LIGHT HOVERCRAFT DESIGN

by

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and

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Acknowledgment

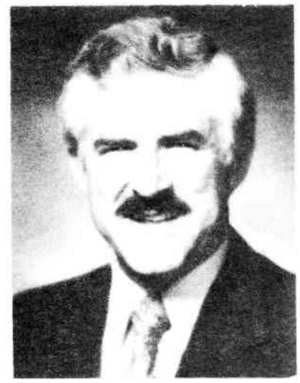
Like so many projects associated with hovercraft, these notes had to be prepared in record time and with no budget. The fact that they were ready for the first Light Hovercraft Design Conference (1987) was entirely due to the dedicated help of Club Secretary Sara Mahler. Her enthusiasm, willing capable cooperation and pleasant disposition are of great good fortune to all hovercraft enthusiasts. Sara, in running Hoverclub affairs and her family, has a work load which would normally take 4-5 persons. On top of this the Mahlers have been building their own hovercraft! Despite everything and with the best of good humor, Sara continues to do all the typing, proofing, correcting, copying, spelling, and grammer and even arranges the printing.

The authors wish to acknowledge Sara's continued help and enthusiasm in preparation of the third edition.

Thanks to Sara from everyone.

ABOUT THE AUTHORS

Christopher Fitzgerald



Fitzgerald is an expatriot Australian who holds a US permanent resident visa. While working on hovercraft research at the Australian Government Aeronautical Research Laboratories he organized a group of talent and formed a part-time business called Australian Air Cushion Vehicle Development in 1961. They participated in the world's first hovercraft race in Canberra, Australia, in 1964. This business later became Neoteric Engineering Affiliates, Pty., Ltd. Fitzgerald received a Mechanical Engineering diploma from Footscray Institute of Technology, Melbourne, Australia, in 1971 and studied Aeronautical Engineering at Farnborough, England.

Fitzgerald has worked as a trainee engineer for the British Hovercraft Corporation and as a research engineer for Ready Mix Concrete Australia, Ltd. In 1969 and 1970, under the auspices of Rotary International, he traveled worldwide in the study of hovercraft. In 1974 he formed Neoteric USA, Inc. in Indiana, and incorporated the Hoverclub of America, Inc., in 1975. Fitzgerald was president of the Hoverclub for a number of years. He was appointed as Rose Hulman Institute of Technology's first Entrepreneur-in-Residence. This part-time position at the Rose Hulman campus in Terre Haute, Indiana, involved regular classroom lectures on engineering design and business. His company has supplied hovercraft to Walt Disney World Epcot Center, the US Army Corp of Engineers, state conservation departments, the general public for recreational purposes, and exported craft to China, Australia, India, Japan, and other countries. Fitzgerald is president and a major stockholder of Neoteric USA, Inc.

Robert Wilson

Wilson is an Australian Engineer and co-founder of Neoteric Engineering Affiliates Pty., Ltd. Early hovercraft experience included participation in the world's first hovercraft race in Canberra, Australia, in 1964.

Practical engineering expertise was gained through a trade apprenticeship course, followed by a technician course, and currently a professional engineering course. Wilson graduated with a Mechanical Engineering Diploma from the Footscray Institute of Technology, Melbourne, Australia, in 1972.

Early work experience includes practical maintenance and repair of most types of automotive equipment. For some years he worked for an automotive parts manufacturer, Repco, Ltd., as a project engineer in their engine test laboratories.

Wilson has been closely involved in the design of all Neoteric hovercraft from the conceptual stage and is the co-inventor for Neoteric patents in several countries.

Current duties include Manager of Neoteric Engineering Affiliates Pty., Ltd. and Technical Director of Neoteric USA, Inc.

INTRODUCTION

This work is an informal collection of ideas and nontechnical notes. Hopefully, it will aid those interested in the process of light hovercraft design. At best it will provide a starting place. Hopefully, future editions will be improved, expanded, and kept current.

"Hovercraft" was the name coined by its inventor, Sir Christopher Cockerell. It has come to mean an amphibious version of the more general air cushion class of vehicles. These are machines that slide along while balancing on top of an air cushion bubble. This bubble is generated by an air pump (fan) while a flexible skirt helps retain the bubble beneath the machine by limiting the air loss. Lubrication provided by this air bubble enables the machine to slide across many relatively flat and smooth surfaces such as grass, snow, ice, water, mud, and sand, and even to cross over certain crops without damaging them.

In order to keep this subject in managable proportions these notes have been restricted to light amphibious air cushion vehicles only (hovercraft). You will find, however, that some scaling laws have been included for the more adventurous who might wish to tackle bigger machines. These laws will help in determining the size and performance of larger versions of your test model or vice versa. For example, you can scale-down your design and build a scale model. This is a much less expensive process than trying to test your ideas on full-scale hardware.

By definition we define light hovercraft to be those hovercraft which carry less than 1,000 kg (2,200 lb) payload.

1. Background

Prior to 1970 hovercraft existed mostly in theory based on principles of fluid mechanics, aerodynamics, economics, and stress analysis. Enthusiasts wanted to build machines and all the theory wasn't much help. Many publications were introduced, and although most were technical, some were especially helpful to the homebuilder. Those which proved useful were:

Air Cushion Vehicles magazine, a supplement to British Flight International magazine, was first published Dec. 31, 1964. Future supplements contained A Plain Man's Guide to ACV Design and Construction, written by G. H. Williams;

Light Hovercraft Design Handbook, edited by David Waters, and published by the Department of Transport Technology, Loughborough University of Technology, United Kingdom, April, 1969;

Guide to Small Hovercraft, compiled by Jan Eglen, Terre Haute, Indiana, 1969; and,

Light Hovercraft Handbook, edited by Keith Oakley, Hoverclub of Great Britain, 1974.

In 1976 the Hoverclub of Great Britain revised their Light Hovercraft Handbook, and, in addition to it being a most valuable publication, it was the only one above which was still in print.

Jane's High-Speed Marine Craft and Air Cushion Vehicles, edited by Robert L. Trillo, is a good annual publication for general reference purposes.

Sir Christopher Cockerell invented hovercraft during the late fifties. Large British built hovercraft began carrying passengers and cars across the English Channel in the late sixties. Military hovercraft also appeared together with hovercraft for rescue, racing, cruising, and heavy load movement. The hovercraft principle is now used for: entertainment, cutting grass, amusement games (air hockey), trains, floating refrigerators, floating burnt human bodies, and even vacuum cleaners (Hoover).

These notes, however, are confined mostly to racing and cruising type light hovercraft.

2. The Design Process

The world's first workable hovercraft was a model. Models can be an inexpensive means for testing ideas and new designs. By using some of the mathematical laws outlined later, a model can be scaled up or down to provide design data and to predict performance for a full-size machine or vice-versa, full-size machines can be scaled down to model size.

In designing hovercraft one of the first steps is to decide what is wanted. This is usually turned into a specification. Difficult as it always seems, the designer must try to write out a series of requirements. Even rough notes are better than nothing. Size, weight, performance, control, cost, noise, life expectancy, appearance, and comfort should be contained in the specification. Improper specifications soon become apparent and, consequently, specifications often need revision. Conflicts arise and compromise becomes unavoidable. Probably the most common specification features are size, cost, performance, dependability/maintenance, appearance, and capabilities. A specification is like a shopping list, it's what you are going after or hope to achieve!

3. Principles

Hovercraft derive lift or hover from a pressurized fluid acting on a surface of the vehicle. The lift surface is defined by the length (L) and width (W) of the machine or by diameter in the case of the early round hovercraft. Today, almost without exception, hovercraft are longer than they are wide. Their length (L) to width (W) ratios approach two. Really fast machines the length to width ratio might exceed three.

$L/W \leq 2$ for standard machines (1)

$L/W \leq 3$ for high speed machines (2)

Length is an important dimension for small hovercraft and probably is one of the easiest means for classifying various machines. Width is usually restricted by highway transportation laws. In the U.S. this is presently 8' 6" maximum but can be increased with special permits. Racing machines are usually less than 7' wide, and cruising craft might be up to 8' 6" wide (or greater with folding side bodies).

If a hovercraft hovers too high it will literally fall over. Therefore, craft usually hover close to the ground. Most racing machines usually do not exceed four foot in overall height when hovering. Cruising machines might reach 8' (to the top of the propeller if propeller driven.) A maximum overall height (D) to width (W) ratio for small hovercraft is 1:1 but more usually 1:2.

$D:W < 1:2$ for racers (3)

$D:W < 1:1$ for prop-driven cruisers (4)
where D is measured from the tip
of the propeller to the ground
while craft is hovering.

4. Lift

Hovercraft are usually supported by the fluid air. For a rectangular machine (L) long and (W) wide the lift surface area (A) is:

$$L \times W = A \qquad (5)$$

If a hovercraft is resting on the ground, air pressure on the underside equals air pressure on the top side.

British electronics engineer Sir Christopher Cockerell discovered that in placing pressurized air under the hovercraft an air curtain seal around the machine's perimeter could be used to prevent this cushion air's escape, and thus increase hoverheight. A peripheral air curtain changes its momentum when injected under the machine and, with sufficient volume and pressure, establishes and maintains a pressurized cushion. This pressure is called cushion pressure (P_c). If cushion pressure is multiplied by surface area of the craft it will equal lift. Once the cushion air pressure lift equals the machine's weight (C), the machine will lift off and hover.

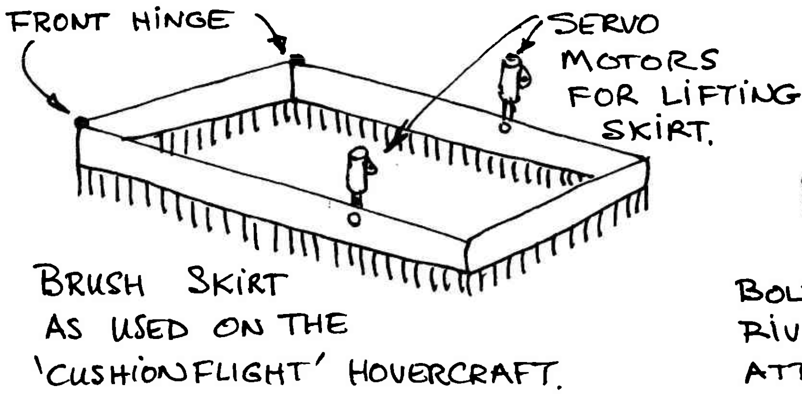
$$P_c \times L \times W = C \qquad (6)$$

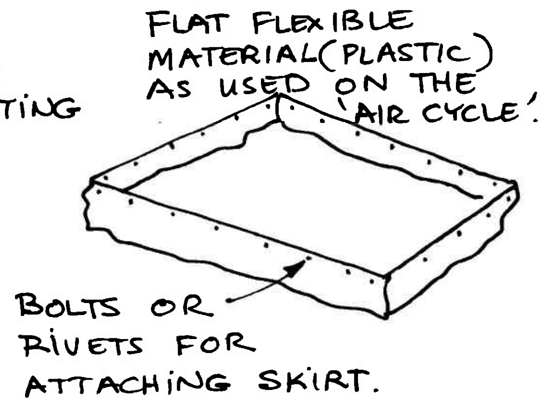
Although Cockerell's air-curtain peripheral seal functioned well, it required too much power and eventually was replaced by a flexible fabric seal. This seal was called a flexible skirt and is found on all craft operating today. Hovercraft skirts represent a breakthrough, following which hovercraft went from what was an 'intriguing idea' to a serious and practical transportation means.

5. Skirts

5.1 Brush Skirt

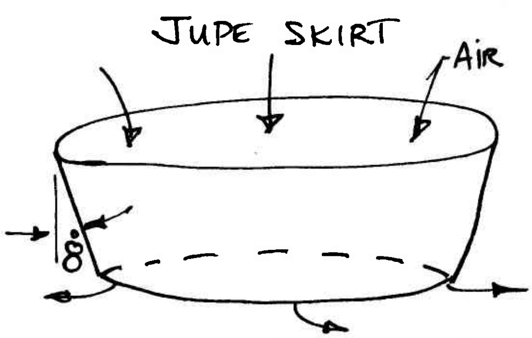
Early experimenters and several manufacturers in the USA used brush skirts. These consisted of brush stubble attached around the edge of the machine. On some machines brush height could be adjusted by controls in the cockpit. A piece of flexible material fixed around the craft's outer edge was one variation on the brush skirt. These skirts proved to be unstable, stiff, and ineffective and are no longer in use.

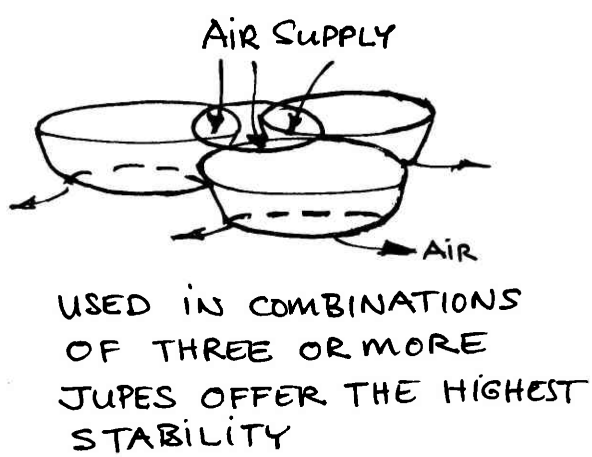




5.2 Jupe Skirt

In 1959 French engineer-inventor, Jene Bertin invented the apparently simplest of all skirts, the jupe. In the US this has been called the cell skirt. The jupe looks like the frustrum of a cone resting upside down. It slopes approximately eight degrees toward the bottom and inflates in a conical shape. The skirt is not widely used but is a practical system that has found favor on various machines manufactured by the authors' company.

