7

Design and analysis of ACV and SES skirts

7.1 Introduction

Early in the development of ACVs, before the flexible skirt had been thought necessary, powerful lift engines were used to obtain a hovering gap of 50–150 mm under the hull hard structure. High-pressure peripheral air jets were used at that time to provide this vertical obstacle clearance over land and water.

These craft had sufficient amphibious capability and vertical obstacle clearance to prove the air cushion concept, but they often encountered terrain with variation in surface elevation larger than 100 mm (for example hollows in the ground, rocks and stones, tall grass). The craft hard structure then collided with the ground. For this reason, they could only operate on fairly smooth or prepared terrain, or smooth water.

These early air jet craft looked most impressive, reminiscent of a flying saucer – they literally appeared to 'hover'. The cushion demanded high power levels to achieve this clearance and they were very 'sensitive' to control. The logical way to increase the clearance height of the hull, while also reducing the height of the air jet to increase stability, was to design a flexible membrane which extended the jets. This was indeed the approach taken initially at Saunders Roe (later BHC), in the UK.

In 1958 C. H. Latimer Needham invented the flexible skirt concept and interested Saunders Roe in the idea for SR.N1. In 1960 flexible extensions to the peripheral jets of the SR.N1 were installed and this enabled a large rigid hull clearance and gave the ACV real amphibious and obstacle clearance capability. A little later this concept was extended by adding an inflated bag around the craft to act as an efficient air distribution duct, from which the flexible jets were extended (Fig. 7.1).

The advantages of flexible skirts can be outlined as follows:

1. significant reduction of lift power;
2. practical obstacle clearance;
3. true amphibious capabilities;
4. decreased calm water resistance, particularly at hump speed;
5. improved manœuvrability by use of skirt lifting and shifting;

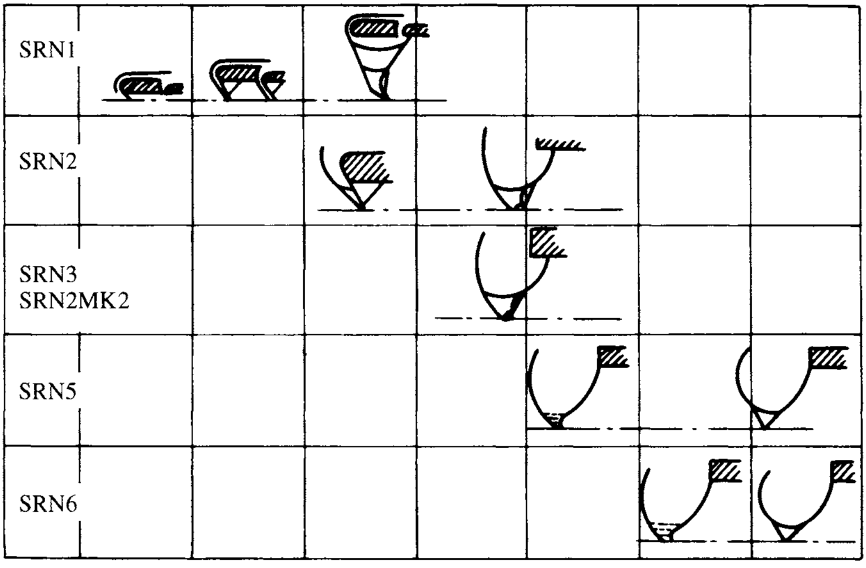


Fig. 7.1 Evolution of BHC skirt section designs from peripheral jet to segment and bag.

6. improved seaworthiness through wave-following capability of third-generation designs such as low bag pressure responsive skirts;
7. improved maintainability of ACVs and SES, since flexible skirts can be easily detached/ attached and replaced.

The appearance of flexible skirts accelerated hovercraft development at the beginning of the 1960s. The function of skirts for hovercraft has proved to be as important to the ACV as that of pneumatic tyres for an automobile.

Skirt configuration greatly affects the performance of an ACV or SES. With respect to air cushion performance, stability and seaworthiness, designers in the 1960s initially concentrated on investigation of internal air flow, the velocity distribution of jet flows from the cushion peripheral jets and the relation between air jet pressure and air gap of the craft. Investigation focused on optimization of the peripheral jet flow models by various theories, such as thin or thick nozzle theory, exponential theory etc., as discussed in Chapter 2.

The flexible skirt developments gradually improved the obstacle clearance and amphibious capabilities of hovercraft. A large air gap under the skirts was no longer necessary because their static and dynamic deformation over rough surfaces or obstacles maintained a sufficient air gap to minimize drag as the hovercraft travelled over it and so attention began to turn away from the air jet theories.

In 1962 Dennis Bliss of Hovercraft Development Ltd led by Sir Christopher Cockerell, invented the convoluted or segmented skirt (see Figs 7.13 (d) and (e)). This concept significantly reduced drag forces by the segments' ability to individually deform to an irregular surface. This allowed the air gap under the skirt to be reduced and save lift power. It was no longer necessary to use peripheral air jets to maintain a visible air gap under the cushion and so high pressures were not required in the bag-like upper skirt.

It should be noted here that two names are used for these convoluted skirt components. The segment generally refers to a geometry where the outer and inner 'faces' of the segment are at 90°. This is stable as an inflated structure. BHC and some others have used a variation where this tip angle is less than 90° and there is reinforcement of the cloth used in the 'unstable' lower area (see Figs 7.1 and 7.9) or alternatively where the base is trimmed horizontally to reduce air leakage through the delta area between the fingers. These variations can prove useful to fit fingers to the underside geometry of a medium to high-pressure bag skirt.

Over a number of years, designers experimented with lower and lower overpressures in the bag compared with the main cushion, to further save installed lift power. Below a p_b/p_c ratio of about 1.2 it was found that the upper part of the skirt also responded better to surface undulations as the craft travelled forward, giving a softer ride. This was the beginning of 'responsive skirt' technology, which has since been continuously developed in China, as well as in the UK. As skirts evolved, the bag/finger type, particularly the responsive skirt, led to a great change in air cushion efficiency, stability, seaworthiness and ride quality.

Skirts have evolved with steady improvements to the ability to deform, while still maintaining overall vehicle stability. Early skirts had a tendency to buckle beyond a certain deformation limit, causing plough-in or overturning due to sudden build-up of drag. The evolution of flexible skirts led designers to be more interested in the investigation of skirt shaping and quasi static analysis of forces acting on the skirt membrane components. This affects craft static stability and the dynamic response, which in turn affects seaworthiness and obstacle clearance.

The design issues concerned with materials, attachment, joints, damage, lifting mechanism design and internal force analysis of skirts will be discussed in Chapter 13. In this chapter we plan to introduce the geometry and theory of skirts, while in Chapter 13 component selection and design aspects will be discussed, based on these fundamentals.

We will discuss three main issues:

1. the main skirt configurations and their development, leading to the current state of the art for hovercraft and SES;
2. the static forces acting on skirts from the terrain and analysis of forces acting on different skirts, leading to determination of skirt section geometry;
3. forces leading to skirt section instability, for example skirt tuck-under over a water surface and skirt bounce, as these phenomena particularly affect the design of bow skirts and bag geometry/pressure ratio.

The study sequence, including static hovering performance, longitudinal and transverse stability, vertical stability and also seaworthiness qualities is as follows:

1. Static hovering theories, including the various jet nozzle theories, in which the relation between the total pressure of the peripheral jet, the air gap and cushion pressure, as well as flow rate, are discussed.
2. Analysis of the jet nozzle, air duct and fan characteristic as an integrated system. This means the characteristics of the air duct and fan have to be studied as well as the jet flow of nozzles.
3. Considering the jet nozzle, air ducts, fan and skirts, as an integrated system and then studying the hovering performance of such systems. This means, based upon

(2) above, that the forces acting on skirts and the deformation characteristics of skirts should be included as part of the system analysis.

7.2 Development and state of the art skirt configuration

Amphibious ACV skirt configurations

We will start with the evolution of Chinese and British skirt configurations, because most of the skirt types applied world-wide to ACVs or SES to date are similar to these (see Figs 7.1 and 7.2).

Initially the flexible skirt appeared as a type of extension jet nozzle. The skirt of SR.N1 is shown in Fig. 7.1 and its plan configuration in Fig. 7.2. Designers attempted to gain the benefit of the peripheral jet air curtain to seal the air cushion and enhance the hovering efficiency, while improving the amphibious and obstacle clearance capabilities through skirt flexibility and drag reduction.

The drag hump was found unsatisfactory with early extended jet skirts, and the inflated geometry was not completely stable. At this time the flexible components were considered as fabric ducts, rather than as 'inflated' structures. This type of skirt was also applied to the Chinese ACV 711-I in 1965.

Figure 7.4 shows the original jetted bag type skirt, which was developed from the foundation of the extended jet nozzle and had increased pressure in the diffusion bag compared to the cushion pressure, to form a stable geometry. This type of skirt was applied successfully to various types of British ACVs; the SR.N2, SR.N5, SR.N3,

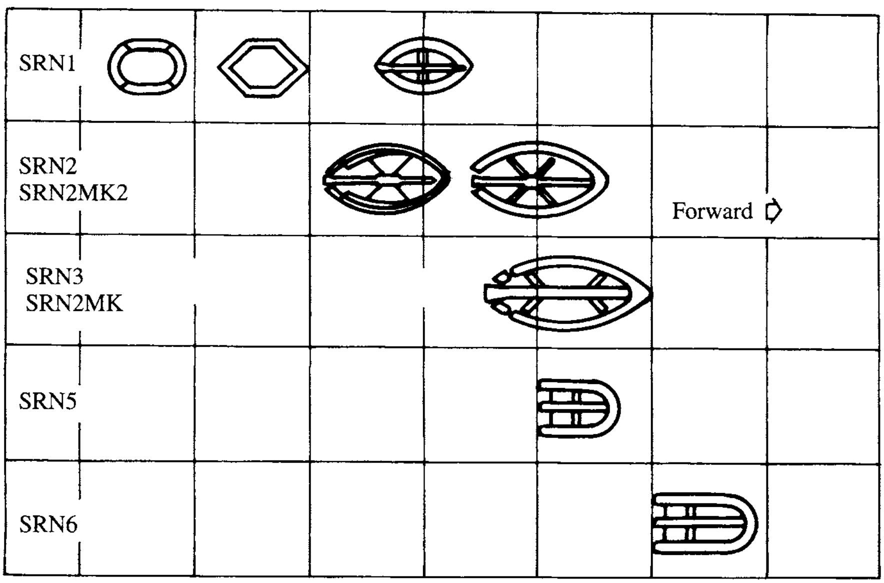


Fig. 7.2 Evolution of BHC skirt plan configuration, including stanility trunks.

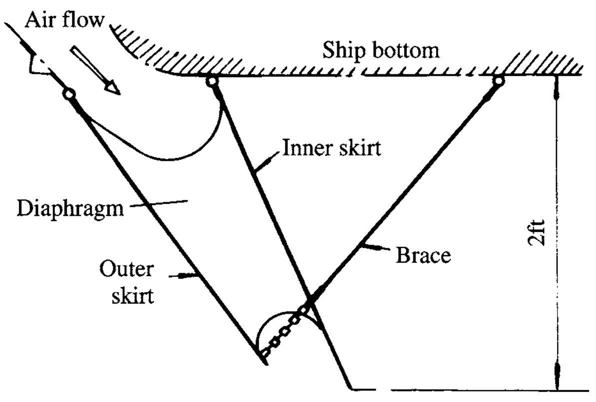


Fig. 7.3 Skirt with extended flexible nozzle.

SR.N6, etc. and was used over a long period of time. This type of skirt was also mounted on the first Chinese ACV, the model 711-I, for trials. The advantages of this type of skirt are that its geometry is stable and prevents wrinkles and crimping of the skirt cloth and can be designed to form an air jet at its base to seal the cushion air for enhancing the hovering efficiency. The disadvantages are that the jet nozzles are easily abraded and are difficult to repair and replace, as well as giving poor drag performance.

In order to form the jet nozzles, designers initially used chains to join the outer and inner skirt cloths (Fig. 7.5), but due to the force concentration on the joints and abrasion due to constant fluttering of the skirt in this area, the joint strength of the cloth/chain connection was unsatisfactory. As a consequence the skirt cloth was always damaged in trials, and operators were obliged to use a large amount of labour to repair the cloth, almost having to repair the skirt cloth with nylon stitching after every operation – poor operational efficiency.

The overhaul life of this skirt was as low as 3 hours, especially at the stern corner, as has been described in Chapter 3. After a time, cloth diaphragms were used instead

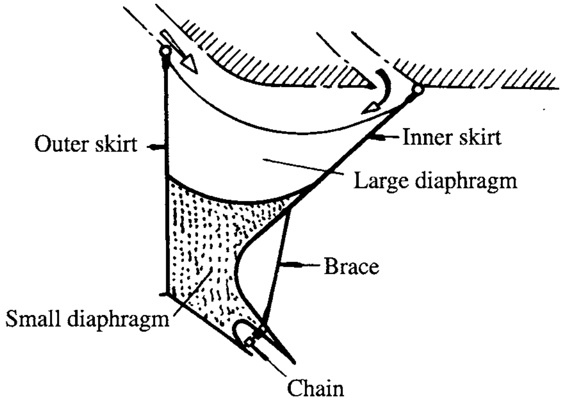


Fig. 7.4 The original geometry of jetted nozzle skirts.

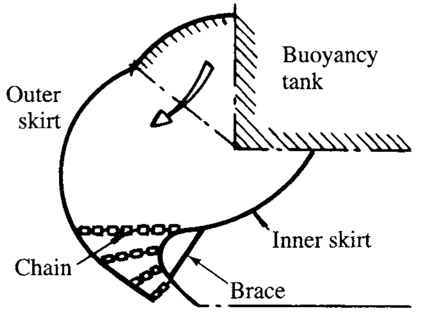


Fig. 7.5 Chain connection for bag and nozzle skirts.

of chains to join the inner and outer skirt cloths, as shown in Fig. 7.6. These were much more successful.

Figure 7.7 shows a sketch section of a bag–finger type skirt, which has been applied world wide to ACVs as a development from the earlier designs. Without the jetted nozzles at the base of this skirt type, the hover gap is similar to that of a simple plenum chamber, with slightly increased efficiency, as the angled segment wall increases the flow constriction somewhat. However, a series of other benefits are obtained, as follows:

- simple structures, easy manufacture and low cost;
- easy to repair and mount, especially for the craft which is intensively operated on a route, such as SR.N6, N4, etc., and which were required to have a long time between overhauls and short repair period for the skirts;
- fine obstacle clearance and wave-following capability (see Fig. 7.8).

