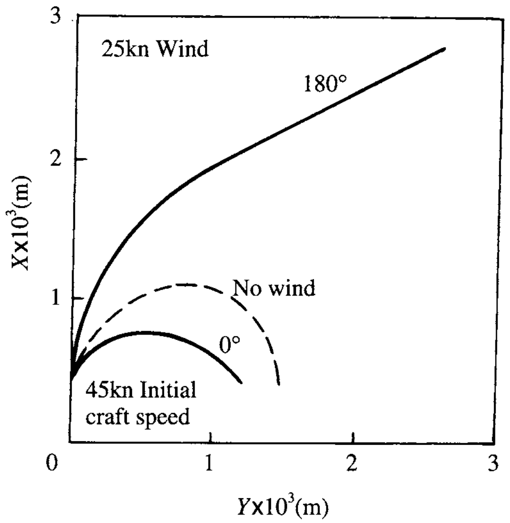


Fig. 6.17 Influence of wind direction with speed of 25 knots on the turning track of US ACV weighing 150 t at the initial speed of 45 knots.

to maximize the control capability and improve the downwind turning performance of an ACV design.

3. Figure 6.18 [55] shows comparisons of the turning track of a 150 t ACV running at initial craft speed of 45 knots in zero wind velocity with three different propulsor layouts:
   (a) First project: single air propeller located on central longitudinal plane and at 12 m aft of LCG;

(b) Second project: two propellers located on both port/starboard at 6 m from central longitudinal plane, and 12 m aft of LCG;

(c) Third project: two propellers located the same as the second project and another two propellers located on both sides of the craft at a distance of 6 m from central longitudinal plane and 12 m forward of the craft LCG.

Owing to the arrangement of two bow rotatable ducted air propeller, the third craft could be operated at large yawing angle and it had a fine turning performance at high speed.

4. Figure 6.19 shows the effect of inward banked turning of 12° on the track of the craft; calculation shows that the turning diameter would be reduced by 23% in the case of inward banked turning of 12 m, because the air leakage under the skirt of the outer side provides a centripetal force and in addition, contact of inner skirts with the water surface led to an increase of water drag of the skirt which increased the positive turning moment. All of this is known by experienced hovercraft pilots.
5. Figure 6.20, from [58], shows a typical turning track calculated by computer. Thus, Fig. 6.20(a) shows the turning track and the change of yawing angle at different locations of the craft, where v_w is the wind velocity, v the craft speed and μ the frictional coefficient of the skirt on the terrain. Figure 6.20(b) shows the time history of rudder angles. Calculation shows that the pilot had to give a positive rudder angle, then a negative rudder angle in order to avoid continuous building up of the turn. After a while the pilot gave a small positive rudder angle again to correct and stabilize the yawing angle and maintain the final angular velocity in yaw of 0.0667 rad/s, thus forming the steady turn. These calculated results of the history of the rudder angle are very similar to the practical operation of pilots.
6. The computer analysis on experimental model MV PP05 (the scaled model of MV-PP5 and MV-PP15) was also carried out in [58]. It was shown that the turning performance of the craft model with puff ports and rudders would be better than that

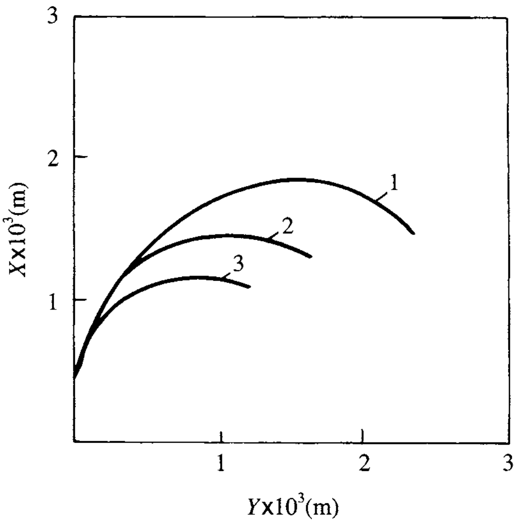


Fig. 6.18 Comparison of turning tracks between various propulsion devices on the US projects' ACV weighing 150 t at zero wind speed condition. 1: single central propulsor, 12m aft CG; 2: two propulsors offset 6m, 12m aft CG; 3: two propulsors offset 6m, 12m fwd CG.