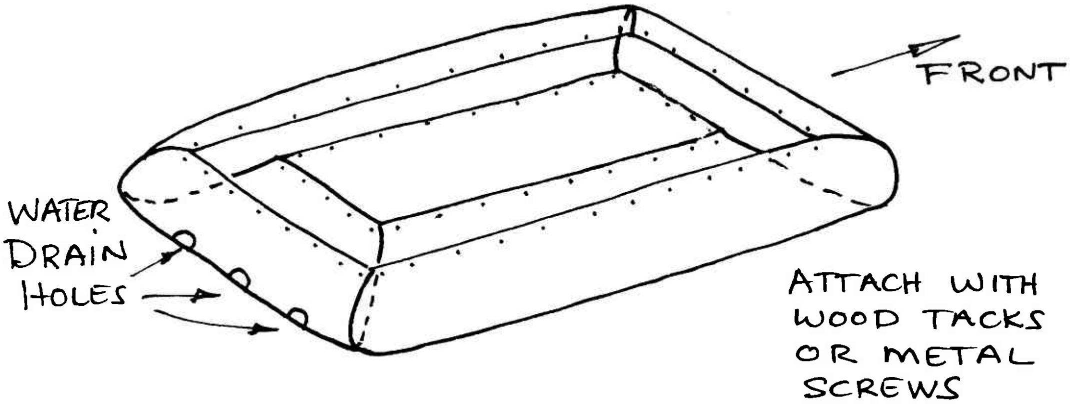




5.3 Bag Skirt

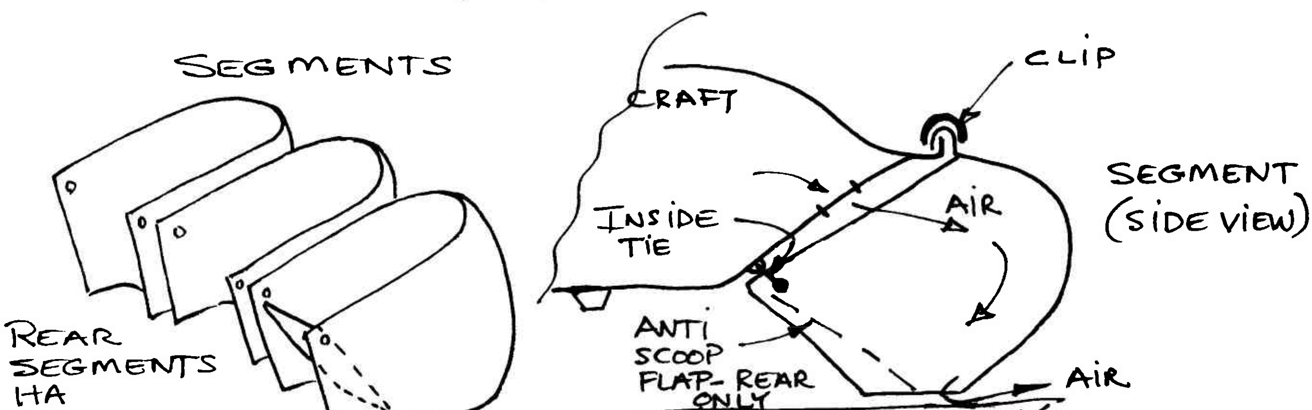
Until recently the most widely used skirt was the bag skirt which is like a giant inner tube fitted around a craft's perimeter. At the present time the bag skirt is found on many homebuilt machines in the

United States but not in Europe. Additional pressure is needed to inflate the bag against air pressure under the craft in the cushion.

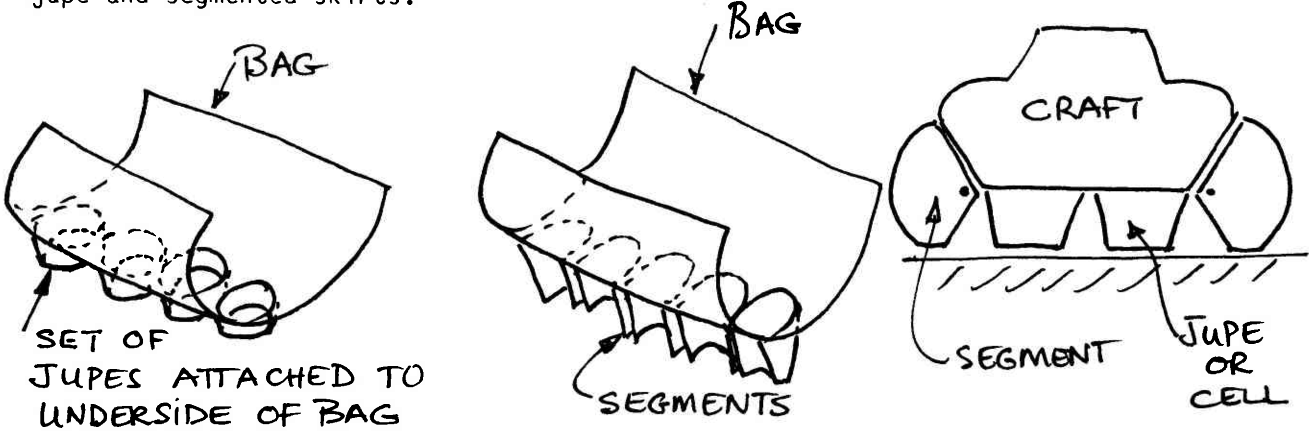


5.4 Segmented Skirt

The convoluted, segmented, or finger skirt was invented in England. The concept was refined during the early sixties by Hovercraft Development Limited, a British Company. Almost every European machine is now fitted with segments and mass produced machines in the USA also use this skirt without exception.



Different skirts can be used in combination. For example, segmented skirts and jupe skirts may be attached to the underside of bag skirts. The authors' company has had success using a combination of jupe and segmented skirts.



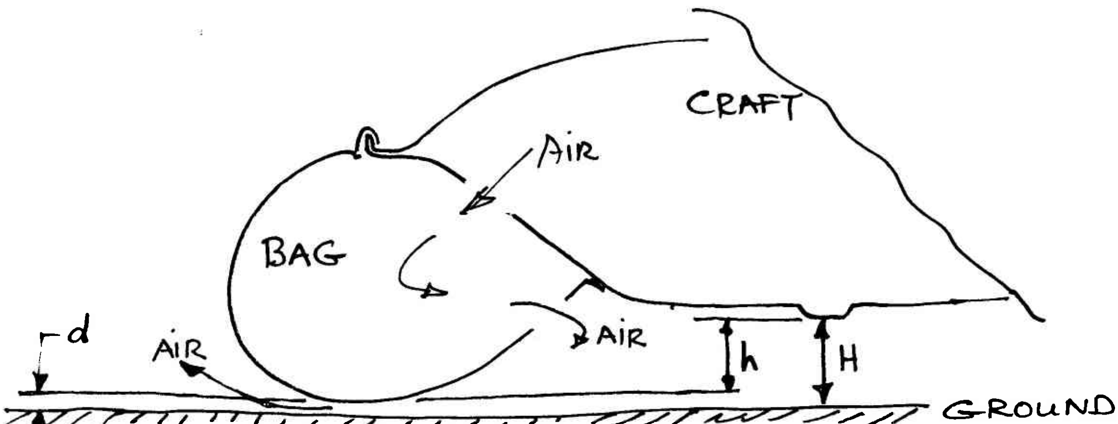
COMPARISONS BETWEEN SKIRT TYPES

	Bag	Segment/Finger	Jupe/Cell
Cost	Low	High	Low
Labor	Low	High	Medium
Drag			
Smooth water	Same	Same	Same
Rough water	High	Low	Very High
Mud	High	Low	Low
Grass	High	Low	Medium High
Ice	Same	Same	Same
Smooth snow	Medium	Low	Low
Rough snow	High	Low	Medium
Repairability	Hard	Easy	Hard
Life	Good	Moderate	Good
Durability	Good	Poor	Moderate
Stability	Good	Poor	Excellent
Plow in	Same	Same	Same
Roll ability for turning	Slight	Excellent	None
Dust and spray	Poor	Good	Poor
Colors available	Limited	Unlimited	Limited
Ease of Attachment	Moderate	Easy	Moderate Hard
Weight of skirt	Low	Moderate	Low
Hump performance	Moderate	Good	Poor Moderate
High speed	Good	Moderate	Moderate
Bulkiness	Poor	Poor	Good
Appearance	Moderate	Good	Moderate
Bounce	Poor	Good	Good
Performance when damaged	Moderate	Good	Poor
Potential for development	Good	Good	Good
Over water rapid take off ability from long time floating mode	Poor	Good	Excellent
Obstabcle capability	Poor	Good	Poor
Complexity	Low	High	Moderate

Each hovercraft has to be designed for a particular skirt type. It can be difficult, if not impossible, to fit a different skirt later on. The bag skirt is probably the most adaptable.

6. Hoverheight

Hoverheight (H) is the distance measured from the ground to the underhull hard structure of an operating craft and is often referred to as hard structure clearance. When air is pumped under the craft pressure builds, the skirting inflates, and the craft lifts. Often one edge rises first. The moment the skirt fully inflates cushion air begins to escape from the gap between the underside of the skirt and the ground. This gap is called daylight clearance (d) or air gap. The amount of air escaping depends on the amount of energy forced into the cushion air by the fan. Almost all light hovercraft use about one-third of their total available horsepower for lift air although very efficient lift air systems may use as little as one-tenth.



In summary very efficient machines use a minimum of .01 HP/(lb. gross weight) for lift:

$$HP/LB. \geqslant .01 \qquad (7)$$

Racing machines might use up to .03 HP/(lb. gross weight) for lift:

$$HP/LB. \leqslant .03 \qquad (8)$$

In terms of craft length, minimum HP for lift is:

$$HP/Ft. \geqslant .45 \qquad (9)$$

and maximum (usually racing machines) is:

$$HP/Ft. \leqslant 2.2 \qquad (10)$$

One German bag skirted racing craft uses 30 HP for lift! Generally greater lift power means less skirt drag because daylight clearance is large and there is more air lubrication. A further advantage can be a stiff, highly inflated skirt as this is effective in improving a craft's dynamic stability, however rough terrain skirt drag increases and so does lift air momentum drag.

Hoverheight (H) is a measure of skirt height (h) and daylight clearance (d).

$$H = h + d \qquad (11)$$

If the hoverheight to width ratio is excessive the vehicle will become unstable and possibly tip over. Craft hovering close to the ground are more stable.

$$H/W < .12 \qquad (12)$$

Daylight clearance is difficult to measure. Skirts tend to be uneven along their lower edges and hovercraft rarely hover horizontally. Lower parts of the skirts frequently scrape the ground surface. For most small machines hovering above smooth and level ground, the daylight clearance (d) is about 1/2" to 1". Daylight clearance should be kept small because the escaping air wastes energy and amuses itself by creating water spray and dust clouds. If daylight clearance is too small, however, skirts, especially the bag type, get stuck on muddy and pebbley surfaces and wear rapidly.

The aerodynamic drag associated with the lift air is approximately based on the following law:

$$(Z/g) \times V = D_m \qquad (13)$$

where

D_m = Lift air momentum drag (lb.),

Z = Total mass of lift air being sucked through the machine's lift system (lb./sec.),

V = Speed of hovercraft (ft./sec.), and

g = Gravity = 32.2 ft./sec./sec.

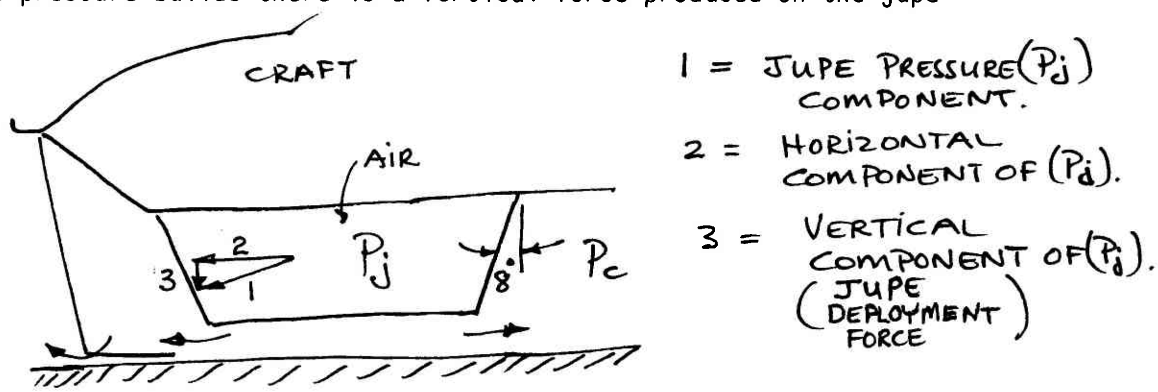
Z can be difficult to determine because it is dependent on air density as well as fan/duct/intake conditions.