There is a loss of dynamic pressure in the air flow past the bag holes. This creates the static pressure in the bag. The fewer/smaller the holes, the higher the bag pressure. High bag pressures, as used early in the design development, lead to high lift system

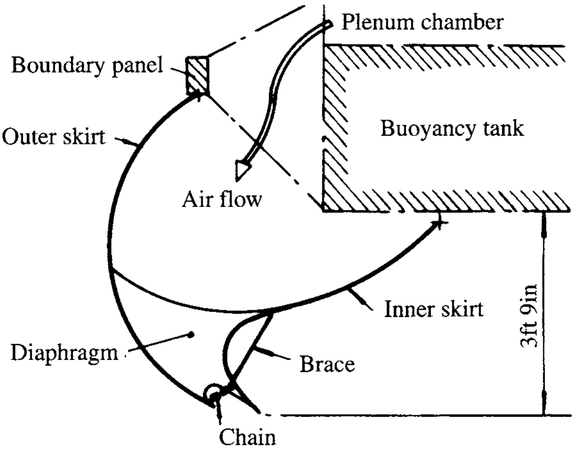


Fig. 7.6 Flexible diaphragm connection for bag and nozzle skirts.

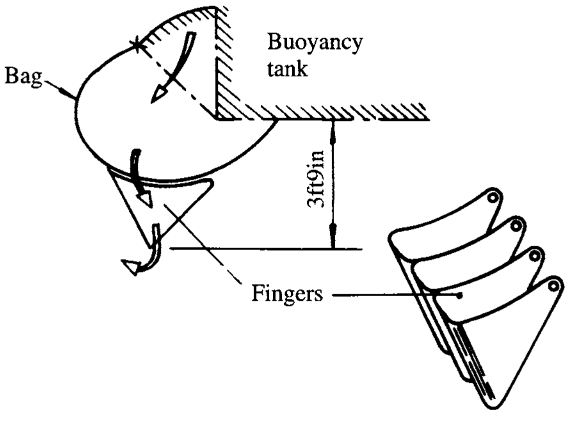


Fig. 7.7 Sketch for bag and finger skirts.

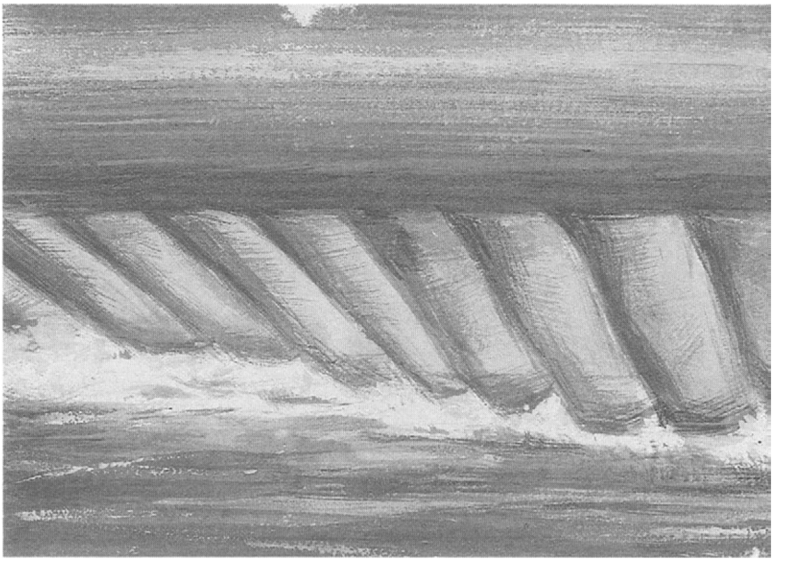


Fig. 7.8 Observation of skirts under the water by means of submersible periscope.

power. Nevertheless, the bag/segment skirt gave a much reduced water drag compared with jetted skirts, also leading to increased service life before replacement. Due to the opportunities for optimization of the bag and finger skirts, or open loop and segment design for smaller craft, these designs have had the largest number of applications world-wide.

The development of skirts based on a craft plan view at BHC is illustrated in Fig. 7.2. It can be seen that the evolution of plan shape has been essentially rectangular with rounded corners. This has been due to its simplicity for skirt geometry, ease of installation and repair, practical structural arrangement and satisfactory speed performance as well as seaworthiness. There are two basic types of stability skirts, the T type and the

+ type. The effect of these on longitudinal and transverse stability has been described in Chapter 5.

Figure 7.9 shows the skirt arrangements and configuration of the British ACV SR.N4. Transverse diaphragms were mounted in the bow skirt bag to form a D-type bag to prevent plough-in of the craft and control of skirt bounce motion. The rationale and analysis of bounce will be described in section 7.6.

Aprons were fitted at the position of the skirt fingers on the SR.N4 bag for easy detachment/attachment of the fingers and the aprons could also be elongated as an anti-spray skirt for preventing spray being blown up to the superstructure and obstructing pilot vision.

Figure 7.10 shows the skirt arrangement and its configuration of the British military ACV model BH.7. It can be seen that the bag–finger type skirt was arranged at the bow and side position and conical cells as the stability and stern skirts. The most difficult positions for this inverted U-skirt plan which have to be designed are the interception area of the stern with the rear side skirt, which is a 90° corner, i.e. the rear corner skirt. This is because scooping often occurs in this area of skirt when operating in displacement mode at low speed and while accelerating through hump speed.

The planing stern skirt with double or triple bags has generally been used in China, which improves water scooping, but it still does not solve the interface problem at the corner of the stern skirt. If the air gap under the corner skirt is high, then a large air leakage will occur from this area, but if this skirt section has no gap, then serious water scooping will occur.

In order to solve this problem, the two-dimensional stern skirt may be employed, namely, the two-dimensional side/stern skirts have to extend as far as the corner of the stern up to the intersection line with each other and some small conical cells mounted here for transition between the side/stern skirt as shown in Fig. 7.11. Figure 7.12 shows the deformation of an ordinary bag–finger skirt and responsive skirt operating in waves. The dotted line denotes the original shape of the skirt, while the solid line denotes the deformation of the skirt in waves. With respect to the ordinary bag/finger skirt, craft plough-in may happen due to the tuck-under of the skirt under the action of the waves.

An alternative is to use rounded corners at the stern as well as at the bow. Such plan-forms are used by most modern amphibious craft of all sizes. Removing the discontinuity introduced by the abrupt change at the right-angled stern corner essentially removes any tendency for scooping and dramatically improves the service life of segments in this area.

Tuck-under resistance of the responsive skirt is provided by a geometry of the bow bag such that the skirt will be deformed upward to yield to waves rather than being pulled backwards; consequently, the tuck-under phenomenon is avoided and the responsive skirt acts as a wave filter to reduce vertical acceleration and water drag in waves. The rationale for this will be introduced later.

In France, an alternative skirt type was developed, called the jupe, invented by Jean Bertin. An individual jupe is a fabric cone with a wall angle of 5–10° to the vertical. When inflated with air from inside it provides a relatively stiff cushion up to the point where the bottom edge begins to crumple or fold up; beyond this, restoring force reduces quickly. The Sedam series of craft had cushions with a series of jupes.

The highly compartmented cushion provided great heave, pitch and roll stability.

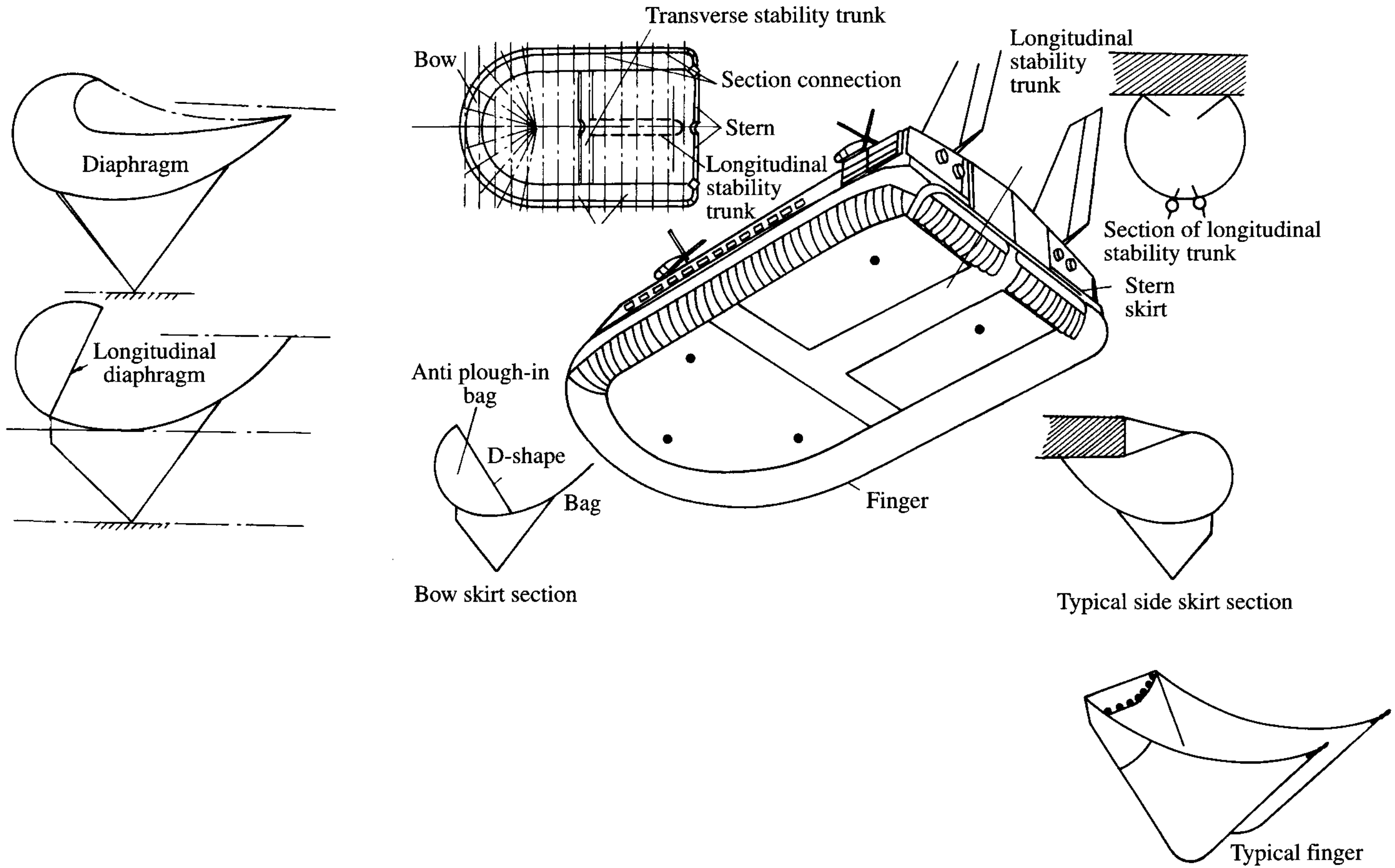


Fig. 7.9 SR.N4 skirt configuration.

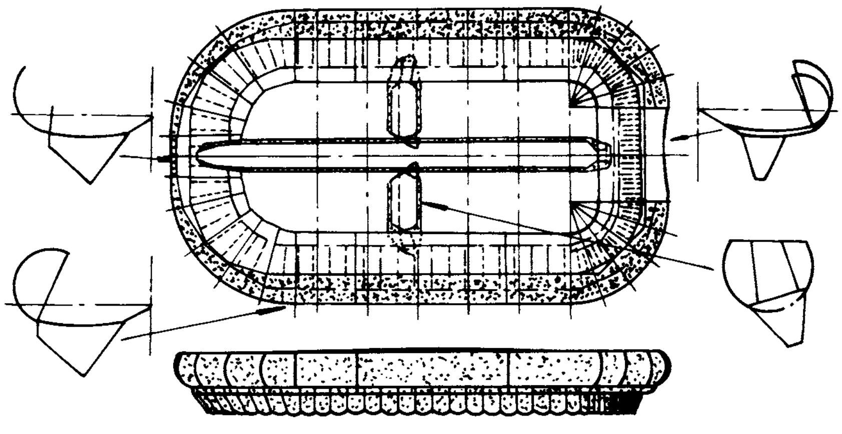


Fig. 7.10 Configuration of skirts on British military ACV BH.7.

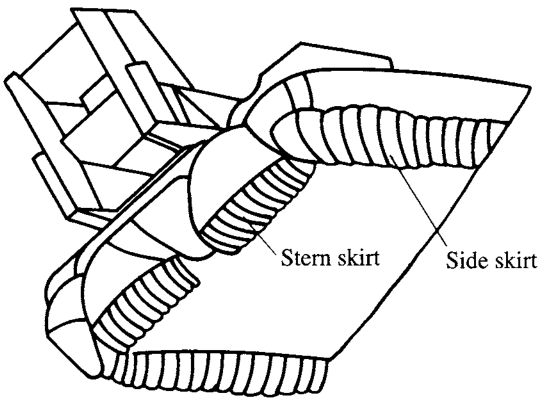


Fig. 7.11 Skirt configuration around the stern corner of SR.N6.

Jupes are not as responsive to waves as a bag/segment skirt and so give rather higher drag, resulting in higher installed power. Significant water scooping drag in the rear area of the stern jupes also reduced the acceleration margin at hump speed. As a result, the design has been superseded by the bag/segment in the industry. This could be minimized by adjustment of flow to the cells, but nevertheless still caused significant wear in this area – larger than for a bag/segment skirt.

The peripheral cell jupes skirt, a mixture of the jupe as applied to the French ACV and the bag and segment skirt, has been applied to one of the prototype LCAC craft, the JEFF-A. Excellent longitudinal and transverse stability was obtained. Maintainability and reliability were improved over a bag and segment skirt with internal stability skirts, since the greater stiffness of the pericells allowed the inner stability skirts to be deleted even though the LCAC is a high-density craft. When the craft operates in the field, it is not necessary to raise the craft in order to remove or reinstall skirt components, which are all at the external periphery of the craft.