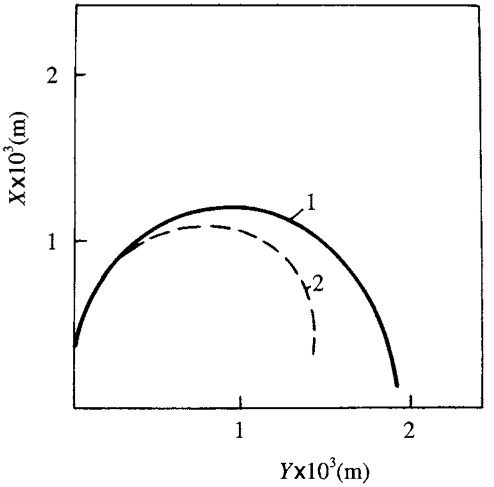
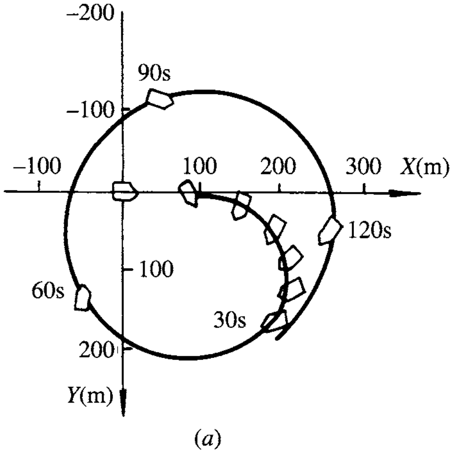


Fig. 6.19 Comparison of turning tracks between bank and non bank turn on the US ACV weighing 150 t with initial craft speed of 45 knots at zero wind speed condition. 1: turn without banking; 2: banked turn with inward heel of 12°.



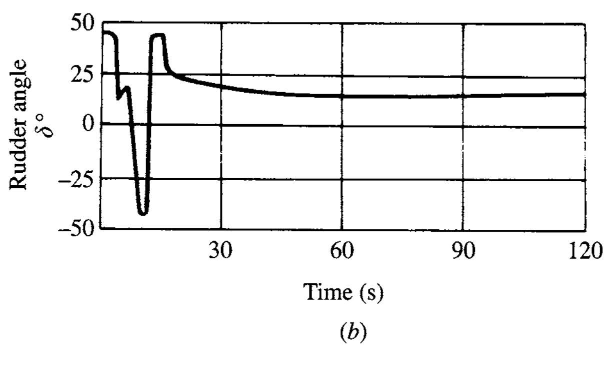


Fig. 6.20 A typical calculated turning track. Wind speed V_w = 60 m/s; craft speed V_s = 31 knots; μ = 0.02.

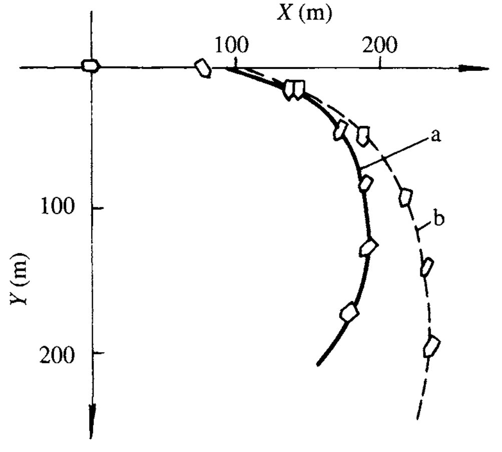


Fig. 6.21 Influence of puff ports on turning track of an ACV: (a) air rudder plus puff port; (b) air rudder control only. $V_w = 0$ m/s, $V_s = 31.3$ Kn, $\mu = 0.02$.

with only single rudder (Fig. 6.21) due to the large positive angle to get the craft quickly into steady turning. The pilots used the puff port only at the initial phase of turning to build up the required yawing angle quickly, then they shut off the puff ports and used the air rudder only to reach steady turning.

Using computer analysis for predicting the manœuvrability of craft, the time and cost of model and full-scale ship tests on manœuvrability may be reduced significantly. In addition, a large number of control surface arrangements can also be investigated. It can be seen that computer simulation provides a time history of turning track and rudder angle which is close to the practical operation of pilots; therefore, the calculation results also coincide with the practical use of control surfaces by pilots.

Owing to the practical difficulties of obtaining the various derivatives and many assumptions for deriving the differential equations of motion, solution of the differential equations is not accurate. Thus computer analysis is a tool which can be used by designers to analyse the sensitivity of changes to control surfaces on manœuvrability at the initial design phase of craft. In addition, tests of radio controlled free-flying models can be carried out to improve the predictions from analytical solutions.