7. Skirt Design and Material

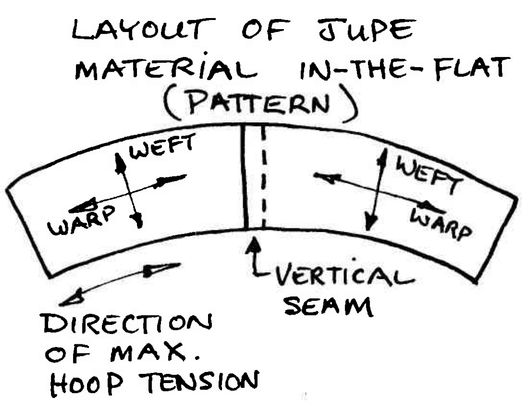
There is now much practical experience available so that design formulas for skirts are not really necessary. However, a few considerations are necessary to ensure a workable skirt system.

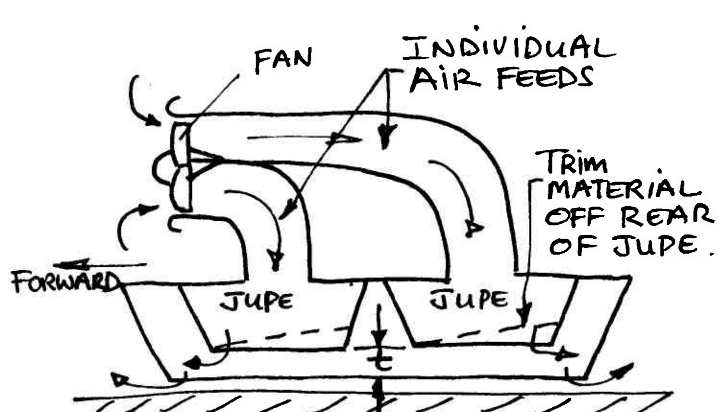
7.1 Jupes

Jupe skirts must taper inwardly about eight degrees. in this way as the pressure builds there is a vertical force produced on the jupe



which will cause its inflation. Jupes are difficult to inflate when sitting on porous surfaces like grass or when taking off from a slope. If the craft controls can cause the machine to move (slide) while on partial cushion this often helps with jupe inflation. It is not too serious a problem for small craft. Hoop tension within the jupe material opposes the jupe pressure force and the system is always in equilibrium. It is important when cutting jupes from sheets of skirt material that the materials least stretch direction is in the direction of the maximum hoop tension. Usually the warp of the material is aligned with the hoop tension direction. Note that very large jupes require more vertical seams in order to control the stretch.





Jupes are usually in combination of three or more and have an outside jupe surrounding inner ones. Inner jupes are trimmed about 1/2"

(t) higher than the outer jupe. Trimming is very important and can be a skilled undertaking. It will effect the pressure balance and, hence, the stability of the system. Sometimes inner jupes are trimmed such that t increases toward the rear. This minimizes water scooping. It is advisable to trim the inner jupes after ground contact wear marks have begun to appear (usually after 1/2 hour operation over black top).

On larger jupes water scooping can produce high drag and some means of jupe stretching (or inner flaps) to dump water has to be devised. This is not usually a problem for small craft except in rough water. The weight of jupe skirt material should be about 16 oz./sq. yd. and the all–around–best material is neoprene coated nylon. These lightweight materials usually have sufficient stretch to prevent serious water scooping.

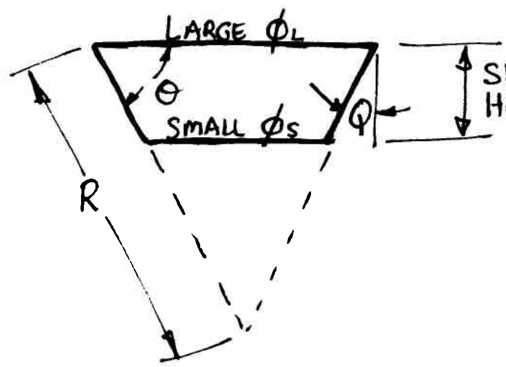
The pressure ratio between the inner cell (P_j) and outer cells (P_c) is usually about 1.2:

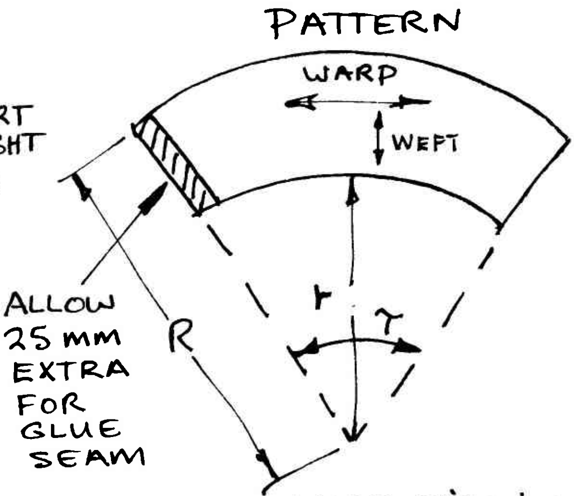
$$P_j / P_c = 1.2 \qquad (14)$$

To obtain the maximum cushion stability each jupe should be fed directly from the fan so that the pressure in one jupe can reach almost the total static pressure output of the fan while at the same time an adjacent jupe can be venting to atmospheric pressure.

Because of the scooping tendency jupes have a high drag in rough water, they also result in a lot of dust and spray. Unlike bag skirts, jupes do not cause hovercraft vertical bounce (heave instability). Drag over mud and smooth water is very low and jupes have very low wear rates. They tend to rip rather than wear because of snagging and resulting excessive hoop tension. A badly torn jupe will drastically reduce the craft's cruising speed and stability.

Jupes are attached to the underside of the craft's hull by metal screws or pop rivets or they can be attached to a diaphragm made from skirt material which is stretched across the underside of the vehicle's hull. This method has been successfully used for the last 14 years on hovercraft manufactured by the authors. Outer jupes are usually attached with bolts, screws, cord, or any number of different patented clip fixtures. An underhull skid method must be devised which will protect the jupes when the machine is dropped or skidded along the ground off cushion. Small projecting wooden skids, glass fabric covered, in the center of each jupe work well. To develop a pattern for cutting out jupes use a large compass made of two sharpened nails driven through a long thin strip of wood. Determine the radius, (R) and perimeter (P) as follows:



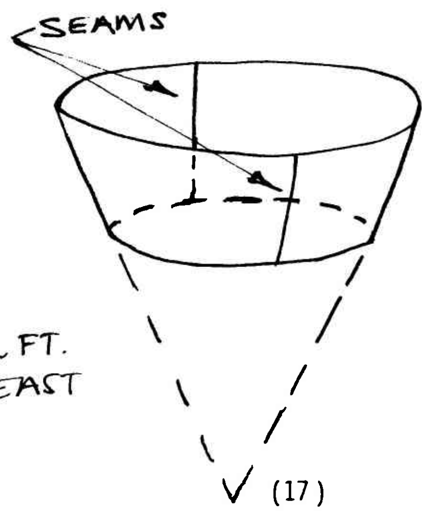


φ IS USUALLY NOT LESS THAN 8° FOR PROPER JUPE INFLATION

WARP: DIRECTION OF LEAST FABRIC STRETCH — CORRESPONDS TO WARP.

Perimeter of Large $\phi_L = \pi \phi_L$ (15)

$$R = \sin\theta / h(1 - \phi_S/\phi_L) \quad (16)$$



- JUPE DESIGN IS BASED ON THE FRUSTUM OF A CONE
- A JUPE OF ϕ_L = 2 FT. SHOULD HAVE AT LEAST 2 SEAMS.

$$r = (R - h/\sin\theta) \quad (17)$$

$$\tau = R \pi \phi_L \quad (18)$$

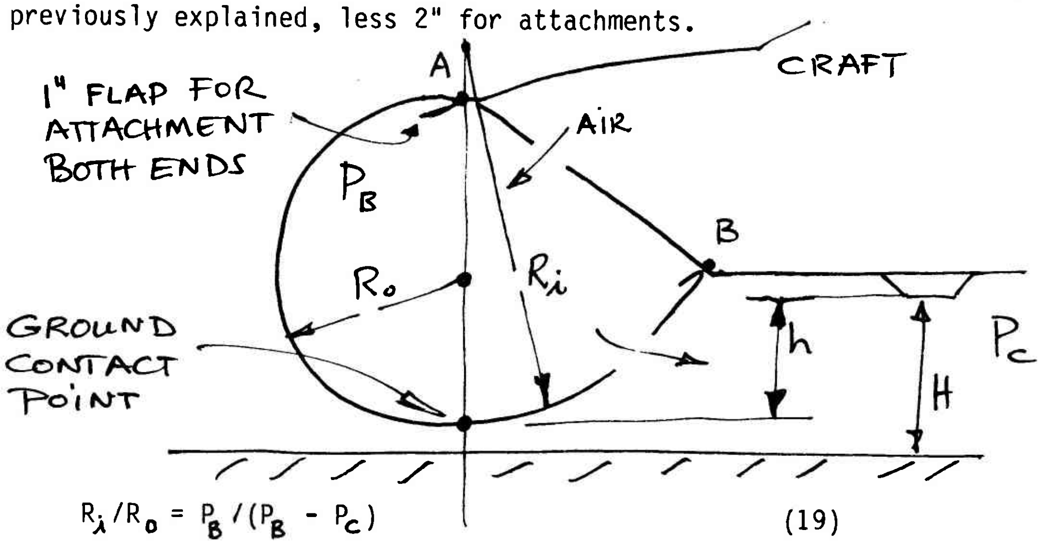
7.2 <u>Bags</u>

The bag is popular as its manufacture uses the least amount of material compared to other skirt types. There is usually little or no wastage. In the US this is still the most common skirt found on homebuilt machines. Fabric for bags is usually the same as for jupes, viz., 16 oz./sq. yd. neoprene coated nylon.

The nylon base fabric is usually about 7 oz./sq. yd. Such material is commonly used in the US for the manufacture of truck tarpaulins and comes 60" wide. For economy this width is halved so that the bag size is 30". Consequently, the hoverheight (H) as we shall soon see, is also limited by this 30".

Bags are of two types, flow-through and non-flow-through. On twin engined machines the non-flow is more common. It is a principle of the bag that its pressure P_B must always exceed the craft cushion pressure P_C; otherwise, the bag will be blown outward by the cushion pressure.

Distance AB measured around the bag is usually limited to 30", as previously explained, less 2" for attachments.



$$R_i/R_o = P_B/(P_B - P_C) \qquad (19)$$

But, for a rectangular craft,

$$P_C = C/LW \text{ so that } R_i/R_o = P_B/(P_B - \frac{C}{LW}) \qquad (20)$$

To determine the shape of the bag calculate the craft weight, C, and lift area, L x W. R_o generally equals the skirt height (h). From experience:

$$P_B/P_C \doteqdot 1.2 \qquad (21)$$

Hence

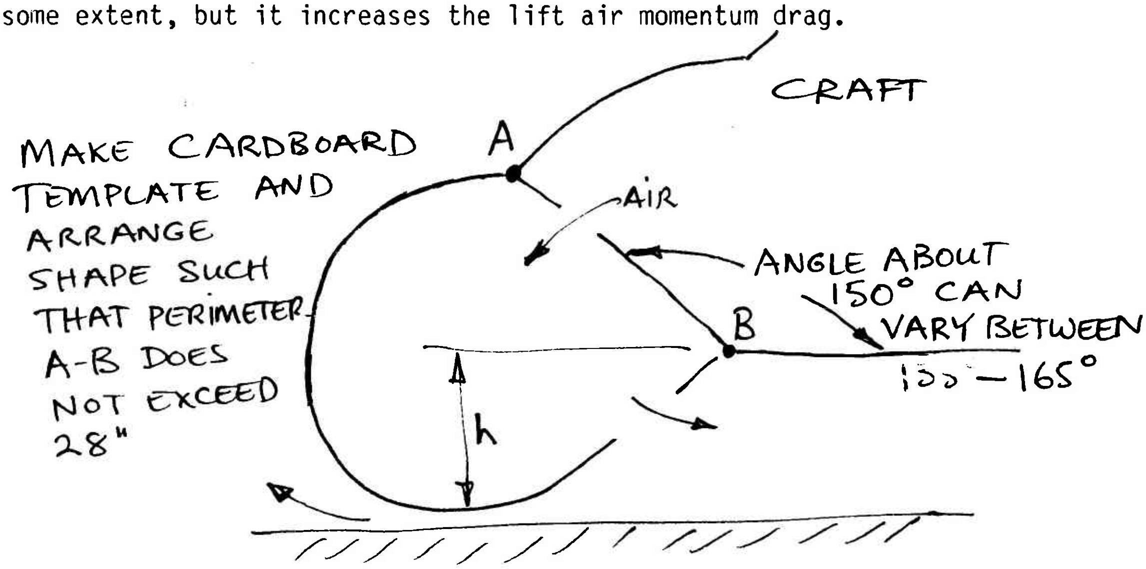
$$P_B = 1.2P_C \text{ Substitute in (20)}$$

Thus

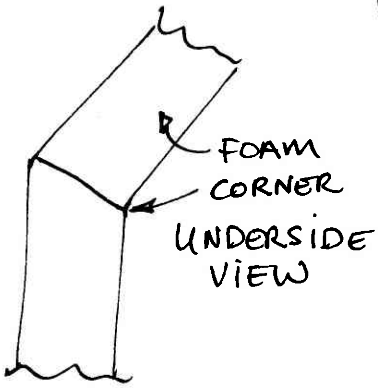
$$R_i = h(1.2P_C/1.2P_C - P_C) \text{ or } 6h \qquad (22)$$

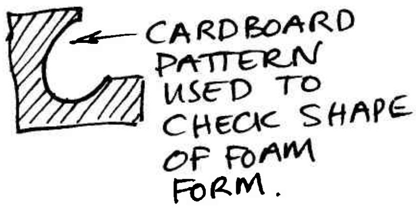
To develop a pattern mark the shape on some cardboard using $R_i = 6h$ and $R_o = h$, measure the distance from A to B to see how close it is to the 28" length of material available.