In Japan, the finger skirt, an evolution of the jetted bag skirt with short fingers, was

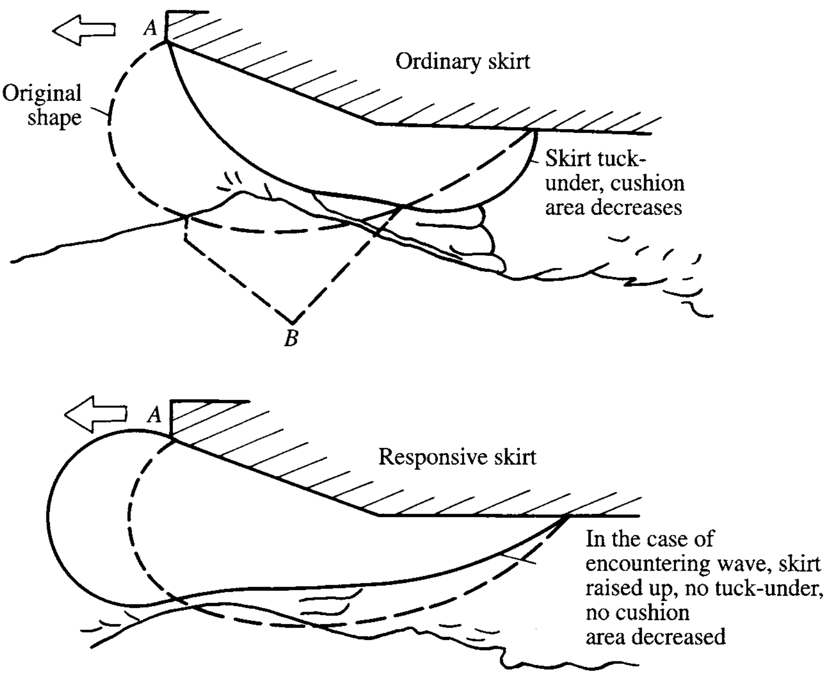


Fig. 7.12 Comparison of deformation between the ordinary and responsive skirts.

used in the 1960s and 1970s, in a similar manner to developments in the UK. More recently they use the low-pressure bag and finger skirt.

In China, the bag–finger type (or large response bag–finger skirts) is used at the side and bow and the double bag planing skirt at the stern in order to reduce the drag at hump speed and above. A D-shape bag was mounted at the bow in order to prevent plough-in and a two-dimensional skirt at the stern and corner to reduce the drag at post-hump speed. Sometimes longitudinal diaphragms are to be mounted in side skirts to improve the skirt's natural frequency bounce motion.

Small amphibious utility ACVs generally use open loop and segment skirts, low-pressure bag and segment skirts, or extended segment skirt designs.

The geometry of all of these skirt designs is determined by static equilibrium of forces, considering the skirt as a two-dimensional section of an inflated membrane. Some of the initial geometrical parameters have been determined by trial and error, through experience with model testing, or operation of actual craft. Where appropriate, these guidelines are included below.

Comparisons between the various ACV skirt configurations

We have followed the development of skirt configurations up to date. The question now is whether there is a single optimum for all ACVs, or whether the designer should select different characteristics for different craft missions.

The segmented skirt offers the best combination of drag coefficient and adaptation to irregular surfaces. With the exception of SES stern skirts the segment has now been universally adopted as the base skirt component. Combining the segment with an inflated bag, or for smaller craft an open loop, allows a skirt to be designed to respond to undulations such as waves and swell, improving ride quality.

The designer's problem is how to select a suitable bag overpressure to obtain the right balance of static stability and dynamic response. This, combined with the overall geometry (straight or tapered), is the main variable to be investigated by a designer of an ACV for commercial or military use.

Simple segmented skirts are used successfully where cushion flow is not so important, for example on small recreational craft, or where compliance is less important than stability, as with a large load-carrying platform.

The following overview of the current skirt types may be helpful.

Bag and finger (segment) (Fig. 7.7)

This is the main skirt type in use for commercial ACVs today. The segment or finger depth is normally between 50 and 80% of the cushion height to the underside of the hull, depending on the bag pressure. In order to allow low bag pressures to be used ($1.05–1.2p_c$), larger craft generally need at least an amidships transverse stability skirt for pitch stiffness. Side skirt finger lower tips are usually placed 10–25% of the finger height inside the gunwale of the craft hull. Finger width is normally between 40 and 50% of its depth.

Responsive skirts use deep rather than shallow bag geometries. At the bow, rather than using a swept back geometry that brings the segments right under the bow, BHC has pioneered the bulbous bow skirt. The geometry is such that during pitch down movement, as the segment crushes, the bag rotates upwards maintaining stiffness and preventing the cushion centre of pressure moving backwards.

BHC also uses a tapered geometry, such that the stern hull clearance is less than at the bow, giving a hull static trim of about 2°. It has been found by experience that amphibious craft seem to have the best balance of dynamic stability and control when the trim is between 1 and 2°. Shaping the skirt allows this optimum to be maintained while minimizing cushion air flow. The optimum trim is directly related to the aerodynamics of the hull and superstructure; it is probably best to start design with 0.75–1° taper, if this approach is used by a designer.

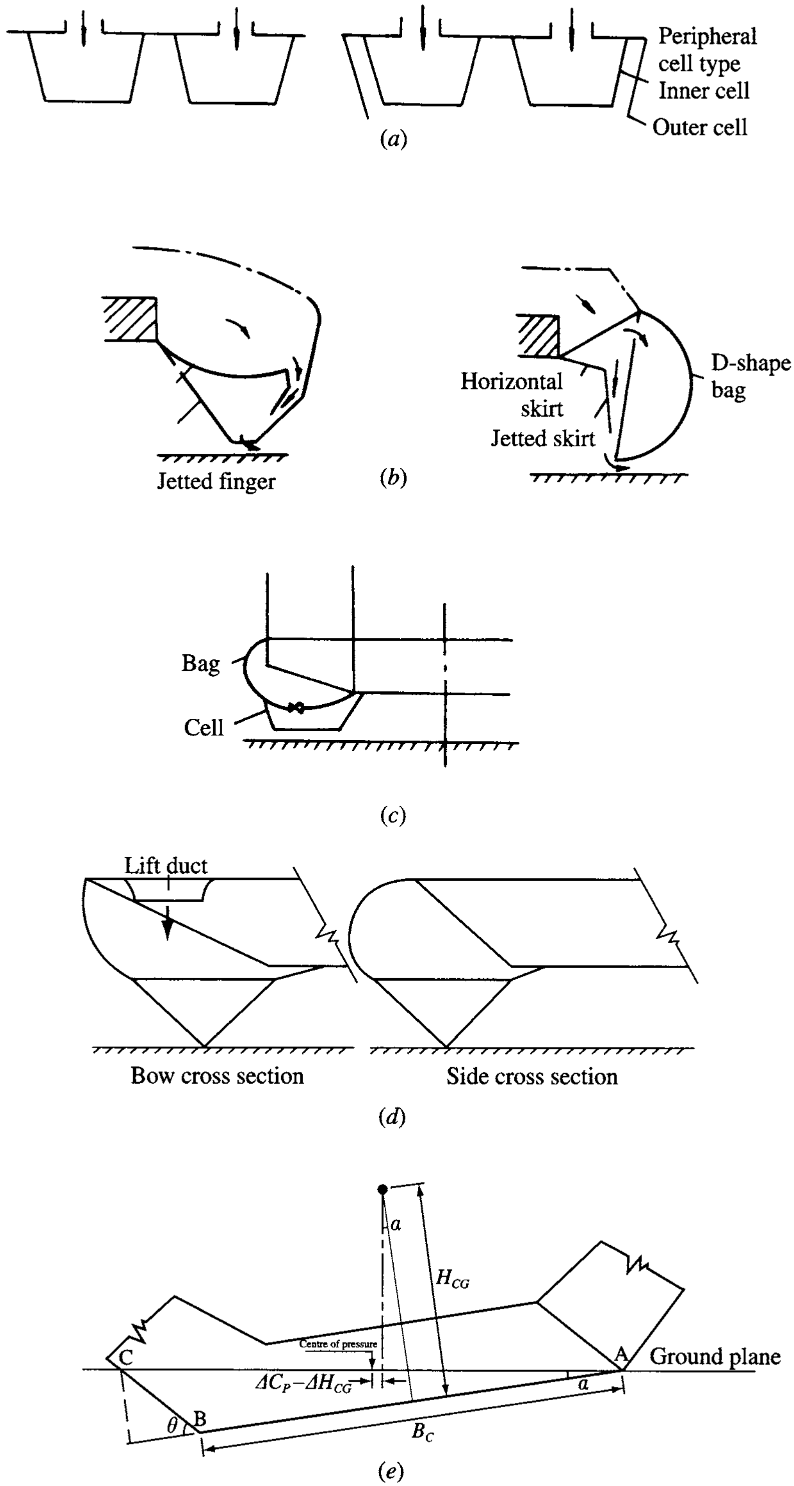
Bag and pericell (Fig. 7.13(c))

This skirt form is where the segments are modified into a similar geometry to a jupe. It can provide similar stiffness to the equivalent bag and finger skirt with stability skirts, for high-density craft. The bag pressure required is high, $1.4–1.8p_c$, so this skirt is less suitable for craft in passenger operation.

Open loop and segment (Fig. 7.13(d))

This skirt is used on smaller craft, generally below 5 t. The loop is at p_c and so this is the most efficient skirt form. The geometry of the loop can be varied to give the right combination of responsiveness for a seaway and skirt shift mechanisms can be used to enhance manœuvring. Tapered geometry is possible, though not normally used.

A swept-back bow skirt is necessary, as it is not practical to design a stable bulbous bow geometry as for a responsive bag and finger skirt. This is not a problem for medium-speed utility craft, for which the skirt is most popular. Around the bow the


Peripheral cell type
Inner cell
Outer cell
(a)
Jetted finger
(b)
Horizontal skirt
Jetted skirt
D-shape bag
Bag
Cell
(c)
Lift duct
Bow cross section
Side cross section
(d)
a
H_{CG}
Centre of pressure
C
A
Ground plane
$\Delta C_P - \Delta H_{CG}$
a
θ
B
B_C
(e)

hull gunwale is brought forward of the outer segment line by 20–40% of segment height.

The stern segments for this skirt are normally 'chip-bags', with the inner segment surface closed as well as the outer. Inner attachments to the hull are via a fabric sheet rather than skirt ties. Both of these items are for prevention of scooping while traversing hump speed.

Extended segment (Fig. 7.13(e))

This a relatively stiff skirt system for small utility and recreational craft in the size range 200–2000 kg. It does not respond greatly to waves and obstacles, except by deflection of individual segments. Segment width follows the same rule as for those attached to a loop, except that the height is now to the attachment at the craft gunwale, width being 20–25% of this total depth. Since the segments are 80–90% hull structure depth, they are generally quite wide and the air escape area is large in the segment delta region. Relatively high cushion flow is therefore required. This is not a problem for recreational craft, which do not have to meet the efficiency requirements of a commercial ACV.

Figure 7.14 illustrates a number of possible skirt plan-forms. Sketch (a) is the single-cell cushion, while (b)–(d) are variations on the skirt with inner keels, the longest keel being lengthwise in (b) and transverse in (d). Sketches (e)–(h) show variations on the jupe or pericell. Sketch (e) combines the bag and pericell with inner keels, while (f)–(h) dispense with the bag to provide a stiffer cushion. Current practice is to use as low as possible p_l/p_c, favouring designs (a) or (d) for optimum drag and seaworthiness.

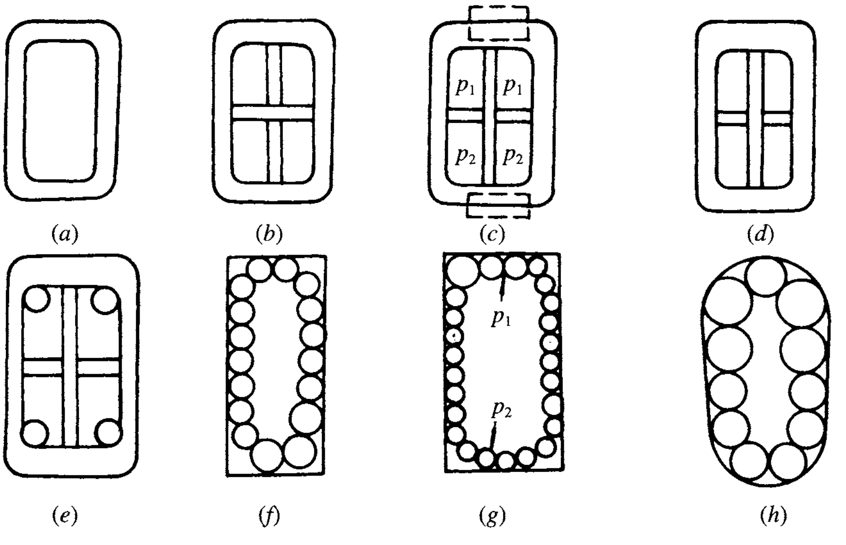


Fig. 7.14 Eight types of skirt considered as options for selection during the design of landing ACV by Bell-Textron Corporation of USA.

Fig. 7.13 (opposite) Configurations of typical skirts of France, Japan, USA and UK: (a) France – jupe; (b) Japan – jetted finger skirt, and jetted D-shaped bag; (c) USA – the bag and jupe; (d) UK – open loop and segment skirt; (e) UK – extended segment skirt.

SES bow and stern seals

SES generally use simple segments, or inflated bag and segment at the bow and multiple lobe bags at the stern. Earlier craft such as the Hovermarine series had ship-shaped bows. A shaped bag and segment bow skirt responded to waves minimizing cushion air loss in a seaway. More recently, SESs have been designed with similar planform to catamarans and almost two-dimensional segmented bow seals have been used on craft from the USA, Norway, Sweden, Germany and Japan.

The design requirements for these SES seals can be summarized as follows:

- A flexible response to the heaving motions of the SES, to minimize cushion pressure variations.
- A suitable damping rate for pitch motion of craft to give small wave resistance in rough seas.
- A suitable depth of cushion layer between the waves surface and the wet deck structure of the SES to attenuate wave slamming.
- The seals scoop less in the water in the case where craft run in waves at post-hump speed.
- The seals may be designed to 'plane' on the water surface at post-hump speeds, so that the seal will be raised up during contact with an oncoming wave and shutting as waves pass. Thus the air leakage rate might be reduced to a minimum and reduce lift power. This is similar to the captured air bubble principle which was put forward as a design many years ago, but which had little success because without flexible seals at the bow and stern, drag was very high in any sea state.

We will now briefly introduce the evolution and development of the seals on the SES.

Early developments

During the early SES development stage most researchers concentrated on the theoretical advantages of the captured air bubble principle, and thus the lift power, in order to be more suitable for development of larger-sized craft. At the end of the 1960s MARIC began to design a balanced seal (Fig. 7.15) mounted on the first

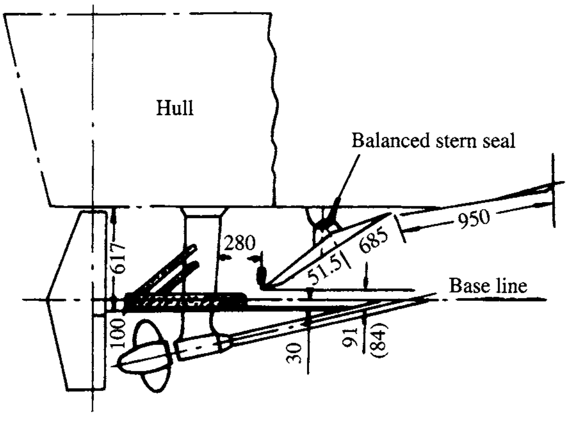


Fig. 7.15 The balanced rigid stern seal on Chinese passenger SES 713.

Chinese passenger SES model 713. The principle is the same as that of the balanced rudder, where the components due to the cushion pressure about the pivot of the stern seal were approximately equal to zero; therefore the stern seal can move up and down with the waves to reduce cushion flow rate and drag.

This type of stern seal has been successfully used on the craft model 713 but could not be developed on later ships due to the difficulty of adjustment of the balance coefficient of the stern seal, and a large amount of sand and mud piled up on the stern seal, which caused a reduction of the post-hump speed and poorer take-off performance of the craft.

Stern seal with air bag

This type, i.e. the inflatable bag, as shown in Fig. 7.16, has been mounted on both Chinese and US craft [61]. Unfortunately, most of these seals, as shown in Fig. 7.16, have not been developed due to their poor practicability and complicated structure.

Three-dimensional bag–finger bow seal and two-dimensional double bag type stern seal

As shown in Figs 1.14, 1.16, 1.17, 7.17 and 7.18, these are widely used on British SES, even though complicated technology is used for manufacture.

Pure finger bow skirt in combination with stern double planing bag

These are shown in Figs 7.16(b) and 7.17, and are widely used on the Soviet SES. With small waves on inland rivers, the bow pure finger skirts satisfy the requirements of seaworthiness for rivers, moreover the manufacturing technology and cost for this type of skirt are simpler and cheaper.

Bow skirts of bag–finger type and multi-bag stern skirt

These types are the general skirt types for the US SES. However, considering the poor abrasion characteristics of flexible skirts, they have studied the new bow seal of the piano keyboard type and composed of GRP in order to improve the operational life of the seal. The seal can be divided into several piano keyboard-like sections, which can be moved freely, and avoiding the coming waves in order to get good seaworthiness, low drag and high life of the seals (Fig. 7.20). This type of bow seal has been developed by the Americans and Dutch.

Two-dimensional bag and finger type bow skirt and stern planing rigid seal

As shown in Fig. 1.35, these are typical seals mounted on the Chinese inland river SES, which have characteristics of fine take-off capability, stable drag and low sensitivity to LCG shifting, but poor seaworthiness due to the larger heaving stiffness of the stern-fixed planing surface than that of the bow bag/finger type of skirts to stop plough-in in following waves.

Thanks to the small waves of inland rivers, these types of seals have been developed; but they are not really suitable to be used on craft operating on the coast or at river mouths. In such cases the seals will be replaced by the two-dimensional

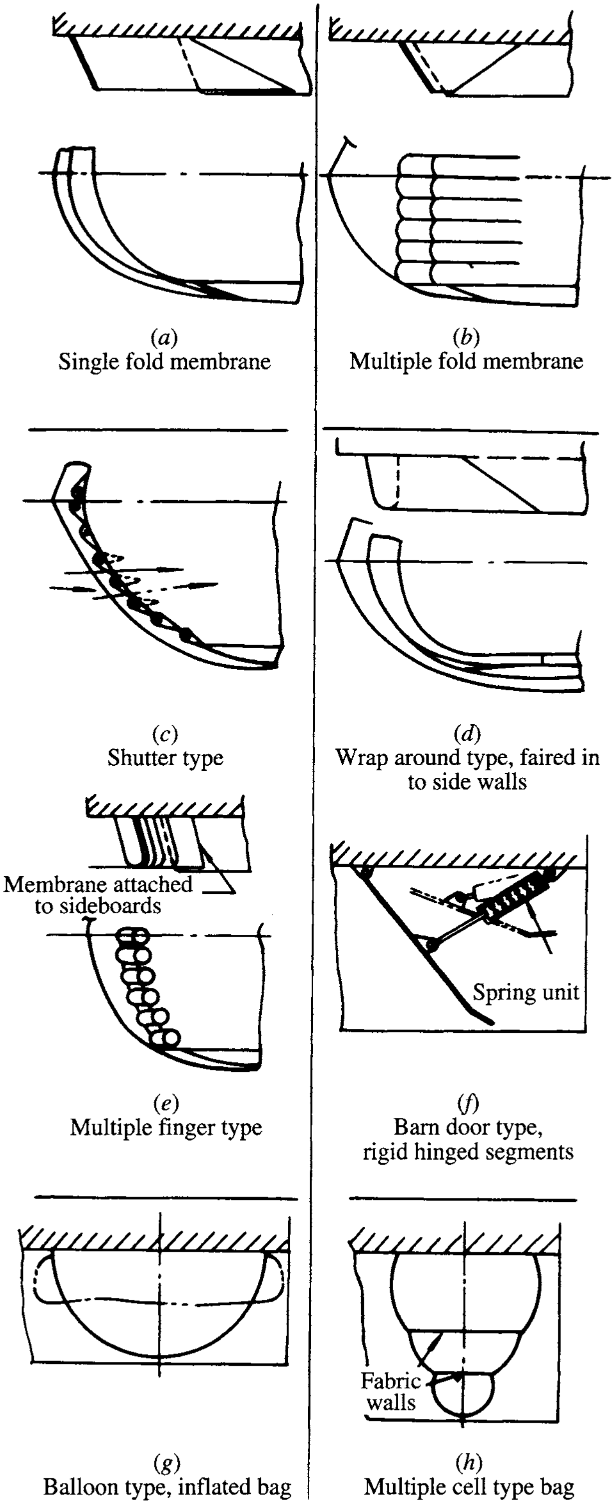


Fig. 7.16 Various experimental seals on US SES craft.

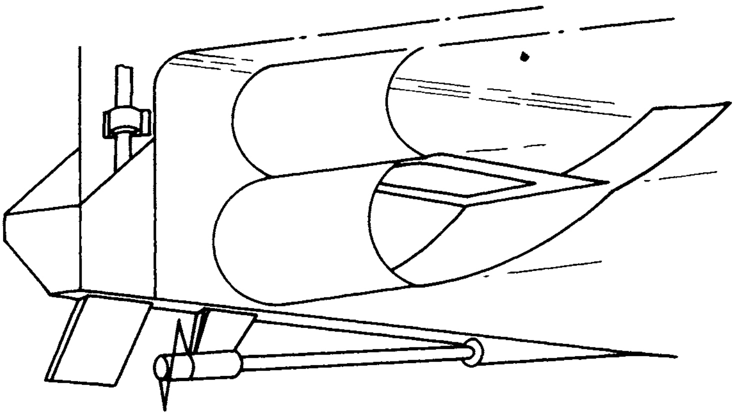


Fig. 7.17 Stern seal (double bag type) on British SES Hovermarine HM-2.

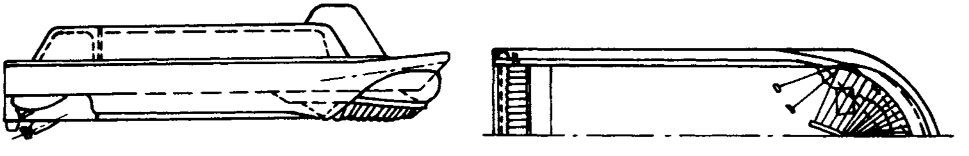


Fig. 7.18 Bow and stern seal of HM-2 Mk 3.

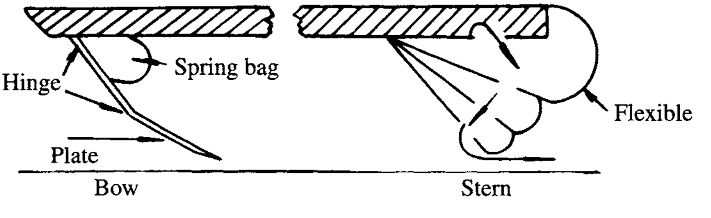


Fig. 7.19 Skirt system on US test SES.

bag–finger type bow skirt and two-dimensional double bag planing stern seals, which are similar to the skirts used on British SES.

Detachable bow/stern seals

Due to the non-amphibious capability of SES, the replacement of seals can be very difficult to carry out and the SES have to be got into floating dock or dock to repair or replace the skirts. For this reason skirt life is always an important parameter and has been investigated by researchers and manufacturers. No doubt detachable bow/stern seals will improve this situation significantly. Such seals have been applied to US and former Soviet SES.

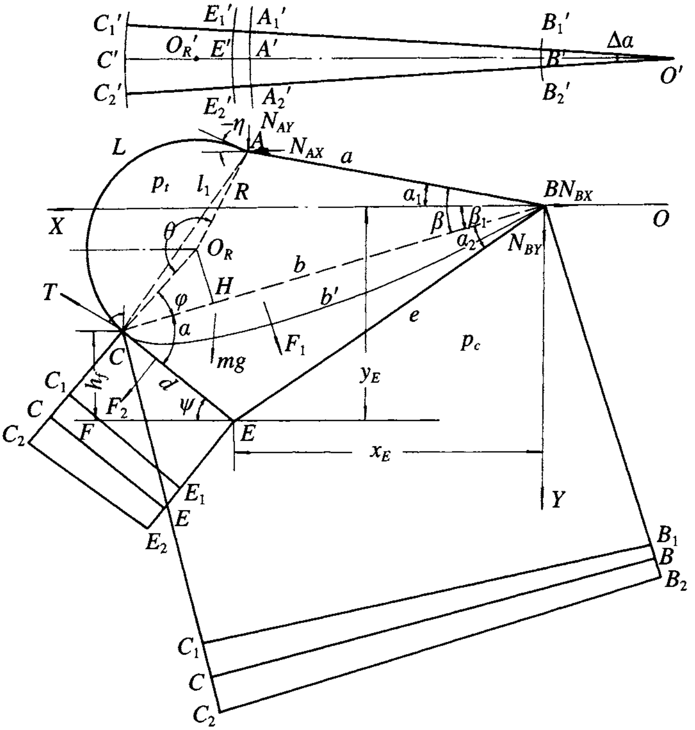


Fig. 7.20 Sketch identifying the principal parameters of bag and finger type skirts.

7.3 Static geometry and analysis of forces acting on skirts

Bag and finger type skirts are the most widely used in both modern ACVs and SES, so this type of skirt is the main object of study in this chapter. We will now review the basis for determining the static and dynamic equilibrium geometry for this type of skirt.

Static geometry of the bag and finger type skirt [62; 63]

Tests of skirts mounted on the craft 711-II and 722 have been carried out at model scale in the skirt test facilities of MARIC. During these tests some related parameters such as bag–cushion pressure ratio were varied and the variation of locations such as the joint point of the bag and finger C and the lower tip of the fingers E (as shown in Fig. 7.19) were also measured for analysis and recalculation.

Results from model tests

The following conclusions were drawn from the tests carried out:

1. *Elastic deformation and hysteresis effect on skirt geometry.* Tension deformation of the skirt fabric does not dramatically affect the shaping of the skirt, therefore it can

be concluded that the elastic modulus and the hysteresis effect of skirt cloth does not seriously affect the static deformation of the skirt, and can be neglected.

2. *Effect of bag to cushion pressure ratio*. Tests demonstrated that the skirt geometry was closely related to the bag–cushion pressure ratio p_t/p_c (p_t – bag pressure, p_c – cushion pressure).
3. *Bag chord length b*. It is found that chord length in the bag b varies only a little with variation of p_t/p_c, thus it can be considered that the lower part of skirt, triangle (Δ) BCE does not vary with the parameters, but that ΔBCE rotates about B in the X–Y plane as shown in Fig. 7.19.

   Meanwhile $b/b' \cong 0.96$–0.97 at $p_c/p_t \cong 0.85$ and b/b' will increase with p_c/p_t and vice versa, where b is the chord length of B′C′and b' the arc length between joints B and C.
4. *Distances A–B*. At a given size of air ducting of the craft, i.e. the linear distance between points A and B as shown in Fig. 7.19, it is found that the geometric parameters which greatly affect the static deformation of the bag–finger skirt are the length of the outer cloth of skirt bag b and its inner length b'. In general the vertical deformation of the skirt increases with b and the finger tip rises, but horizontal deformation increases with L and the finger tip drops down.

   It can be seen from this that skirt shaping and its deformation can be changed with L and b and it is found that the wave-yielding capability is fine when the vertical deformation of the skirt is large (Fig. 7.12). In addition, static stability can be improved when the horizontal deformation of the skirt is large. Nevertheless skirt tuck-under will occur in the large responsive skirt under the action of hydrodynamics, if no preventative measures are taken. For this reason it is not suitable for anti-plough-in of craft unless restraint diaphragms are installed in the bag.
5. *Diaphragms*. Experiments show that the D-shape bag will not affect the shaping and deformation of the skirt, if the diaphragms are loose in the static hovering condition. In the case of tight diaphragms, the joints of bag and finger C will be under the control of diaphragms to reduce the vertical deformation of skirt and enhance the anti-tuck-under stability of the skirt. But experiments demonstrate that the diaphragms of D-shape bag have less effect on the location and variation of the finger lower tip.

Mathematical models and their expressions can be formed, based on the physical models which are the basis of the experiments; thus comparison of the solution of equations with experimental results can be used to find the correction coefficients. This method can be developed from the two-dimensional skirt to the three-dimensional one.

Equations for static geometry and force analysis of skirts

The outer and inner geometry lines of the skirt form concentric circles (i.e. the arc, $B_1'B_2'$ and $A_1'A_2'$ are part of concentric circles), as shown in Fig. 7.19. If we take small element Δa as the investigated object, then the arc section $OC_1'C_2'$ is the projection of this element on the X–Z plane. The quadrilateral $C_1C_2B_1B_2$ is the section plan of the bag arc in this element, which is perpendicular to the line $\bar{B}\bar{C}$. The quadrilateral $C_1C_2E_1E_2$ is the section plan of the finger element perpendicular to the line C′E′.