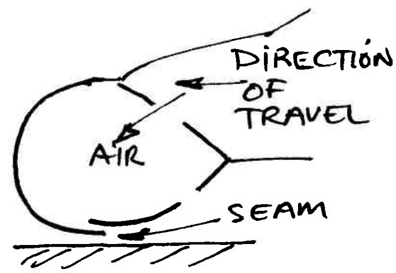
The objective is to employ the full 28" of material in order to achieve the maximum hoverheight. When distance A to B is more than 28" reduce R_o and draw R_i at 6 x R_o since $R_o = h$. Repeat this procedure until the distance is 28". Some racing craft employ bags pumped up so hard that $R_o = R_i$, the bags become cylinders. This is fine for stability, but the skirt drag is high, especially over uneven terrain. Increasing the daylight clearance and thus lift horsepower will offset this drag to some extent, but it increases the lift air momentum drag.



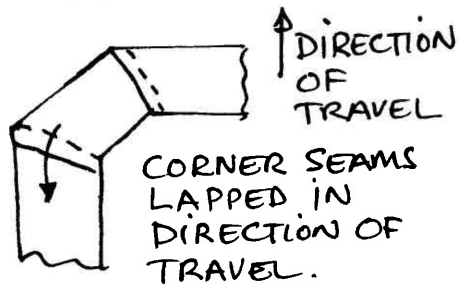
An alternative approach is to use a thin strip of plastic 28" long and bend it between A and B and the ground. The relative position of A and B should be as shown in the sketch. Make a cardboard template of this shape. Actually the shape of the skirt corner joints will determine how closely the skirt will resemble the theoretical shape in operation, corners actually force the shape of the bag. h should be about 6". If it is very small, like 3", the bag will bulge out and bounce uncontrollably. Corner joints will depend upon the plan view shape of the craft which we will come to a little later. For the meantime, to find the shape of the fabric at the corners, construct a solid skirt. This is achieved by turning the machine upside down, then using polyurethane foam blocks carve out the corner areas only. Shape full scale corner pieces using a cardboard template. Drape the material over the corner and mark the shape of the joint. This can be done first using inexpensive paper, then transferring from the paper pattern to the skirt material. Allow a 1" glue seam. Seams should always lay in the direction of travel as much as possible, i.e.,







NOTE: BECAUSE HOVERCRAFT ARE SYMMETRICAL, FOAM CORNER FORM IS REQUIRED FOR ONE SIDE ONLY.



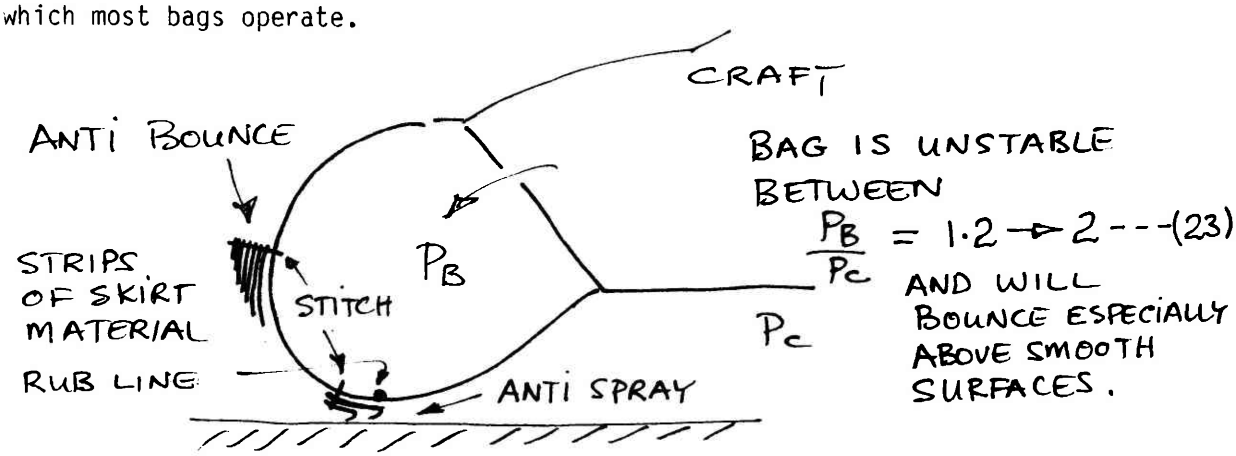
Now it is very important that the relative position and shape of each corner with respect to each of the other corners be obtained before cutting the final skirt panels.

Making skirts is an art. The more simple the craft's shape the easier fitting the bag becomes. Complicated bag shapes can be manufactured by using the method outlined here. Another commonly used approach in the US is to tack the material to the underhull along A and B and see that the material hangs straight without creases. The joints can be pinned together then removed, glued, and sewn. Coat the thread with epoxy or urethane to prevent fraying. Bags can be fitted to curved hulls and other odd shapes but with more difficulties. The drawback of this approach is that no two skirts will be alike and each hovercraft could have different characteristics depending on the quality and actual shape of the skirt.

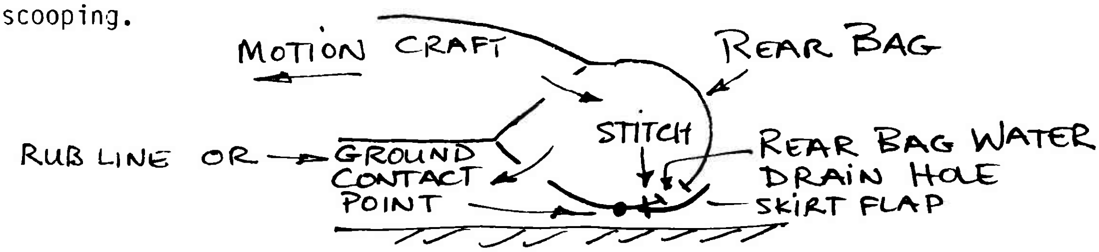
Bags assume different cross section shapes depending upon the attachment points, the pressure ratio between the bag and cushion, as well as the local skirt height. Creases in the bag will cause drag, wear, and uncomfortable operating characteristics.

For best results when bonding skirt seams, properly clean, glue, and rivet using solid aluminum rivets with large flange aluminum backing washers placed on each side of the seam and spaced about 1 1/2" apart. However, neoprene contact (weather stripping) cement will, for most applications, be adequate.

There is a natural tendency for bags to bounce. This is especially bad over smooth hard surfaces like concrete and ice. Diaphrams fitted internally will reduce bounce but this solution is uncommon. Instead several strips of skirt material are sewn along each side of the bag to help damp out oscillations and to act as a spray deflector. It is thought that bounce is most likely to occur when the bag cushion pressure ratio lies between 1.2 and 2.0. Of course this is the ratio at which most bags operate.



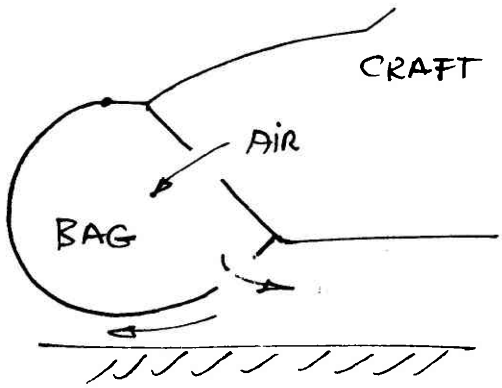
Floating in water, bag skirts take on water. Consequently, before a craft can accelerate this water must be removed. Several holes about 2" diameter or slits 3" long are placed across the rear bag just above the bag contact line. Sometimes flaps made from skirt material are attached forward of the slits or holes to prevent snagging and scooping.

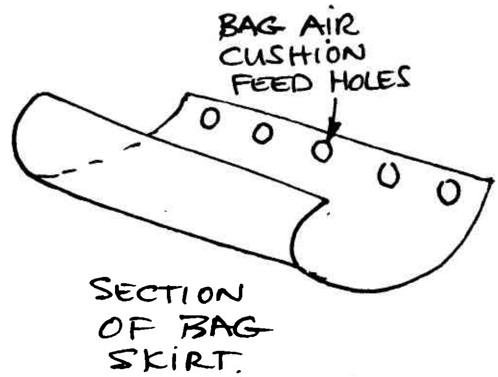


<u>Non-flow-through</u> bags are usually inflated through a splitter plate connected by a small duct placed directly under the lift fan in the fan duct. Its size is usually 10% of the lift duct area. The remaining duct area provides the lift air for the cushion. For best overall craft performance lift air should be introduced into the forward part of the cushion.

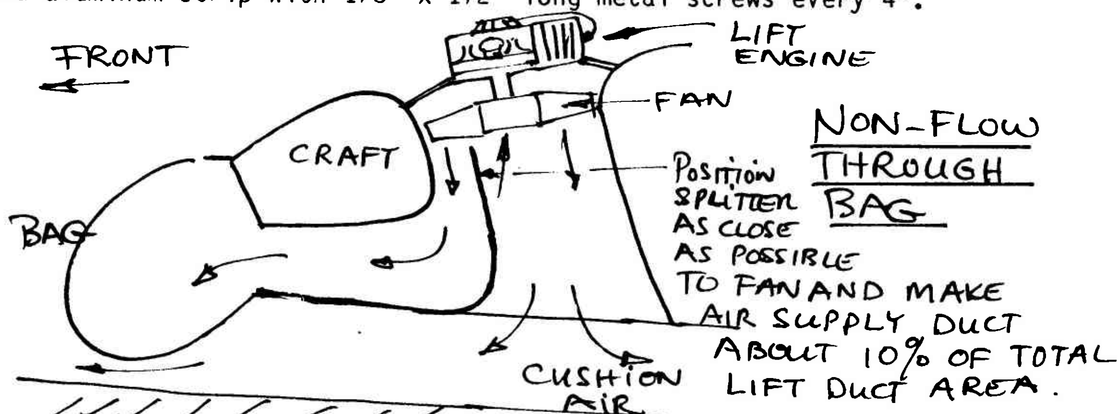
<u>Flow-through</u> bags are usually fed by taking air, about 1/3 of the total flow, from a single thrust duct. This duct is usually mounted to the rear of the craft. Another duct channels air around the periphery of the craft. The air then bleeds through annular holes, 50 or more, about 3" diameter, from the peripheral duct into the bag. The bag has a similar number of holes through which the same air feeds into the lift cushion. Often all of the lift air is fed directly into the bag but pressure losses can be high as the bag cross sectional area is usually

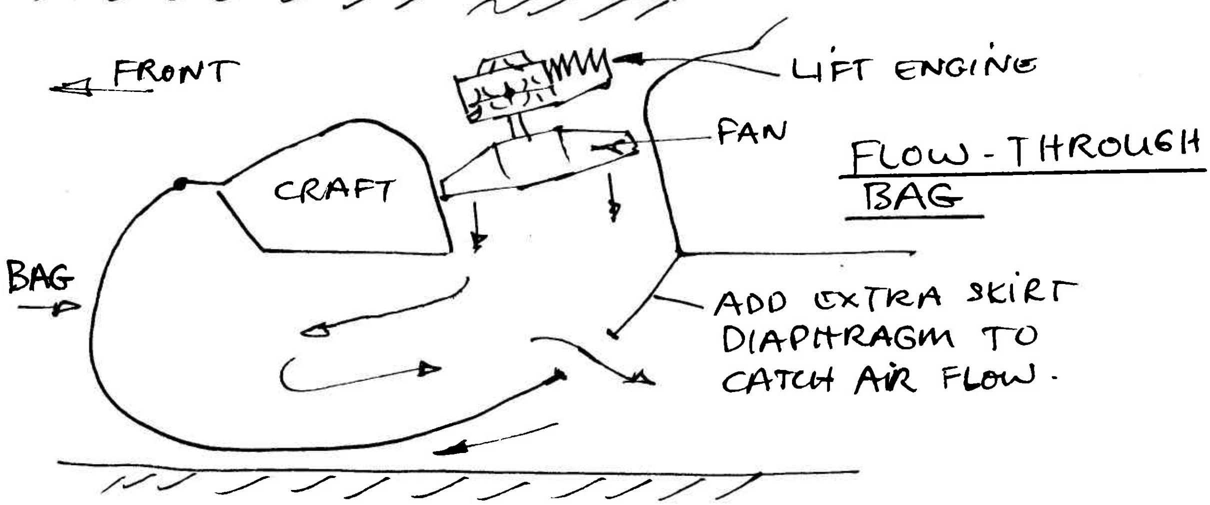
small forcing air velocity up, causing the resulting pressure losses. The total area of all bag air feed holes should exceed 1/3 of the fan lift duct supply area so that the proper bag to cushion pressure ratio can be achieved. If the bag is too rigid either cut more holes in the bag or enlarge the existing ones. It's best to start with too few holes and increase until acceptable performance is achieved.