MARIC experiments have demonstrated that both the joint point of the bag finger and the lower tip of finger E rotate about the axis through the point B. The length of finger d can be considered as invariable (i.e. line C′E′ does not wrinkle under the action of the cushion pressure) and the chord line of inner bag b is assumed to be approximately constant. Thus we take the ΔBCE as a free body for calculation.

For a thin inflexible ring as shown in Fig. 7.21(a), the following relation holds:

$$\pi r_1^2 \; p = 2\,\pi\, r_1\, t_1 \tag{7.1}$$

where p is the cushion pressure (N/m^2), r_1 the radius of the inflatable ring (m) and t_1 the tension of the membrane (N/m). For any given membrane width and unit length, the membrane tension can be obtained through the following equation (Fig. 7.21(b)):

$$2\, t_1 \sin(\theta/2) = 2pr_2 \sin(\theta/2) \tag{7.2}$$

thus

$$t_1 = pr_2 \tag{7.2a}$$

where θ is the angle as shown in Fig. 7.21(b)(°).

It can be shown from equation (7.2a) that the radius of the inner part of the bag R_1 is

$$R_1 = Rp_c/(p_b - p_c) \tag{7.2b}$$

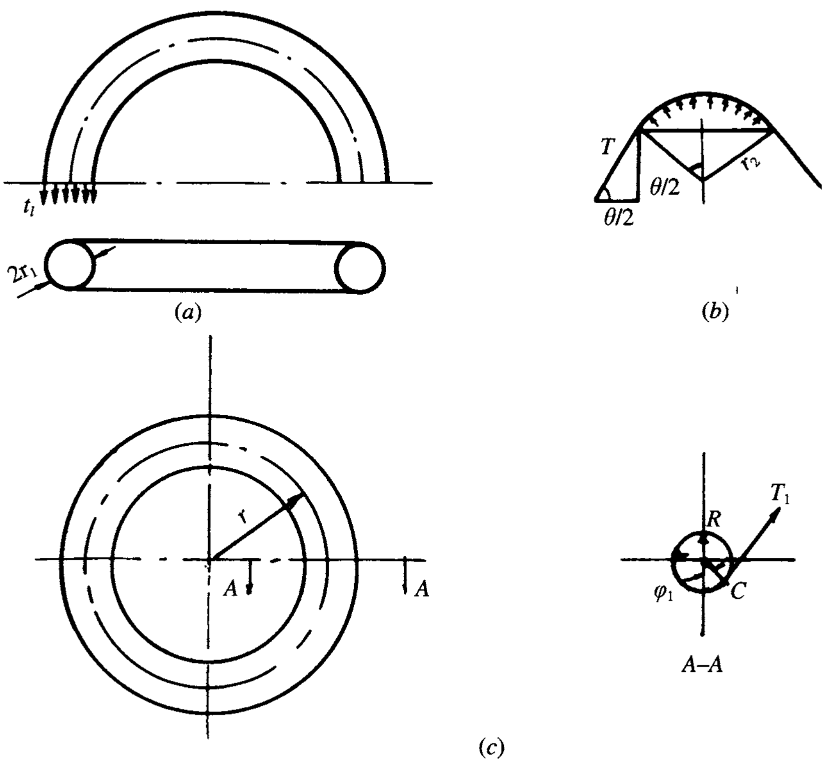


Fig. 7.21 Tension calculation for various inflatable diaphragms: (a) tension acting on inflatable loop; (b) tension on inflatable diaphragm; (c) tension acting on any point of diaphragm on inflatable circular life belt.

If the fingers are attached to the bag itself, as in a BHC skirt, the pressure force F_2 will deform this inner bag curve slightly. Readers are referred to section 7.6 for appropriate equations.

The tension of membrane T, at any given point on the inflatable circular torus, can be derived by the following expression as shown in Fig. 7.21(c):

$$T_1 \cos \phi_1 \, 2\pi \, (r + R \cos \phi_1) = \pi[(r + R \cos \phi_1)^2 - r^2]\, p_t$$

thus

$$\mathrm{T}_1 = p_t \, R \, K_r \tag{7.3}$$

where T is the tension of the membrane (N/m), p_t the pressure in the inflatable circular life belt (N/m^2), r the radius of the large circle at that point (m), H the radius of the small circle at that point (m) ϕ_1 the angle between the tension direction and abscissa and K_r the correction coefficient due to the three-dimensional effect; according to the equilibrium condition mentioned above, which can be written as

$$K_r = (2 + R/r \cos \phi_1)\,/(2\,(1 + R/r \cos \phi_1) \tag{7.4}$$

The tangential tension at any given point of the section is related to R/r and ϕ_1 and it is equivalent to that in two dimensions. If r equals infinity, where $K_r = 1$, $T_1 = p_t\, R$, it becomes the same as equation (7.2). Knowing the tension acting on the membranes due to the action of any given air pressure, the method can be developed to calculate the tension acting on the skirt bag.

There are four forces acting on ΔBCE:

- the tension of skirts at point C;
- the difference of pressure between the bag and cushion acting on the curves of inner bag BC;
- weight due to weight of the skirt fabric;
- the force due to the cushion pressure acting on the finger CE.

These forces can be calculated and substituted into the equilibrium equations. Thus the coordinates of C, E at different cushion and bag pressures can be obtained.

For curved sections, a piece with the spreading angle of Δa, like a segment of an orange, can be taken as the free body for calculation, and the equilibrium equation of forces can then be expressed as follows:

1. Tension T acting on the curve C_1C_2,

$$T = K_r \, p_t R r_c \, \Delta a \tag{7.5}$$

   where R is the radius of the curve at the outer bag (m), $r_c = \mathrm{O'C'}$ (m), p_t is the cushion pressure (N/m^2), T the tension acting on the curve C_1C_2 (N) and K_r the correction coefficient due to the three-dimensional effect, obtained according to equation (7.4)

$$K_r = \frac{(2r_o + R \cos \phi_1)}{[2(r_o + R \cos \phi_1)]}$$

   $r_o = \mathrm{O'O'_R}$ (m), when $r_o \Rightarrow \infty$, the tension is similar to the tension on the inflatable membranes per unit length at two-dimensional condition, i.e. $T = p_t R$. It is the same as in equation (7.2).

2. The force acting on the curve of inner bag $B_1B_2C_1C_2$ due to the difference of pressure between the bag and cushion is thus

$$F_1 = b/2\,(r_B + r_c)\,(1 - p_{ct})\,p_t\ \Delta a \tag{7.6}$$

where $r_B = O'B'$ (m), $p_{ct} = p_c/p_t$ and F_1 is the force acting on the curve at inner bag $B_1B_2C_1C_2$ (N).

3. Force acting on the skirt finger, F_2, is

$$F_2 = d/2\,(r_E + r_c)\,p_{ct}\,p_t\ \Delta a \tag{7.7}$$

where r_E is the outer radius O′E′ (m) and d the length of the skirt finger (m).

4. Weight of skirt fabric at X, with the spreading angle of Δa

$$mg = W_c\,r_c\,\Delta a\,K \tag{7.8}$$

where mg is the skirt cloth weight (N), W_c the weight of the two-dimensional section of skirt ΔBCE per unit length (N/m) and K the correction coefficient due to the three-dimensional effect, i.e. the ratio of skirt cloth weight per unit length of the curve with the radius of r_c, to W. Generally we take $K = 0.8$.

5. The formation of the skirt and some parameters such as the location of joints, can be obtained by the following equations. Taking the moment about the BZ axis with the foregoing four forces and according to the equilibrium condition, putting the sum of moments equal to zero, then

$$\begin{aligned} K_r\,P_t\,R\,r_c\,\Delta a - b\cos\phi &= b/2\,(r_c + r_b)\,\Delta a\,(1 - p_{ct})P_t\,(b/3\,[r_b + 2r_c]/[r_b + r_c]) \\ &\quad + d/2\,(r_c + r_E)\,\Delta a\,p_{ct}\,P_t\,(b\cos a\ d/3\,[r_c + 2r_e]/[r_c + r_e]) \\ &\quad + Wc\,r_c\,\Delta a\,K\,K_m\,b\cos(\beta - a_1) \end{aligned} \tag{7.9}$$

where K_m is the coefficient due to the CG of the skirt cloth, i.e. the ratio of vertical distance between the BZ axis and the action line of skirt weight to the base-line and ϕ, a, β are geometrical parameters of the skirt as shown in Fig. 7.19. Thus equation (7.9) can be rewritten as

$$\begin{aligned} \overline{\mathrm{CH}} &= R\cos\phi \\ &= [K_1\,b/2\,(1 - p_{ct}) + d\,p_{ct}\,(K_2\cos a - K_3 d/2b \\ &\quad + K_4\,K_m\,W_c/p_t\cos(\beta - a_1)]\ 1/K_r \end{aligned} \tag{7.10}$$

where K_1, K_2, K_3, K_4 and K_r, are correction coefficients for the three-dimensional effect. The skirt will become two-dimensional, i.e. both the inner and outer mounting lines will be linear, if r_b, r_c, r_E and r_o tend to infinity.

In the case where the skirt is located at the bow or stern corners of the ACV, the inner and outer mounting lines are curved (where B is the inner mounting point and A is the outer mounting point) and r_o is not larger than R, and the skirt can be considered as three-dimensional, then the four coefficients can be shown as

$$K_r = \begin{cases} \dfrac{(2r_o + R\cos\phi_1)}{[2(r_o + R\cos\phi_1)]} & \text{Three-dimensional} \\ 1 & \text{Two-dimensional} \end{cases}$$

$$K_1 = \begin{cases} 2/3 + 1/3\, r_b/r_c & \text{Three-dimensional} \\ 1 & \text{Two-dimensional} \end{cases}$$

$$K_2 = \begin{cases} 1/2 + 1/2\, r_E/r_c & \text{Three-dimensional} \\ 1 & \text{Two-dimensional} \end{cases}$$

$$K_3 = \begin{cases} 1/3 + 2/3\, r_E/r_c & \text{Three-dimensional} \\ 1 & \text{Two-dimensional} \end{cases}$$

$$K_4 = \begin{cases} \mathrm{K} & \text{Three-dimensional} \\ 1 & \text{Two-dimensional} \end{cases} \qquad (7.11)$$

In addition some complementary relations concerned with the dimension ACB can be written as follows:

$$a^2 = b^2 + (2\,R \sin \theta/2)^2 - 2b\,(2\,R \sin \theta/2) \cos (\pi/2 - \theta/2 + \phi) \qquad (7.12)$$

$$a^2 = (2\,R \sin \theta/2)^2 - b^2 + 2ab \cos \beta \qquad (7.13)$$

$$R = L/\theta \qquad (7.14)$$

where a and L are the geometrical parameters of the skirts and air ducts.

During calculation of the location of points C and E and the shaping of skirts and in the case where the parameters of the skirt and location of inner/outer mounting positions are given, then the values of L, b, a, d, W_c, K_m and K in the foregoing equation (in general, when $p_c/p_t = 0.8$–0.95, then $b' \approx 1.02b$–$1.05b$) are given, then ϕ, θ, β can be obtained according to equations (7.10) and (7.12)–(7.14).

This equation can be solved with aid of a computer by progressive approximation methods. Thus the shaping of the skirt, i.e. the coordinates of points C and E, can be obtained as

$$x_c = b \cos \beta_1$$
$$y_c = b \sin \beta_1 \qquad (7.15)$$
$$x_E = e \cos (\beta_1 + a_2)$$
$$y_E = e \sin (\beta_1 + a_2) \qquad (7.16)$$

where

$$\beta_1 = (\beta - a_1)$$
$$e = (b^2 + d^2 - 2bd \cos a)^{0.5}$$

Thus the x_c, y_c, x_E, y_E corresponding to the changing p_{ct} can be obtained, namely, the static deformation of the skirt caused by the change of p_{ct}.

If the finger tip location (x_E, y_E) of the skirt, the inclination angle of the skirt, finger depth d and the size of air duct are given, then L, b, b' and the other skirt parameters, which satisfy the design bag–cushion pressure ratio, can be obtained, and the problem concerned with laying-off the skirt can be solved.

Comparison between the experimental results and calculation

Reference 62 introduces experimental data obtained by MARIC and comparison with theoretical calculations, as follows:

1. Calculated and experimental results of the location of bow skirt point E for ACV model 711-II and 722-I are shown in Figs 7.22–7.24. It can be seen that the theoretical calculations agree with experimental results very well. The method above has therefore been used further for design, analysis and laying-off of ACV and SES skirts in China with good results.
2. From these calculations, it can be seen that in the case where the mounting point and configuration parameters have been given, then the location of points C and E will vary with bag/cushion pressure ratio p_t/p_c. As a general rule, with higher bag pressures, the skirt base-line will drop down as the bag/cushion pressure ratio increases.

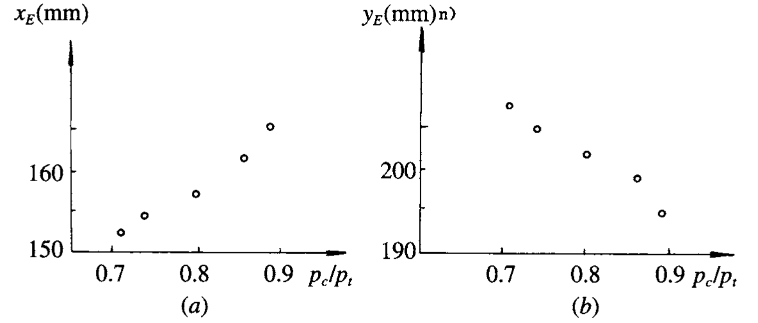


Fig. 7.22 The variation of locations for side skirts finger tip on model 711-II with changes in p_c/p_t: (a) variation of horizontal location X_e; (b) variation of vertical location Y_e.

Calculation of supporting forces acting on the joints of bag/finger skirts

The supporting forces acting on the joints (such as points A, B) are not difficult to calculate. First of all, the components of the four forces T, F_1, F_2 and mg on the x and y axes can be written as

$$
\begin{aligned}
T_x &= p_t R \sin(\phi + \beta - a_1) \\
F_{1x} &= -p_t b\,(1-p_{ct}) \sin(\beta - a_1) \\
F_{2x} &= p_t d\, p_{ct} \sin(a - \beta + a_1) \\
mg &= 0 \\
T_y &= -R p_t \cos(\phi + \beta - a_1) \\
F_{1y} &= p_t b\,(1-p_{ct}) \cos(\beta - a_1) \\
F_{2y} &= p_t d\, p_{ct} \cos(a - \beta + a_1) \\
mg_y &= mg
\end{aligned}
\tag{7.17}
$$

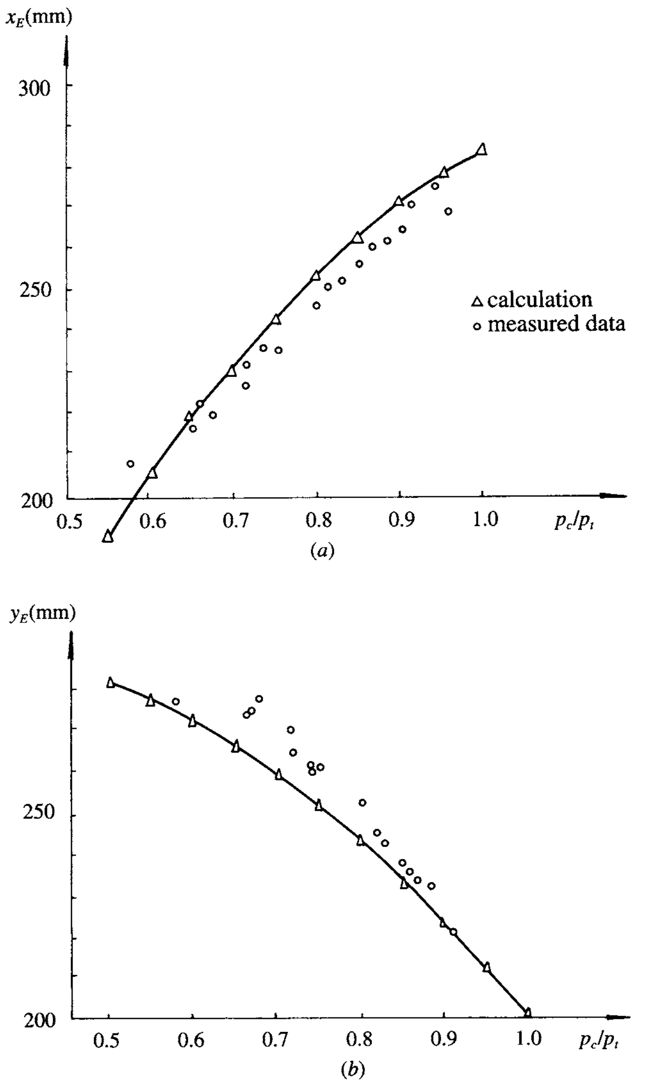


Fig. 7.23 The variation of location for finger tip of modified skirt on craft type 711-II with high responsiveness.

Then the supporting forces acting on joints A, B can be calculated:

$$
\begin{aligned}
NA_x &= -p_t\, R \cos \eta \\
NA_y &= -p_t\, R \sin \eta \\
NB_x &= -\,(T_x + F_{1x} + F_{2x} + mg_x) \\
NB_y &= -\,(T_y + F_{1x} + F_{2x} + mg_y) \qquad (7.18)
\end{aligned}
$$

where η denotes the angle between tangent of curve AC at point A and the x axis as in Fig. 7.19.

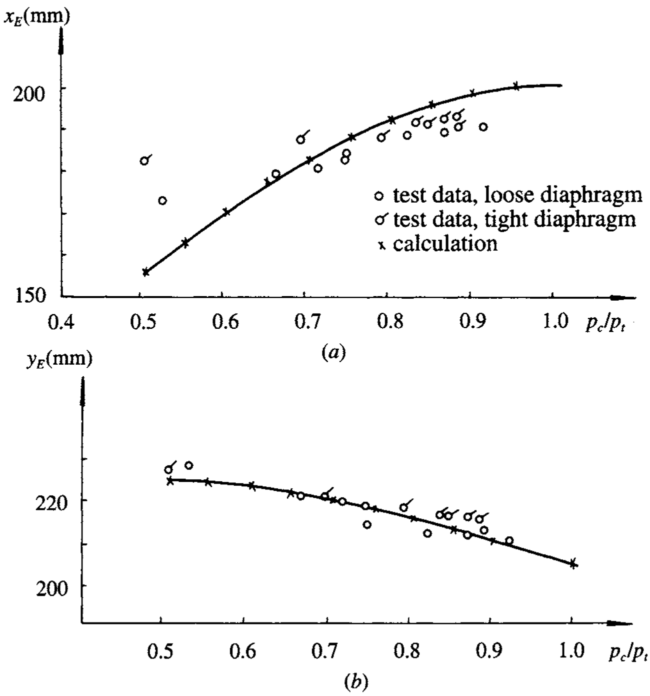


Fig. 7.24 The variation of locations x_E and y_E for bow skirt finger tip.

7.4 Geometry and analysis of forces in double or triple bag stern skirts

The geometry for bag skirts is initially designed using static balance of forces, using a two-dimensional unit slice of the skirt. Drag and other dynamic forces are initially ignored. These are considered later when analysing the craft response to waves.

For both ACVs and SES, most stern skirts on Chinese craft are double or triple planing bags, the advantages of which are:

1. In contrast to bow skirts, bag–finger type stern skirts add to water scooping drag because the direction of cushion pressure acting on the fingers is the same as that of oncoming flow. On the other hand, the double or triple loop planing skirt can plane on the water surface to reduce drag and improve response to the water surface.
2. The hole area S_{d1}, S_{d2}, S_{d3} can be varied to adjust the bag geometry by adjusting the pressure ratio between loop segments p_{t1}/p_{t2}, p_{t2}/p_{t3}, p_{t3}/p_c, etc. as shown in Fig. 7.25.

   Adjusting the response of the skirt bag to waves will improve the seaworthiness of the craft. Its natural period can be changed by changing pressure ratio p_t/p_c, or its damping response by changing volume and inter-bag feed-hole areas. It is difficult to specify a general optimum, so it is recommended that designers experiment with this parameter until the relation between pitch stiffness and skirt drag gives a

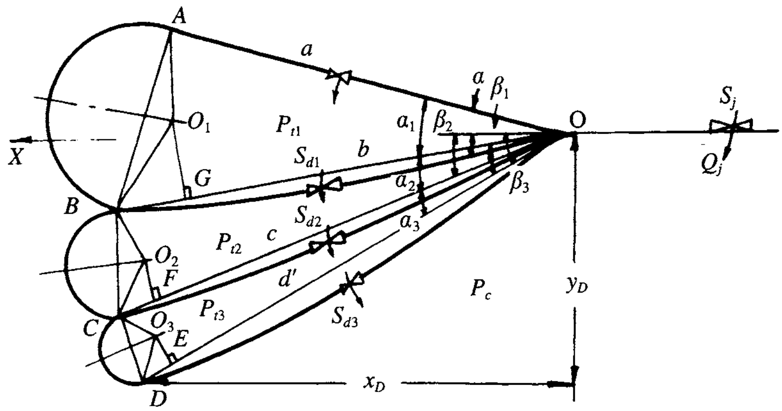


Fig. 7.25 The principal geometric parameters of triple bag skirts at stern.

satisfactory balance between craft motion response and drag forces which control the acceleration of a craft through hump speed.

3. The mounting angles β_1, β_2, β_3, etc. of the skirt bags can be adjusted to obtain the optimum angle of attack of the lowest bag. This will also affect the drag forces generated by the stern skirt. Having too flat an angle can lead to local flutter and skirt bounce on smooth surfaces.

The bag volumes and bag holes total area (S_{di}) can both be adjusted in order to provide a desired capacitance–resistance match and good wave response. At MARIC we often use the bag–finger skirt for the bow skirt and multiple bags at the stern skirt, both for ACVs and SES.

From the theoretical point of view, the calculation method for multi-bag skirts is similar to that for the bag–finger skirt as shown in Fig. 7.25 [64] :

1. The geometrical location of lowest skirt tip, X_d, Y_d, can be determined first, based on the requirements of the craft cushion area. Normally this is slightly inboard of the outer attachment point (A).
2. The bag pressure P_{t1}, P_{t2}, P_{t3}, areas of bag holes S_{d1}, S_{d2}, S_{d3} of various layers of bags, and flow rate into stern bag Q_d, flow rate into cushion Q_j and area of air inlet into cushion S_j, etc. can all be determined. A starting point is to use $P_{t1}/P_{t2}/P_{t3}$ = $1.2p_c$ and feed-hole area 5%.
3. The bags' volumes and their geometrical parameters such as β_1, β_2, β_3, (or a_1, a_2, a_3) etc., and the chord length of inner bag area a, b, c, d, etc. can be determined. These may be varied to achieve the balance of requirements between seaworthiness response and stiffness for stability of the craft.
4. The equilibrium condition for forces such as
   (a) tensions T acting on skirt cloths at points D, C and B;
   (b) force F due to difference of pressure between the different bags acting on OD, OC and OB;
   (c) force F_2 due to bag pressure and acting on the curve of the outer bag CD, BC, AB;
   (d) weight of skirt bag W_b

may be determined in a similar way to the calculation method for bag and finger skirts mentioned above.

According to the equilibrium of moments, namely the sum of moments about the OZ axis of these four forces (T, F, F_2 and W_b) equalling zero, the radius of curvature (i.e. R_1, R_2, R_3 and the coordinates of O1, O2, O3) and the length of curve on various outer bags AB, BC, CD can be obtained. The calculation can be started from the lowest bag, then extended to every bag.

By the same reasoning, if the skirt bags' geometry, such as the sizes of the inner/outer bag of skirt, can be given, then the coordinates of points B, C and D can also be obtained by this method.

However, the assumption implicit in the calculation above, that the cushion pressure acting on the stern skirt is uniformly distributed, may not be accurate, particularly in the case where craft are running on a water surface. Cushion air is blown from the air cushion just like a venturi tube as shown in Fig. 7.26.

According to [65], the pressure acting on the base of the skirt bag is not uniformly distributed, sometimes even some suction pressure is exerted on the stern bag as shown in Fig. 7.26. This method can therefore only be used for initial geometry and the detail shaping of stern skirts is generally determined by experiment in a skirt test facility which includes a water surface.

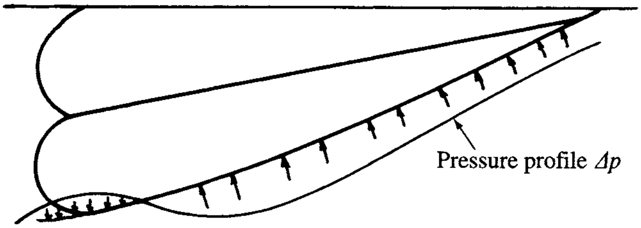


Fig. 7.26 Pressure distribution acting on the inner surface of a stern skirt.

7.5 Geometry and forces for other ACV skirts

Extended segments (Fig. 7.13(e))

The geometry for an extended segment is basically the same as an open loop and segment. The lower tip should be placed 10–20% of segment height inwards from the gunwale. It is normal to use an outer face angle between 40° and 45° (lower angle gives higher stability). Segment width is 40–50% of skirt depth. Above the main segment, the fabric sides are continued. An outer panel is sewn on to the segment forming a loop. The 'loop' radius is smaller than an open loop geometry.

The segment may be attached directly to the hull, or a short tie may be incorporated. The tie can allow some rotation of the segment, giving some responsiveness to this skirt.

Bag and pericell (Fig. 7.13(c))

This type may be considered a further variation on the bag and segment. Consider first a segment with an inner face. The force on this inner membrane will tend to distort the inner bag downwards; on the other hand, since the sealed segment will now have a higher pressure than p_c, the bag geometry will be flatter.

Now consider opening the segment rotating the walls more vertically, say to 35°. The air flowing through the segment cell will now be released at its base and the pressure in the cell will be close to p_c. If the toe line of the cell is horizontal, small vertical movements will seal the cell against the ground and the internal pressure will rise to p_b. If the movement is fast, the pressure transient in the cell will be rather higher than p_b as flow is reversed into the bag.

To soften this response, the toe line can be angled upwards 10–20°. The first part of the heaving motion will then cause a response similar to a bag and segment, then in higher roll or heave the ground plane will seal the cell and cause the stiffer response.

Open loop and segments (Fig. 7.13(d))

The open loop and segment is similar to a bag and segment, where there is no bag overpressure, thus the relations in section 7.3 all apply for detail calculation. The inner bag line becomes a straight line. Fig. 7.13(d) shows typical geometries for a side, bow and stern skirt of this type. The relations between loop radii and segment geometry are indicated graphically. Best results are obtained with this type of skirt when the hull depth is 70–100% of the cushion depth. It is advisable to keep the side loop intersection angle with the segment top less than 15° to minimize the tendency to bounce. Bounce is also a problem if the segment tip is outside the gunwale line.

At the stern, segments are sometimes raised from the base-line, leaving a clear air gap of 5–15% of cushion depth to reduce scooping at hump speed. This can lead to increased wear rate on the stern corner segments and so is only recommended if a prototype skirt gives problems.

Stability skirts

A number of different stability skirt configurations are shown in Figs 7.2, 7.9, 7.10 and 7.14. They are generally a series of almost circular trunks inflated to p_b, extended to between 60 and 80% of cushion depth. For deep cushion craft, inflated cones (similar to chip-bag segments) may be mounted on the circular trunk. The forces applied by these trunks may be determined from the membrane tension force, equation (7.2).

7.6 Analysis of forces causing the tuck-under of skirts

In the previous two sections, we have introduced the static shaping and force analysis for two- and three-dimensional bag–finger skirts. These are the basic theories for predicting the skirt shaping. In general the static shaping of bag and finger bow or side skirts, both running on water or over land, can be accurately predicted by this method, so it has become the basic method for skirt design.

That is fine statically. Unfortunately there is another problem This relates to the dynamic response of bow skirts which might cause the plough-in of an ACV through skirt tuck-under.

The responsive skirt with low natural frequency is widely applied to modern ACVs and also SESs. Due to the application of this type of skirt, the location of bag and finger interface joints (X_c, Y_c) and lower tip of fingers (X_E, Y_E) will vary considerably with the bag–cushion pressure ratio.

This gives the advantages and features of the responsive skirt. It may also lead to a reduction of the tuck-under resistance of skirts. For this reason, it is necessary to study the hydrodynamic characteristics of skirts, the rationale of skirt tuck-under and the measures for improving the tuck-under resistance. The hydrodynamic characteristics of skirts and the skirt tuck-under resistance are introduced as follows.