Bag attachment is usually by gluing, then using mechanical fasteners such as tacks or metal screws and backing washers. These should be placed 3 - 5" apart. The author's company uses glue and 1" x 16G aluminum strip with 1/8" x 1/2" long metal screws every 4".





7.3 Segments

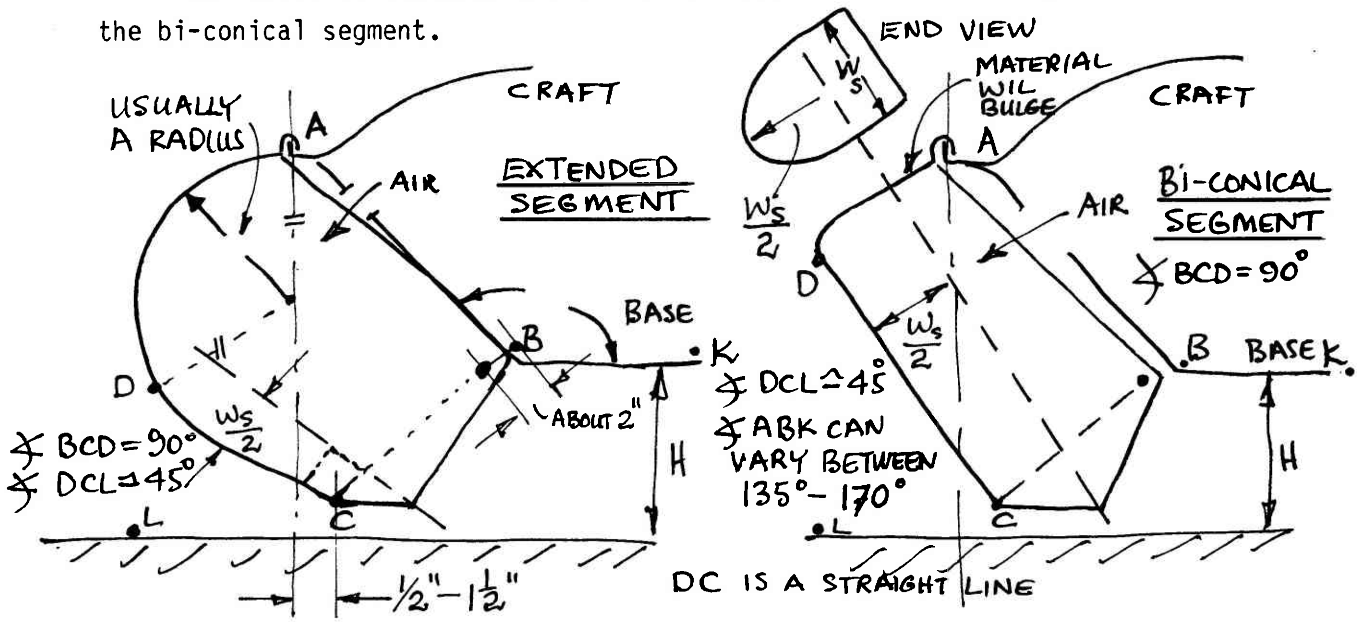
Segmented skirts are often referred to as convoluted skirts or finger skirts because they look like closed curved fingers. Segments were developed by Hovercraft Development Limited in England and were first fitted to large hovercraft around 1962. Today they completely dominate the European craft as well as the mass produced US craft market. They offer less resistance when passing over grass, rough ground, waves and choppy water. It is difficult for cushion air to escape from segments as they have good sealing properties. Better sealing means less dust, less spray, less noise, and less horsepower. Segments do not bounce like bags. Segments give a soft ride but are not as stable as the bag or jupe skirt types. Craft fitted with segments tend to roll and pitch. Such characteristics are desired for racing as they usually allow tighter turns and trim by pilot body movement (kinesthetic control). Segments are usually made from lighter weight materials than bags, such as 6 oz./sq. yd. neoprene coated nylon or 6 1/4 oz./sq. yd. pack cloth (nylon or treylene with a thin urethane coating on the outside). Segments can also be manufactured from 16 oz./sq. yd. neoprene, PCV, or urethane materials. The lower segment edges, in contact with the ground, wear rapidly. Light material is more easily damaged than heavier and segments are not as durable as bags. Some efforts are presently being made to develop segments with easy-to-repair wear sections. Wear is usually confined to a small area where the segment touches the surface.

To repair segments replace the worn lower areas with a stitched on patch. Segments tend to scoop. Because of this they are frequently breaking the plastic wire ties which are used to secure them under the hull. Segments are commonly attached to the craft perimeter by folding the segment material over the machine edge and securing using steel clips and Plastic Trim-Lok. When an inner segment plastic wire tie snaps the segment will blow out. Adjacent segments then swell and effectively seal off the escaping cushion air. Usually replacing the plastic tie is a matter of reaching under the craft and passing a new tie through a securing clip in the hull and the segment flaps (see next sketch). Plastic wire ties are designed to be the weak link and will snap before the segment is damaged.

In the 6 1/4 oz. lightweight materials a wide variety of colors are available, consequently finger skirts tend to be brightly colored rather than black which is the common color of most neoprene materials.

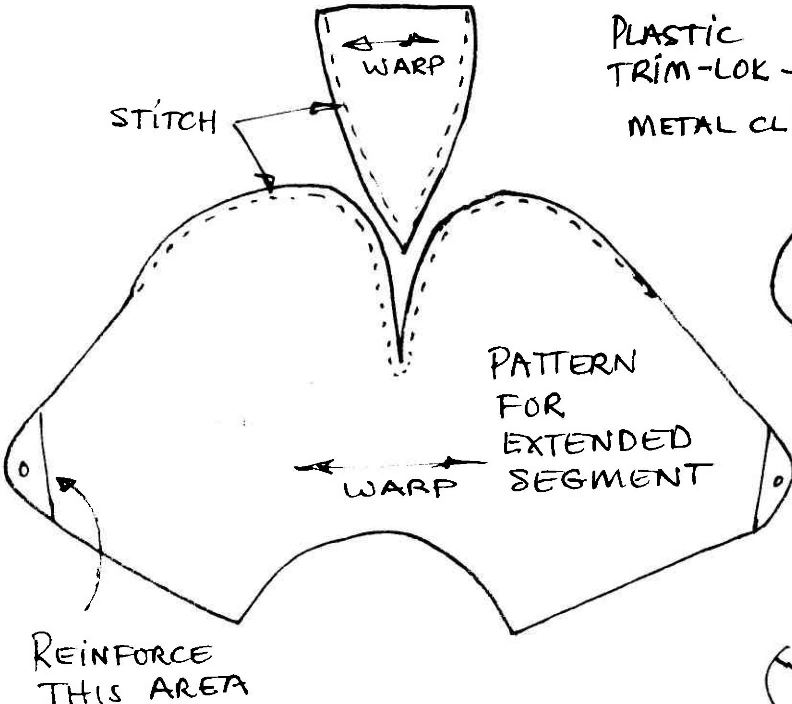
Since segments scoop, mostly at low speed, rear segments are always fitted with anti-scoop flaps. Segments are easy to attach and the plan view shape of the craft can be more varied than the machine fitted with the bag or jupe skirt. Segments are usually about 6" wide and it works out that most small hovercraft have between 55 and 65 segments. Almost all segment craft have cushion feed air holes in the craft hull, as does the flow-through bag skirt. Holes are positioned so as to align with each segment. Consequently, there are usually between 55 and 65 holes. Some machines have larger holes at the front, regular holes at the back and none along the sides, but in the majority of designs each segment is fed individually. Hull air feed holes are usually about 3" in diameter.

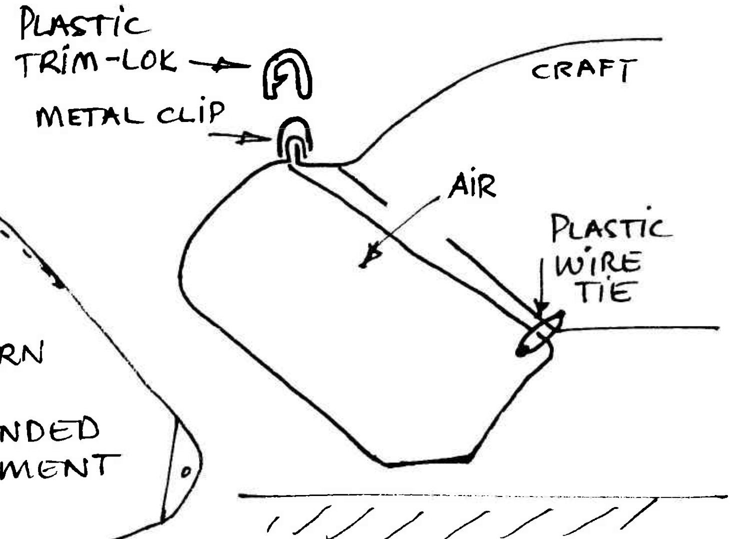
Two types of segments are in common use. The extended segment and the bi-conical segment.

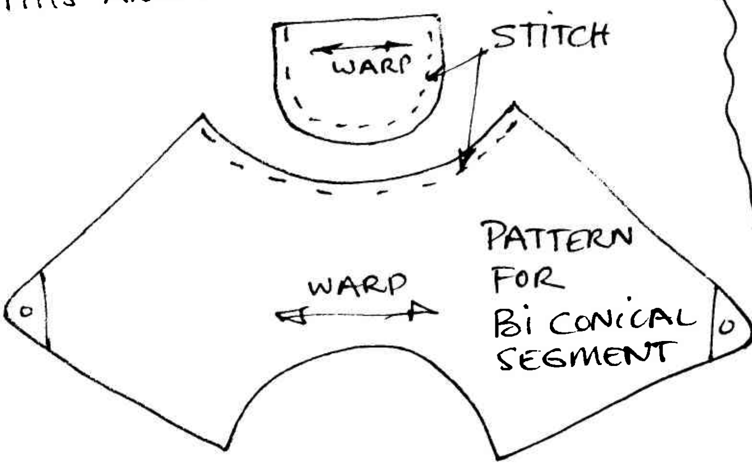


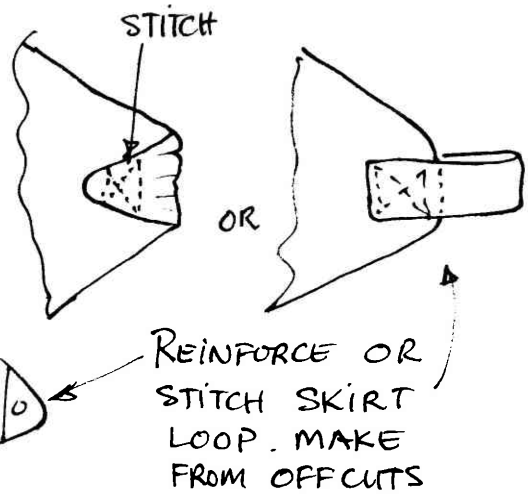
Point C should be inside the vertical line down from A.

One simple method for developing a segment cut out pattern is to make a full size urethane foam plug of the segment. Shape a urethane foam block to width (w_S) and side view as shown above. Carve the top corners to make gentle curves so that they blend together. After draping skirt material across the form use contact cement to hold it in place. Cut the material so that only one continuous seam around the top edge of the segment is required. The material will tend to wrinkle -- this should be avoided as much as possible. When the skirt material is removed from the form it will give the segment cut out pattern. If properly made a single stitch line is all that is required for individual segment construction. Material should be tailored so as to avoid gaps. Seam allowance must be added to both pattern parts when making the cardboard master-cut-out pattern. The resulting patterns should look like the following:









Cut out the material with warp as shown. Stitch with right sides together.

In summary, the segmented skirt is the more popular skirt type at present. For speeds approaching 85 MPH, the high pressure bag seems to work best and with the least problems. Skirts are a technology in its infancy and much scope for improvement and breakthrough exist. The future of hovercraft, to a great extent, depend on the outcome of continued skirt development.

8. Lift Air Supply

We have seen that there are at least three skirt options for preventing cushion air from escaping. Now we should look at what it takes to actually force the lift air under the hovercraft.

Almost without exception axial flow fans are responsible for pumping air through practically every light hovercraft today. Axial flow fans are efficient and capable of pumping air at the required pressure (up to 4" of water gauge static pressure) and at the required volume. The axial fan's characteristics, coincidentally, happen to suit the air requirements of the light hovercraft. In addition, these fans are readily available at moderate cost (about 1/40 to 1/80 of total vehicle cost). All European machines use two proprietary brand fans, the Multi-Wing and the Breeza. (Multi-Wing seems to be preferred.) The same applies in Australia and the US; but in the latter there are more four-bladed wooden fans in use, especially for cushion air-supply purpose on homebuilt units.