Basic assumptions

1. We take the two-dimensional bag–finger type skirt as an example and assume that the fingers are connected with bag at the fore and rear parts of the skirts, but not at other parts as shown in Fig. 7.27.
2. The wetted depth of the skirt will not be as deep as up to the skirt bag, namely the draft of the skirt is less than the height of the fingers. The finger will stick to the water surface flat in the case where the tiny finger is pushing the water surface, thus the lift of the skirt in this area will be compensated by cushion pressure. The water friction of skirts has to be taken into account.
3. The air pressure is uniformly distributed in inflatable skirts.

Analysis of forces acting on the skirt

1. Tension acting on curved sections of the skirt bag (see Fig. 7.28) under the action of uniform pressure, the forces acting on AC, CD, DB are

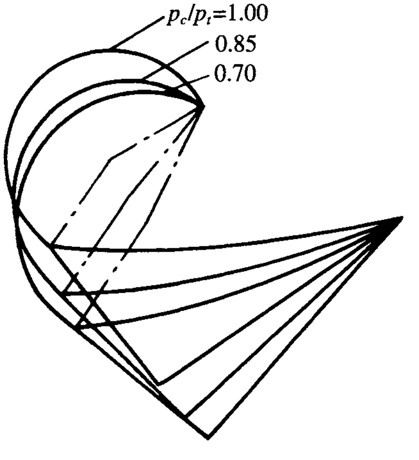


Fig. 7.27 Influence of bag cushion pressure ratio p_c/p_t on skirt shapes (test results).

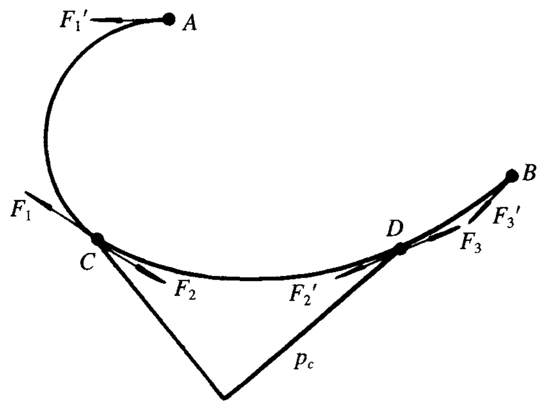


Fig. 7.28 Forces acting on bag and finger side skirt.

$$F_1 = p_t R_1$$
$$F_2 = (p_t - p_c) R_2$$
$$F_3 = (p_t - p_c) R_3 \tag{7.19}$$

where R_1, R_2, R_3 are the radius of curvature of AC, CD, DB (m) and F_1, F_2, F_3 the skirt cloth tension at A, C, D per unit length of skirt (N/m).

2. Hydrodynamic force acting on the skirt fingers. In the same way as the skirt drag analysed in Chapter 3, the finger sticks partly to the water surface and the part not touching the water surface has local bending deformation as shown in Fig. 7.29. Thus the friction drag due to water can be written as

$$F_5 = K_w p_c l_2 \tag{7.20}$$

where F_5 is the drag of skirt finger per unit length (N/m) and K_w the hydrodynamic coefficient of skirts, which can be written as

$$K_w = \zeta \, 0.5 \, \rho_w \, V_w^2 / p_c$$

where ζ is the water friction coefficient of skirts, V_w the flow speed (i.e. craft speed) (m/s), l_2 the wetted length of the skirt, which can be written as follows, from equations (3.12) and (3.13):

$$l_2 = \frac{d_w}{\sin \theta} \cdot \frac{1}{a}$$

$$a = (1 - K_w [(1 - \cos \theta)/(\sin \theta) - \theta/57.3]) \tag{7.21}$$

d_w is the submerged depth of fingers (m) and θ the inclination angle of the finger (Fig. 7.29)(°).

Meanwhile, the water friction drag of the finger is balanced by the tensions of the finger fabric, thus it can be written as

$$F_s = R_w p_c$$
$$\therefore R_w = K_w l_2 \tag{7.22}$$

where R_w is the radius of curvature at the bending area of the finger (m).

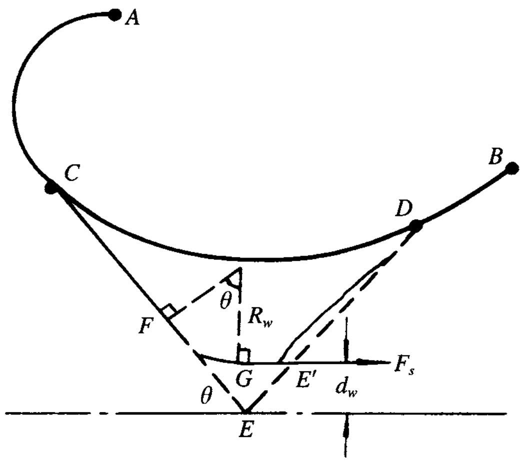


Fig. 7.29 Force acting on skirt components once finger contacts water surface.

Analysis of forces acting on fingers under the action of cushion pressure

Reference is made to Fig. 7.30. Forces acting on fingers under the action of cushion pressure F_4 can be written as

$$F_4 = (d - R_w\,\theta - l_2)\,p_c \tag{7.23}$$

where d is the finger length (m), F_4 forces acting on two joints C and D of the bag and finger via the diaphragm, and according to the theory of force analysis for a flexible rope the force can be written as

$$F_{4c} = F_4\,(d - d_h/2)\,d$$
$$F_{4D} = (F_4\,d_h)/2d \tag{7.24}$$

where $d_h = d - R_w\,\theta - l_2$, F_{4c} is the tension of the skirt fabric at point C, the direction of which is along CE (Fig. 7.30), and F_{4D} the tension of the skirt fabric at point D, as shown in Fig. 7.30.

Since the finger is in contact with the water surface, which may cause bending of the finger fabric, the diaphragms will be wrinkled, so that the direction of force F_{4D} is tangential to the direction of the curve at the point D′. The point of action is at D.

Force acting on the diaphragms of D-shape bags

Two conditions may be taken into account:

1. The pressure in a D-shape bag is the same as the bag pressure. In this case, no force acts on the diaphragms. If the diaphragm is tightly mounted, then the direction of force acting on the diaphragm will be in the direction of the diaphragm, which can be represented as

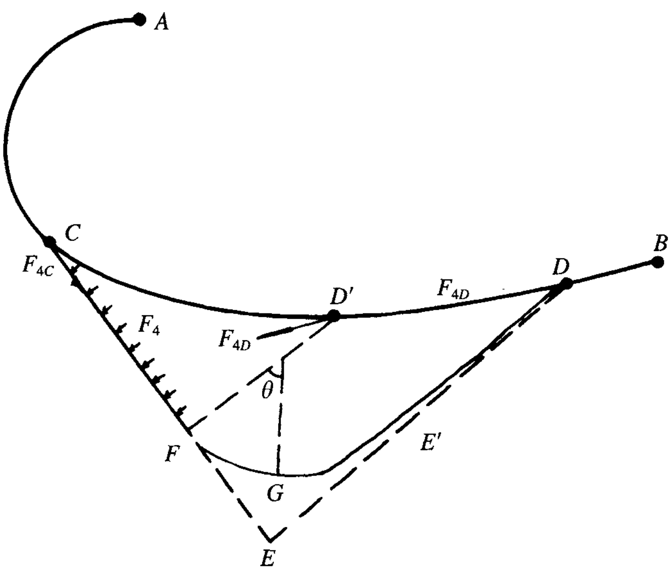


Fig. 7.30 Hydrodynamic forces acting on skirts running on water.

$F_{1w} = 0$ (where the diaphragm is loose)
$F_{1w} = F_{1w}$ (where the diaphragm is tightly mounted, the value of which can be obtained from the equilibrium equation by iteration)

2. In the case where the pressure in a D-shape bag differs from the bag pressure, then

$$F_{1w} = (p_t - p_D)\, R_{1w} \tag{7.25}$$

where F_{1w} is the tension of fabric on a D-shape bag per unit length (N/m), p_D the pressure in a D-shape bag (N/m^2) and R_{1w} the radius of curvature of the diaphragm in a D-shape bag (m).

Skirt weight

In comparison with hydrodynamic forces, the effect of skirt weight *mg* is small and now we assume that it is acting on points C and D. We use the unit weight of a two-dimensional slice of the skirt section, i.e. weight per meter, to evaluate the skirt loading.

Equilibrium equation of forces and its solution

Summing the forces mentioned above, the forces acting on point C are $F_1 F_{1w}$, F_{4c} F_s and the forces acting on point D are F_{2d}, F_{4d}, F_3 as shown in Fig. 7.31 respectively.

Because the skirts are in equilibrium, then summation of the components acting on points C and D on the x, y axes will be equal to zero, then

$$\Sigma F_{Cx} = \Sigma F_{Cy} = \Sigma F_{Dx} = \Sigma F_{Dy} = 0 \tag{7.26}$$

This equation can be rewritten as

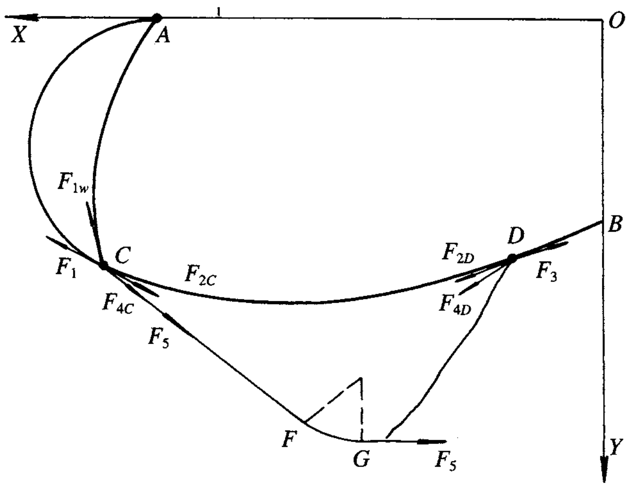


Fig. 7.31 Forces analysis for deformed fingers.

$$F_{1x} + F_{1wx} + F_{2cx} + F_{4Cx} + F_{5x} = 0$$

$$F_y + F_{1wy} + F_{2Cy} + F_{4Cy} + F_{5y} + K_{cmg} = 0$$

$$F_{2Dx} + F_{4Dx} + F_{3x} = 0$$

$$F_{2Dy} + F_{4Dy} + F_{3y} + (1 - K_c)mg = 0 \tag{7.27}$$

where mg is the weight of the skirt on ΔCDG per unit length (kg/m) and K_c the coefficient of effective skirt weight.

The value of K_c is very difficult to estimate due to the fact that a part of the weight is supported by the water surface. In general, thanks to the small effect of skirt weight on geometry and part of the skirt weight supported on the water surface is far less, this component of the skirt weight can be neglected and does not cause large errors. Coefficient K_c can be determined by the relation between the location of points C, D and the CG of the skirt.

Now the cushion parameters p_c, p_t, the geometrical parameters of skirts d and length of curves AC, CD, DB, AC (diaphragm of D-shape bag), the location of points A, B, the parameters due to the emerged location of the skirt such as K_w, d_w, etc. are given, then the four variables R_1, R_2, R_3, β_2 (the angle between BD and the y axis) can be solved by the four equations (7.27).

In the same way as the methods for static shaping of skirts, the locations of points C, D and the angle between the F_5 and the y axis may be determined and the tuck-under sensitivity of the skirt can then be estimated. The calculation mentioned above is rather complicated, but it can be solved with the aid of a computer.

Comparison between the theoretical calculations and experimental results

Experiments at MARIC are normally carried out in a circular water tunnel. The experiments for tuck-under of skirts with various configurations, emerged depth of the finger, and friction coefficients of the skirt are all carried out in this facility.

Comparing between the theoretical calculations and experimental results obtained, MARIC has derived the following conclusions:

1. It can be seen from data plotted in Fig. 7.32 that theoretical analysis agrees well with experimental results.
2. Larger K_w (namely the larger skirt finger friction drag coefficient) gives deeper emerged length of finger d_w, so that the fingers tuck under more easily.
3. Based on calculated results for the various skirt parameters, bow skirts are less resistant to tuck-under, so one has to take care to design a large deformable responsive skirt for this location.
4. The diaphragms of a D-shape bag with the tension of F gave the capability to control skirt tuck-under, particularly in the case where the diaphragms were tightly mounted (rather than loose in the static hovering condition).
5. The calculation method mentioned above can be used in the design of bow skirts. In the case of selecting or designing the configuration of a bow skirt, the ability to prevent tuck-under had to be checked according to the K_w and permitted emerged depth d.

7.7 Skirt bounce analysis

Bounce is a low frequency vibration of the skirts, which occasionally occurs in an ACV hovering static over a smooth surface or at low speed, both on Chinese ACVs such as models 711-IIA, 716A and 7161I, and various ACVs from the UK and USA. During bounce, the skirts vibrate with a large amplitude, which will be several times

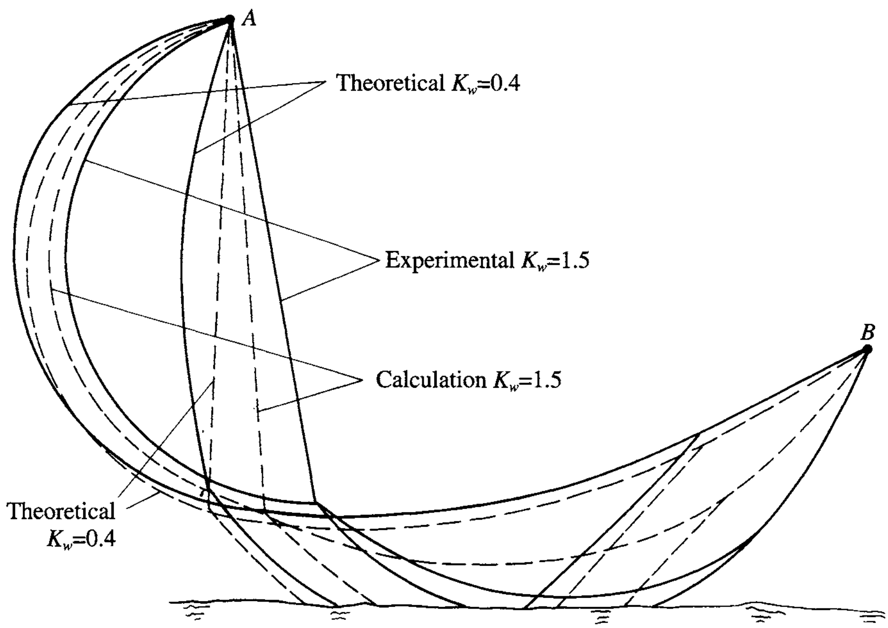


Fig. 7.32 Comparison of tuck-under between analysis and experiment.