Fan manufacturer's catalogs list fan diameter, number of blades, blade angle, RPM, fan horsepower, pressure rise, and volume flow of air. Wooden fans will often be sold to match lawn mower 4-cycle engines which rev up to about 3600 RPM.

A fan is usually selected to suit the lift engine being used. The engine size is determined from manufacturer's specifications. For most small craft fan lift diameter will vary between 18" and 30". The lift fan should have three blades minimum and be chosen from a fan catalog so as to absorb the maximum engine output HP at the stated RPM at normal air temperature and pressure. Always use the largest possible fan diameter. Locate the manufacturer's maximum recommended tip speed, it's usually given in ft./sec. or m./sec. Then calculate the maximum diameter (D) in ft. as follows:

$$D = 60 \times \text{Max Tip Speed} / \pi \times \text{Max RPM} \qquad (24)$$

Because HP, diameter, and RPM are now known, fan selection can proceed. Try to choose a fan with three or more blades. The catalog will usually show fan pitch, pressure rise and volume flow, but sometimes at a lower RPM. When this happens it is necessary to use fan laws to project the catalog stated performance to other speeds and horsepower. These laws are as follows:

Volume varies directly with fan speed

$$Cfm_2 = Cfm_1 \times (RPM_2/RPM_1) \quad (25)$$

Static pressure varies with the square of the fan speed

$$P_{S_2} = P_{S_1} \times (RPM_2/RPM_1)^2 \quad (26)$$

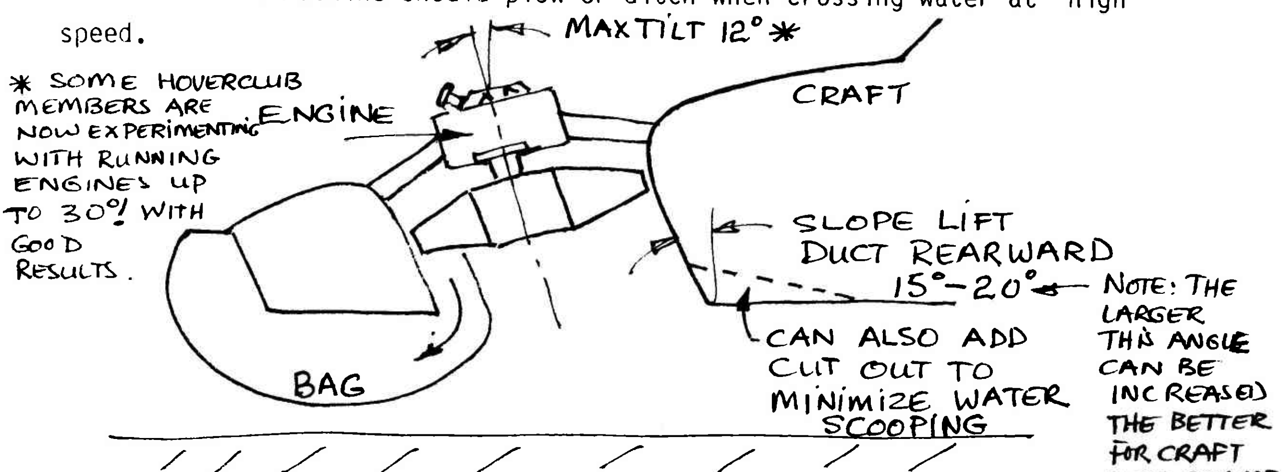
Horsepower varies with the cube of the fan speed

$$HP_2 = HP_1 \times (RPM_2/RPM_1)^3 \quad (27)$$

Note: The use of these laws are limited to fans operating up to the manufacturers maximum fan tip speed.

Best positioning for the lift fan is to mount it in the front of the machine and tilted slightly forward. For high speed craft with forward facing lift fan inlet, once the craft reaches about 60 MPH most of the lift will come from ram air.

Because there is a difficulty of getting standard US 4-cycle lift engines to run at angles greater than about 12 degrees most lift fan installations should remain below this angle. It is also advisable to slope lift fan ducts rearwardly thus preventing water ricocheting into the fan if the machine should plow or ditch when crossing water at high speed.

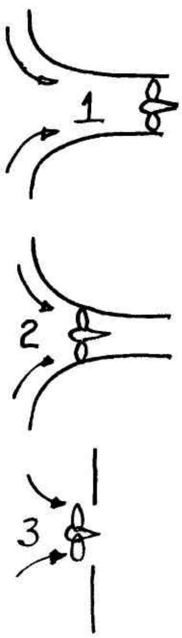


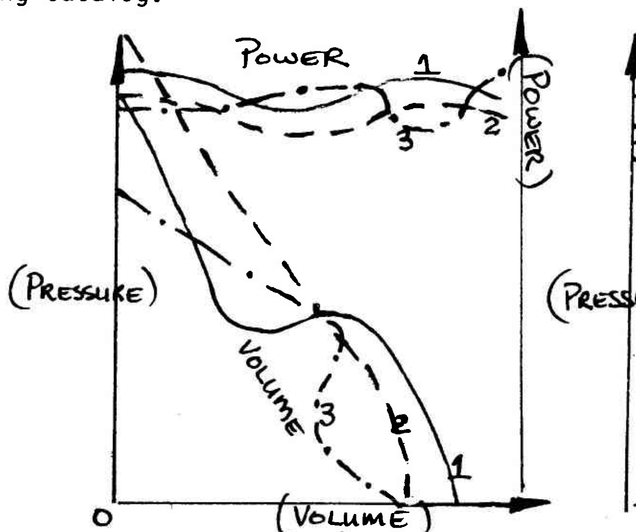
8.1 <u>Duct Flow</u>

Since we are dealing with pushing hovercraft through air at speed, streamlining is important. Inside the ducting, air is being pushed at speed so ducts should be smooth, intakes should be rounded and smooth, and obstructions to air flow minimized.

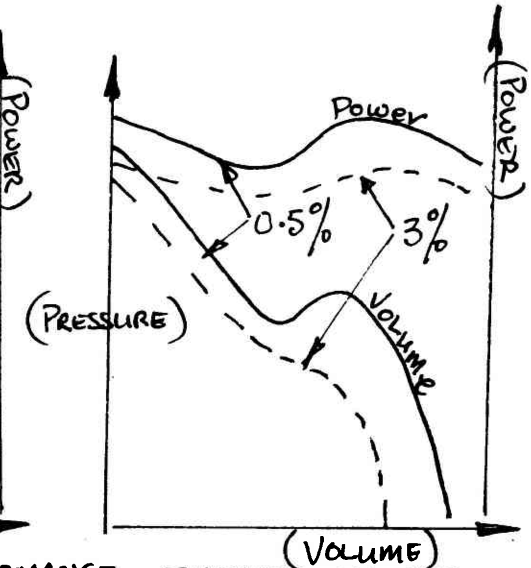
The following graph shows effect of increasing fan tip clearance on volume flow and pressure. (Taken from the Multi-Wing catalog.)

A smooth bell mouth intake is also recommended. The effect of different inlet conditions are shown in the following graph taken from the Multi-Wing catalog.





COMPARATIVE PERFORMANCE FOR INLET CONDITIONS 1, 2 & 3.

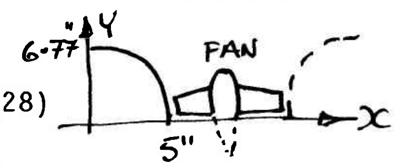


INFLUENCE OF TIP CLEARANCE ON PERFORMANCE. AS A PERCENT OF FAN DIAMETER.

Thrust from a fan is directly proportional to projected intake area up to twice the fan disc area. The recommended fan intake bell mouth shape for hovercraft is an ellipse with a ratio of major to minor diameter of about 1:35. One formula for designing the bellmouth profile for a 24" diameter fan is:

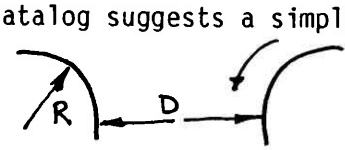
$$\frac{6.77}{5} = 1.35$$

$$(Y^2/6.77^2) + (X^2/5^2) = 1 \qquad (28)$$



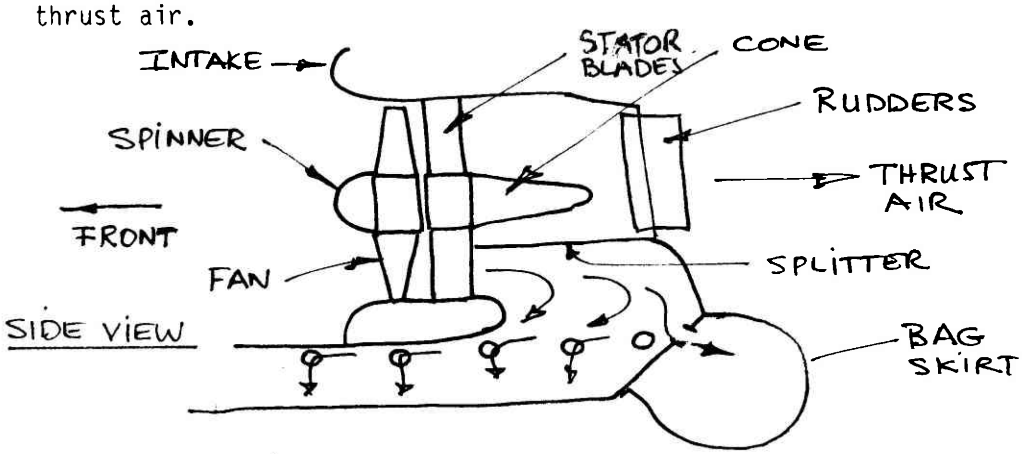
The Multi-Wing catalog suggests a simpler formula:

$$R = 0.12D \qquad (29)$$

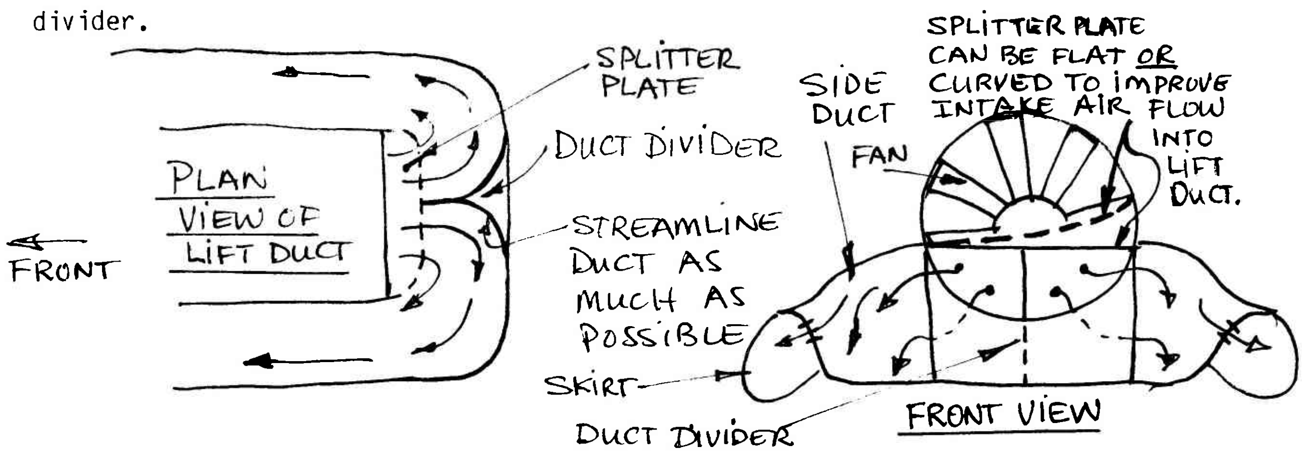


Fan tip clearance should be as close as possible, usually about 1/8", although most craft builders only achieve 1/2". Obstructions in the air stream should be avoided where possible. The type of front mounted lift fan discussed is best suited to the non-flow-through type bag skirted hovercraft. For flow-through bags and segment skirted craft the air must be ducted from the fan into peripheral ducts located inside the machine. This usually requires that the air is turned around sharp corners. Whenever air, that is moving, has to be turned a loss of pressure results and has to be made up by increased horsepower.

The least complicated and most common lift system is the single duct. This duct is always located at the rear of the craft, 1/3 of the duct area is split off for lift air while the other 2/3 is used for the thrust air.



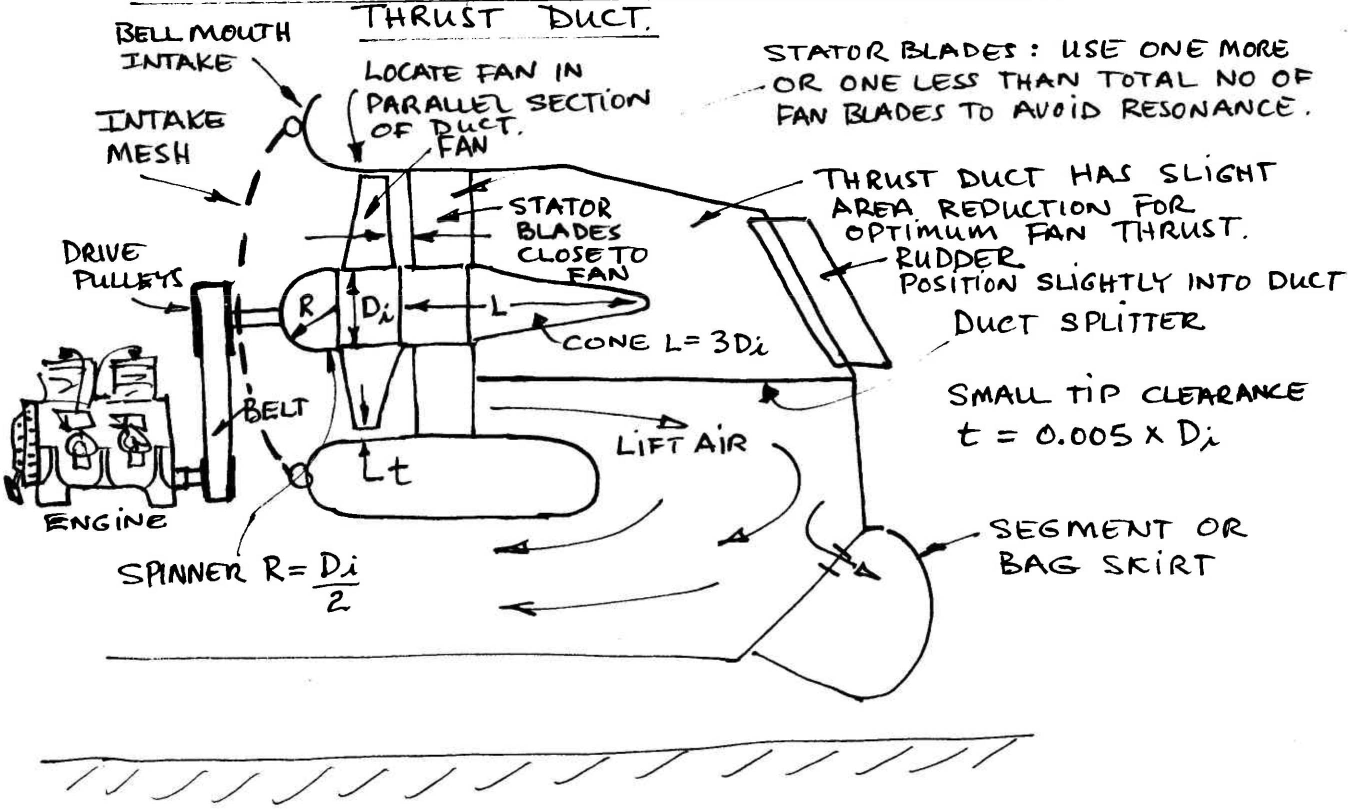
Because this type of duct system requires more turns than the front lift duct system it has greater pressure losses and thus requires greater energy for its operation. In fact, about 40% more power is needed than for a front mounted lift duct. Further, as we shall soon discuss, it is best to have more air flow into the air cushion at the front than at the rear. Some builders try to partially solve this requirement by having large diameter skirt cushion air supply holes at the front, smaller ones at the back, and none along the side. This same duct system will also work for bag skirts. It is the most popular system because of its simplicity. Practically every design has a duct divider.



Jupe skirted hovercraft are not in common use. However, for their optimum performance each jupe should have its own duct feeding directly from the fan. This is probably the most complicated system. Its advantage, however, is its high stability.

Fans and propellers are actually like sirens. When they spin around quickly they generate eddies (vortices and turbulence) and these, in turn, produce noise -- just like a whistle. The quietest fans are windmills, because their large diameter allows a moderate fan tip speed. Consequently, to minimize noise, fan and propeller tip speed must be as low as possible and should always be within the manufacturer's recommendation. Also, good inlet air flow conditions are necessary in order to avoid turbulent air arriving at the fan or prop. Ducts and fan shrouds improve fan tip aerodynamics which result in less tip-generated noise. Much of the noise comes from the tips since this is where the air velocity is the greatest and where most eddies are generated.

ELEMENTS FOUND IN A PROPERLY DESIGNED THRUST DUCT.

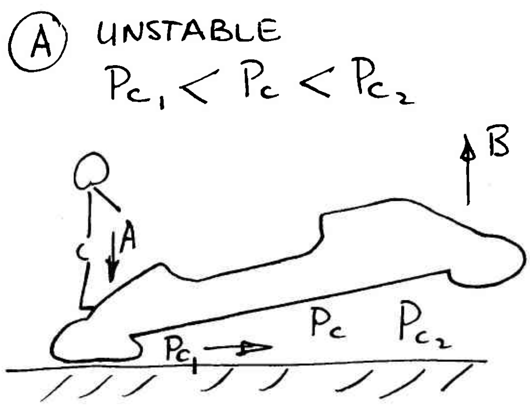


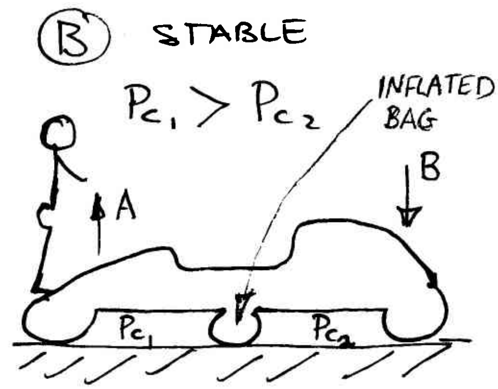
9. <u>Stability</u>

If a craft hovers too high it will want to fall over. If someone stands on one edge of a hovering craft the craft will sink to the ground at that point. If a heavy person sits on one side the craft will tend to sink down on that side. The less its tendency to sink or fall the more stable the craft is said to be. When craft fall over they are of little use. Interestingly, we have one such design in the US. After a number of years and much criticism it is still being successfully marketed by one of the science magazines to unsuspecting homebuilders.

Hovercraft are mostly twice as long as they are wide. Like the tightrope walker who employs a <u>long</u> pole to help keep balance, hovercraft tend to be more stable in their <u>long</u> direction.

When one side of the craft is depressed by body shift or a wind force it will sink and like a bellows it will compress the air on the sinking side. The opposite side will tend to rise up causing the cushion air to expand. As soon as this begins the higher pressure air moves toward the lower pressure air.





Remember, when air moves its pressure drops, so that the air moving away from under the low side looses pressure. When it reaches the low pressure side it slows down and its pressure increases. This has the effect of producing forces A and B which would be most helpful if only they had the opposite directions. (See Sketch A above.) The ground and the underside of the hull act like an air diffuser. One solution to this dilemma is to remain reasonably close to the ground and maintain the hoverheight (H) to width (W) ratio below 0.1.

Bag skirts are more stable than segments because the bag acts similarly to an outrigger on a boat. When the bag touches the surface, the more it is depressed the more the bag flattens out along the surface. Bag pressure on the collapsed side does not decrease as we see the cushion pressure doing. Consequently, the restoring moment, acting through the machine center of gravity, is an approximate function of bag pressure times the bag contact area times the distance from the center of the contact area to the craft center of gravity. To a lesser extent when a segmented craft rolls, the segments on the lower side flatten out along the ground surface also. As this happens the cushion lift area increases by some small amount in the area of segment contact. This increased area will also provide a restoring moment roughly equivalent to the cushion pressure in the collapsed segment times area change times distance from center of area change to craft center of pressure.

Another way of explaining this stability is to consider that the craft rolls about the lower lip of the 'upgoing' segment such that the collapsing 'downgoing' segment effectively moves the contact line outboard, increasing the cushion area locally and generating a righting moment'.

If jupes are used, the jupe under the depressed side is forced down so that its escape area is decreased and, consequently, its pressure rises because the air flow through the jupe decreases. The converse occurs in the opposite jupe. The common solution for solving instability is to compartment the cushion which is what the jupe does, and, in so doing, prevents the movement of air within the cushion. This is most effective by using inflated bags within the cushion. (See Sketch B above.) However, such complexities are unheard of on small hovercraft. In fact, most operators would be unaware of instability; when their machines sink to one side, they lean to the other until it comes back up. This method of craft control has already been referred to as kinesthetic control. Slightly unstable racing craft can be a real advantage because this instability leads to an ability to rapidly and easily bank for more rapid and effective turns. Drivers shifting their weight around inside their machine is referred to as trimming.

Typical stability curves for the three common skirt systems are shown on the page 34.

Stability is defined as a percent of the center of cushion pressure shift. This is the ratio the center of pressure Cp shifts compared to the length or width of the craft depending on where the stability is being measured. M is the stability moment which is the stability force times a distance measured about the center of gravity. (See p. 34)

9.1 Trim

Trim is very important for all hovercraft and can be one of the most troublesome problems, especially when the machine carries a payload which flings itself around and in so doing influences the control of the craft! Such payloads can be one, two, or more persons. Unless both driver and passenger are experienced, passengers will often move, and in so doing counteract the efforts of the driver! In some instances this can lead to accidents.

Trim means simply that driver weight at the front should be balanced by the weight of the engine at the rear. Fuel weight is always changing; consequently, the tank is usually to be found as close to the craft's center of gravity as possible. Trim is a real problem when drivers vary in weight from 90 lb. to 330 lb. The best solution, if it could be achieved, would be to concentrate all variable weighty items above the craft's center of gravity. You would have the gas tank under the engine, the driver sitting on the engine, and the passenger(s) sitting on the driver's head! This is impractical of course, it would look terrible and also have a tendency to be unstable and to want to fall over.

One solution is to fit the engine in the back, the fuel tank in the center, and the driver and passengers in the front on a long seat so that the driver's weight can be moved backward or forward for trimming purposes. For machines which seat four passengers, some mechanical trim means is necessary. Either move the front two seats or fit ballast tanks in the forward and aft vehicle areas and pump fuel back and forth. Not much good, however, when the fuel runs short. Sometimes these tanks are filled with water instead of fuel. This is common on many larger light hovercraft. However, it cuts across the path of good design.

Every unit of weight added to a hovercraft means that much less payload, all other things being equal. A far better solution is to design a skirt system that will automatically sense the trim change and increase pressure locally. This is not difficult to achieve using jupe skirts. At the authors' company seat/payload movement are used on the Neova 2 and the Neova 4 hovercraft and auto cushion pressure adjustment is successfully employed on the Neova 4 and Neova 6 light hovercraft.

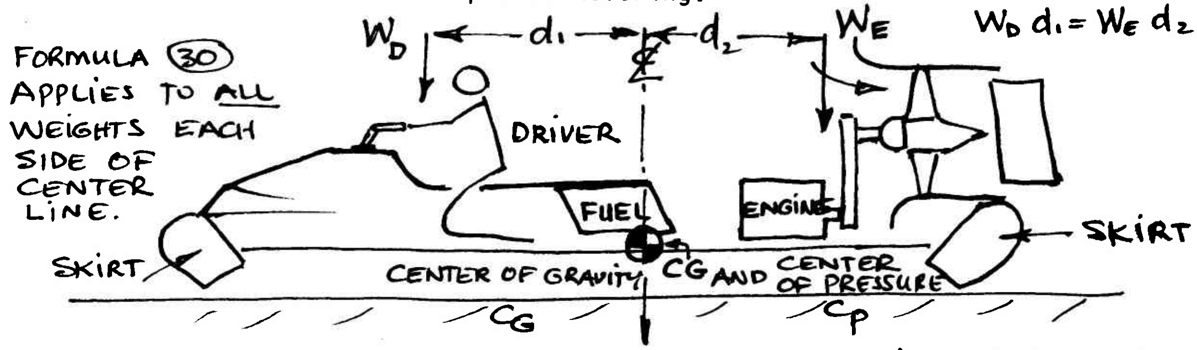
Some machines use a horizontal elevator mounted in the thrust air stream for trim purposes. The chief drawback of the elevator is that its lift depends on thrust air velocity and the speed of the propeller.

It's quite useful at high speed but limited at low speed.