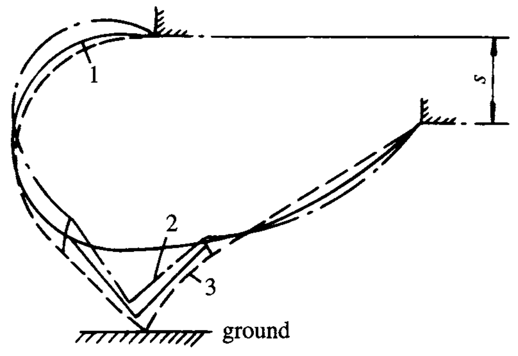


Fig. 7.33 Profile variation of skirt during bounce. 1: neutral position; 2: bounce up, air spilled; 3: bounce down, ground reaction.

the static air gap under segments or fingers (see Fig. 7.33), thus causing a heavy vibration of the hard structure in heave, which is harmful to equipment, engines and instruments and uncomfortable for the crew.

In recent years, due to the appearance of low bag pressure responsive skirts, particularly the large deformation skirt, the probability of bounce motion, similarly to skirt tuck-under, has increased.

Investigation of the causes of bounce and development of methods for preventing

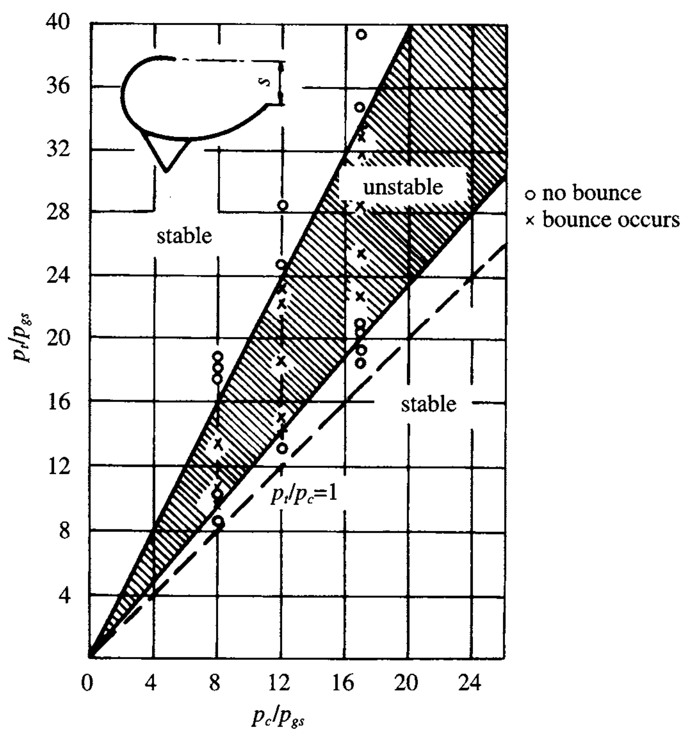


Fig. 7.34 Bounce boundary.

it are an important requirement for the designer. Refs 50 and 66 introduced some experimental investigations on this subject and obtained encouraging results. Figures 7.34 and 7.35 show the vibration range for bag/finger skirts and indicate almost the same results, but show different experimental results for bounce motion of open loop skirts. In this case, ref. 50 noted that no bounce motion occurred, but it has occurred with this skirt during tests in a Chinese skirt test rig [66].

Strictly speaking, the theory for bounce has not been completely verified, but a simple explanation for bounce can be described as shown in Fig. 7.36 [4].

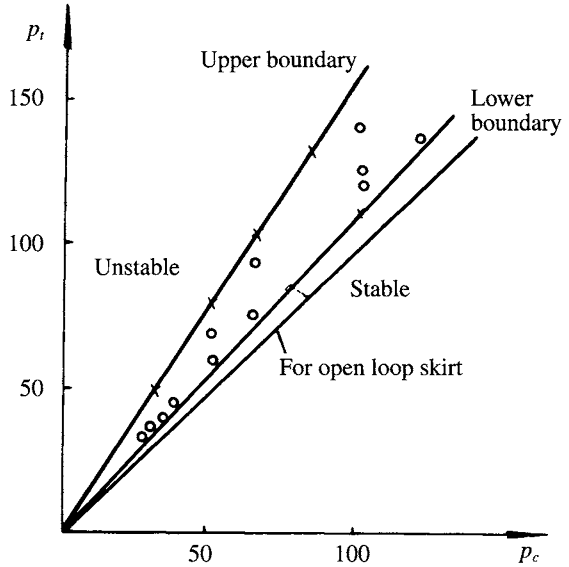


Fig. 7.35 Bounce boundary.

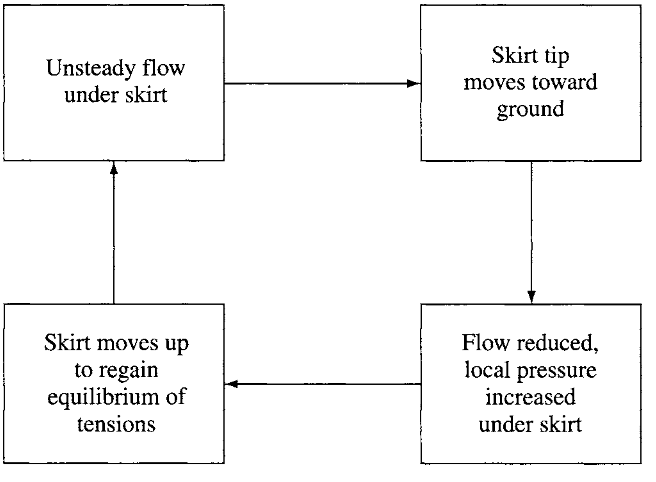


Fig. 7.36 Brief rationale for bounce.

A large radius loop or bag membrane has very little damping, particularly for small movements of a segment, as the radius changes very little. Where a significant length of the skirt is over a flat surface and this section can move as a unit, a small disturbance of the cushion air flow can begin a motion, normally downwards, sealing the cushion. Local static pressure rises, causing the skirt geometry to change, lifting it. The static pressure reduces as air is again released under the skirt and the cycle starts again. The period of oscillation is the natural period in rotation for the total skirt section.

The methods available for preventing bounce are:

1. Introduce anti-bounce diaphragms in the bag or loop to increase the damping for vibration, the shape of which is similar to the D-shape bag (Fig. 7.37). This method has given good results for solving the bounce problems which have arisen on Chinese ACV models 716-II and 711-IId.
2. Change the length of the inner bag and the outer bag of the skirt in order to change the static deformation of the skirt and adjust the natural frequency of the skirt vertical vibration.
3. Strap weights (small sandbags or similar) to the skirt at the bag/segment outer attachment. These are generally only needed in the centre section of side skirts. The mass required is relatively small, since the lever arm about the skirt rotation point is large. This is normally optimized during craft trials.

7.8 Spray suppression skirts

The high-velocity air escaping from an ACV or SES cushion will entrain water with it. This forms droplets which form a spray curtain. The higher the cushion pressure,

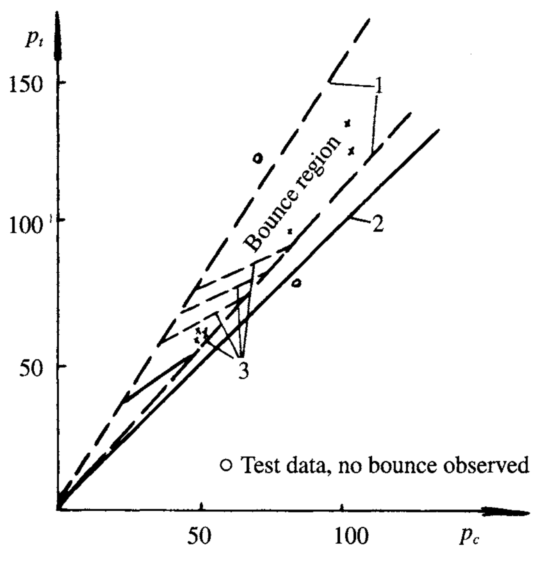


Fig. 7.37 Protection function of D bag skirts against bounce. 1: bounce boundary; 2: open loop skirt; 3: test data, bounce restrained by diaphragm.

the greater the quantity of water spray. Over land, the cushion air creates a dust or sand curtain over dry terrain.

This spray curtain will normally be thrown back on to the structure of an ACV or SES and may then enter engine intakes if they are not protected by filters. In cold climates, water spray will become an ice rime on the structure after a while, adding to the effective mass of the craft. This ice can also be dangerous since vibration, either from the cushion or the engines, can break pieces off which are then drawn through air propulsors or possibly the lift fans, causing damage or failure. In both cases, a spray suppression apron around the bow and front part of the side skirt in the case of an ACV is found to be very effective in reducing spray to an acceptable level.

There are several types of spray suppression apron. The simplest comprises a shaped piece of material which simply drapes over the bag or loop, reaching approximately halfway down the height of the segments or fingers (see Fig. 7.38(a)). A neater design, but rather more complex, comprises segment-like inflated teeth in the top half of each segment (Fig. 7.38(b)). Air pressure for inflation is provided from the cushion.

Aprons

These will flap, and they need to have an open top to avoid inflating. Flapping will be restrained by installing some weights (similar to domestic curtain hem weights) or heavier material for the lower section. Use tapes to restrain an apron and do not restrain at the segment top, just lay over the bag. Do not allow operation of a craft with a badly torn apron as this will affect performance and abrade the bag.

Teeth

These are shaped like double segments. Use cushion pressure (i.e. bleed from top of segment) to inflate. Use geometry shown in Fig. 7.38(b) approx. Attach to top of segment. Use lightweight material.

7.9 Skirt dynamic response

A skirt will respond by adjustment of geometry to two basic inputs, changes in pressure within the cushion and deformation against a solid boundary such as a wave. The deformation will change the volume of the cushion and the air distribution system and by doing so alter the balance of dynamic and static pressure within the system.

A responsive skirt is one where the segments or fingers are able to follow an undulating surface by adjustments in the skirt section geometry without inducing large changes in the pressure field in the cushion. By definition such a skirt will be less stiff than a 'non-responsive' skirt. The optimum for a given craft is therefore likely to be a skirt with just sufficient responsiveness for its mission requirements and no more.

In the next chapter we discuss ACV and SES motions in a seaway. To simplify an already complex analytical problem, skirt response is considered only as the cushion stiffness. The designer will therefore need first to assess the minimum stiffness required for static stability from the skirt system (see Chapter 5) and once this is known, the stiffness characteristic giving most favourable motions in the design environment can be determined and the skirt geometry adjusted, so long as the dynamic requirements are greater than those from static analysis.

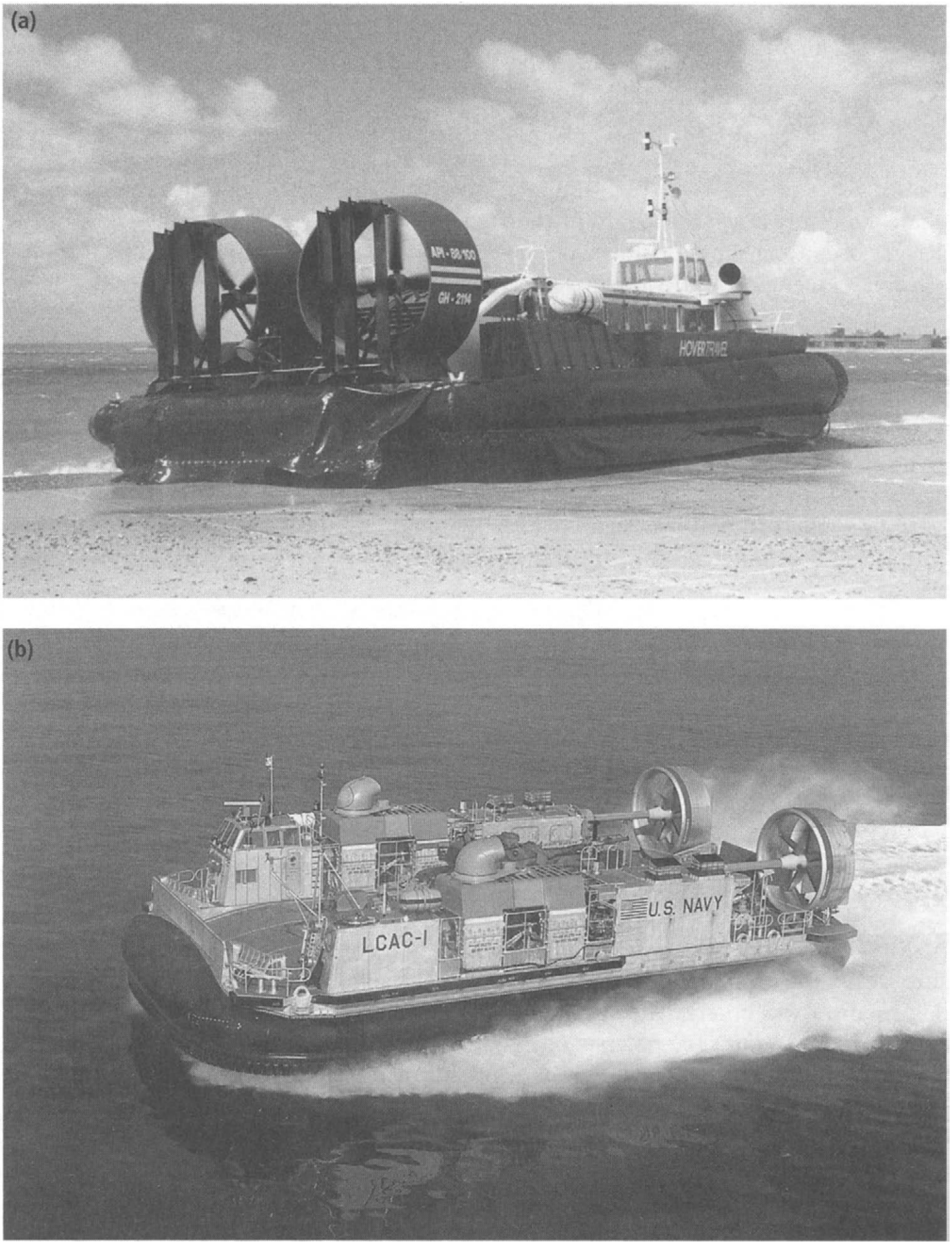


Fig. 7.38 Spray suppression skirt types: (a) spray suppression apron; (b) spray suppression 'teeth'.