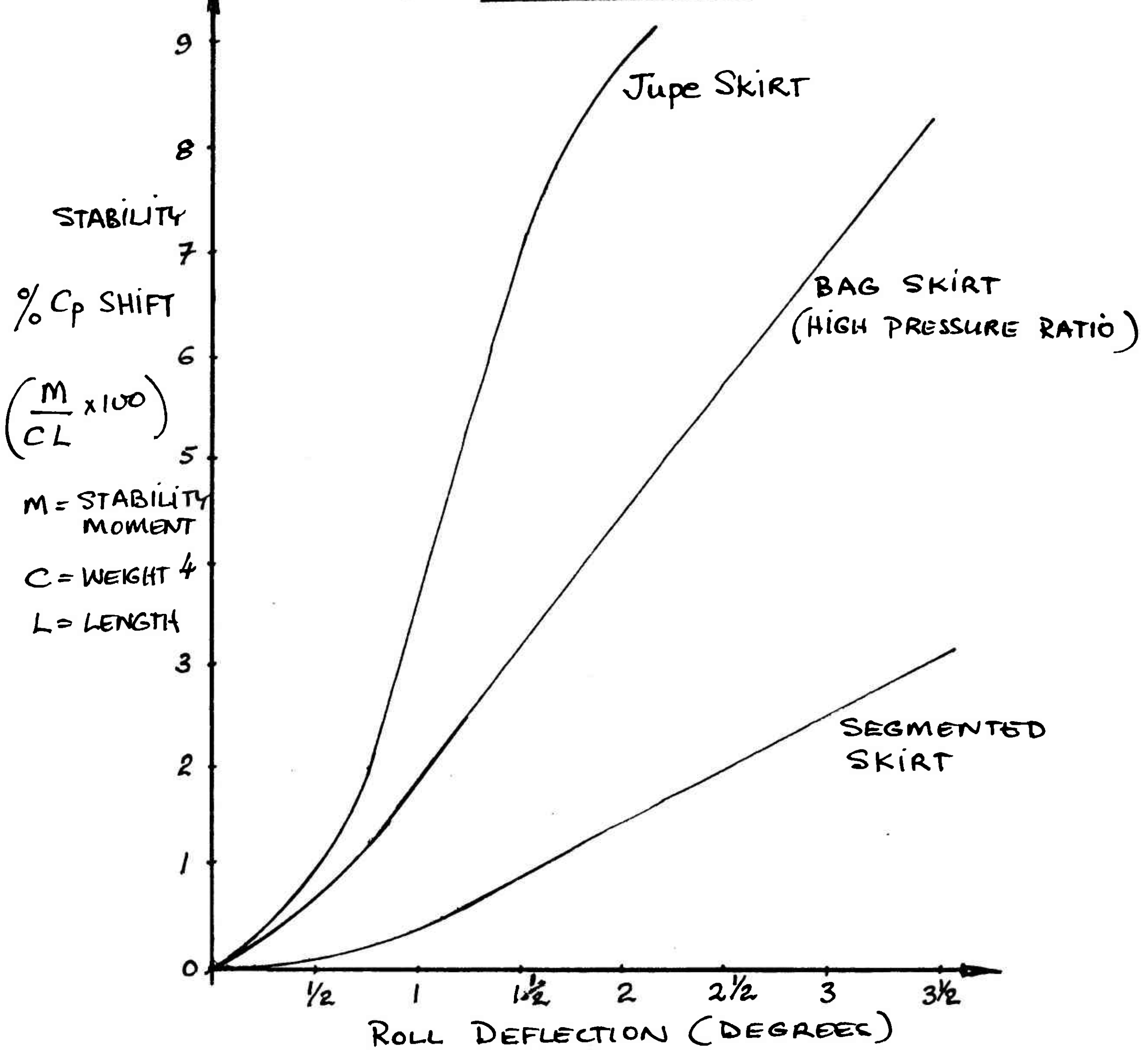
Trim is constantly changing as the payload shifts about, wind strikes the vessel from different directions, fuel decreases, thrust changes, skirt drag changes, wind drag changes. Until now we have said little about motion other than upwards hovering.

FOR TRIM

$$W_D d_1 = W_E d_2 \quad (30)$$



TYPICAL STABILITY OF THREE SKIRT SYSTEMS OVER LAND



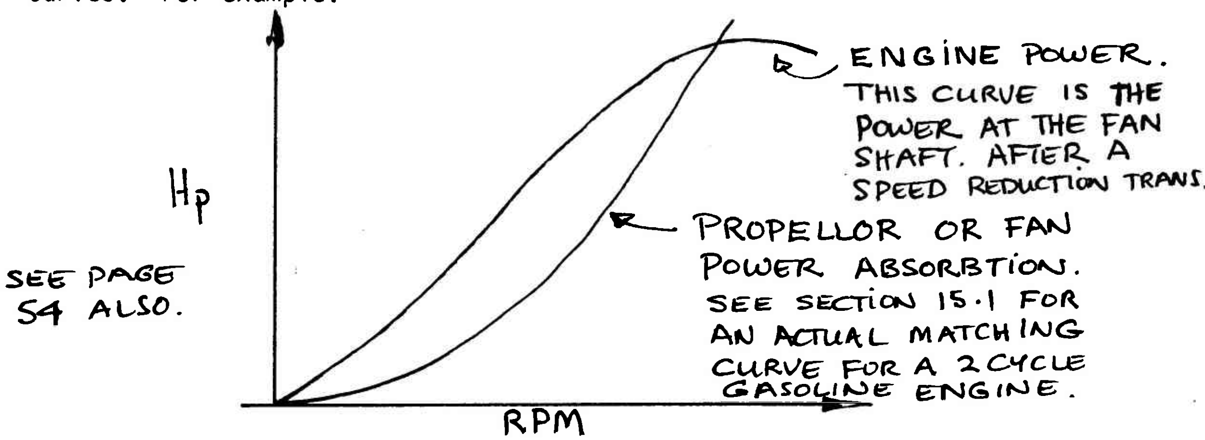
10. Thrust

All the obvious ideas for thrusting a hovercraft along have been tried: wheels, paddles, poles, tracks, winching, towing, jet engines, ducted fans, propellers, and even rockets. Wind sails are still an untried option and there is no reason why a wind surfer hovercraft wouldn't work. Anyhow, of all these devices the ducted fan and propeller have proved the most suitable. Almost every European hovercraft uses ducted fans but in the US there is an even mixture of ducted fans and open and ducted propellers. Some comparisons follow:

	Ducted Fan	Ducted Prop
Rudders	Yes	Yes
Reverse Buckets	Yes	No
Cost	Same	Same
Static Thrust (lb./HP)	Between 3 and 6	Between 5 and 8
Thrust at Speed	Estimate 2 - 5	Estimate 2 - 5
Weight	Less	More
Safety	Good	Worse
Thrust Line	Low	High
Profile	Low	High
Noise	Slightly Higher	Slightly Lower
Cross Wind Performance	Fair	Poor

Diameter of the fan or the propeller, more than any other criterion, effects the thrust output. Large diameter helicopter rotors can achieve 12 lb./HP of static thrust. Such large diameters cannot be incorporated into small hovercraft. The next best alternative is the propeller. This gives the best static thrust and, consequently, acceleration. Its major drawbacks are the difficulty of guarding such large devices and the high thrust line. Ducted fans are safer, more compact, have lower thrust lines, and, consequently, are favored by the majority of hovercraft customers despite their lower thrust/HP capability.

Selecting one or the other depends on many considerations. From a technical standpoint, once a decision has been made as to what to use, then a power output curve for the selected engine and an absorption curve for the fan or prop will be needed. Such information is usually provided by the respective manufacturers. Start by matching these curves. For example:



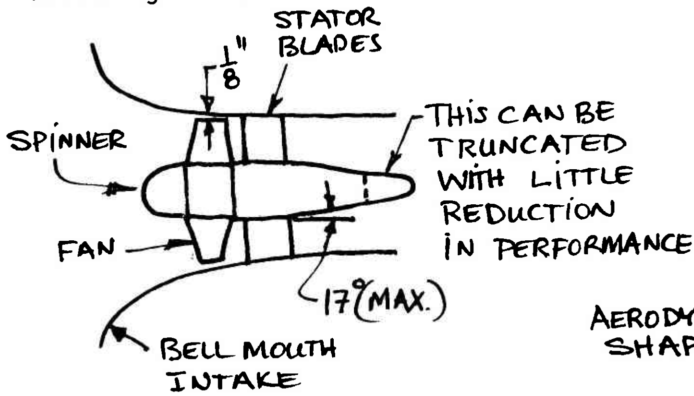
In most cases the fan or prop will have to be geared down since commonly available engines generate power at higher speeds than either fans or props can absorb it. Aircraft piston engines being an exception to this rule.

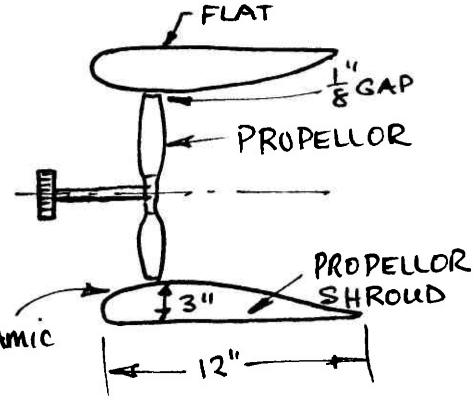
A reduction, therefore, is required which generally will be either chain, sprocket, gearbox, or belt and pulley. Of these, the latter is by far the most popular. Most European craft use timing belts and nylon pullies. It is similar in the US. But more HTD belts with aluminum pullies, PolyVee and even standard V belts are used in conjunction with aluminum pullies. For the larger sheaves homebuilders are using wood. Of all transmissions the HTD belt offers the most technical advantages. It is very efficient, won't slip when wet, requires little attention, rarely needs adjustment, and needs minimal pretension. This means lower bearing loads and lower stress loads in the mounts. It is, however, slightly more expensive than other belt types and requires more precise alignment than the average V belt drive.

Generally one should aim to keep the thrust line as close to the craft center of gravity as possible. Thrust lines are usually considered to act through the center of the fan or prop disk area or the center of the thrust duct outlet. Some European machines have two and even three thrust ducts. Such an approach is aimed at lowering the thrust line while increasing the total disk area of the thrust system. One large prop can produce the same thrust as several small ducted fans, but thrust line is high.

No doubt, multi-ducted fan arrangements are complicated mechanically. Many European Formula One machines have a lift fan duct and engine up front and two thrust ducts across the rear.

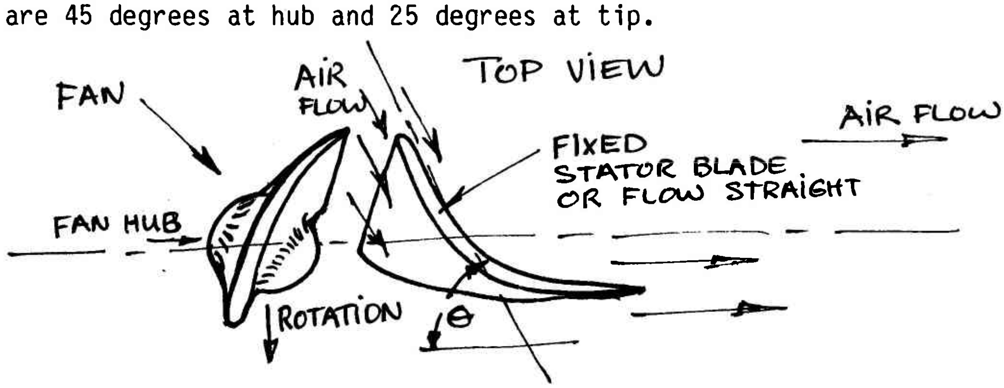
To achieve the maximum thrust a fan must be fitted in a smooth duct. The fan blade tip clearance should be minimum, usually not exceeding 1/8".

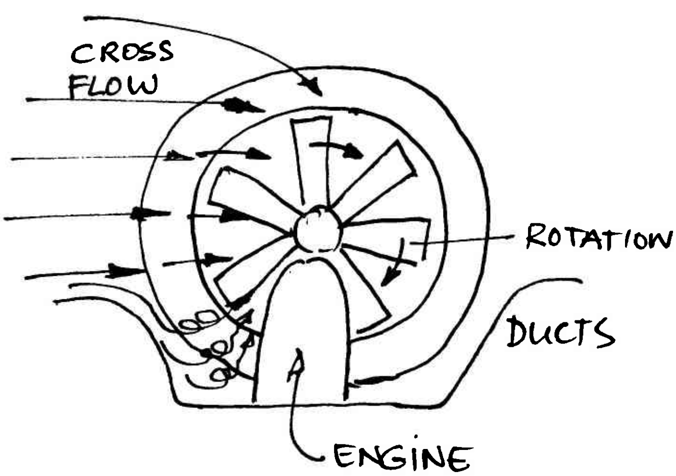




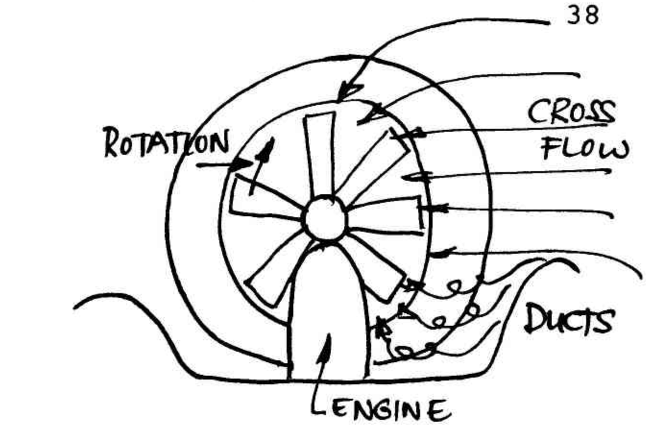
Most European machines are running 1/2" or more because of safety considerations. Deflected ducts won't contact fan blades during hard impacts that often occur during racing. If fan or prop tip gap is large the duct is mostly serving as a guard, not as a thrust enhancer.

A fan duct inlet must be as free from obstruction as possible and have a large gentle curve like a bell's mouth. The center of the fan (the fan hub) should be equipped with a streamlined spinner and the rear of the fan hub should have a cone. Directly behind the fan should be fitted a set of stationary blades (stator blades). To remove the spiral movement of the air usually one more or less in number than the number of fan blades are used in order to avoid any resonance troubles. Stator blades require proper design but generally they face in the opposite direction to the fan. They, like the fan, have more twist at their hubs than at the tips. Stators are about 6" long and do not have any curve at their outlet. Typical stator blade angles 'θ' for a 24" Multi-Wing fan are 45 degrees at hub and 25 degrees at tip.



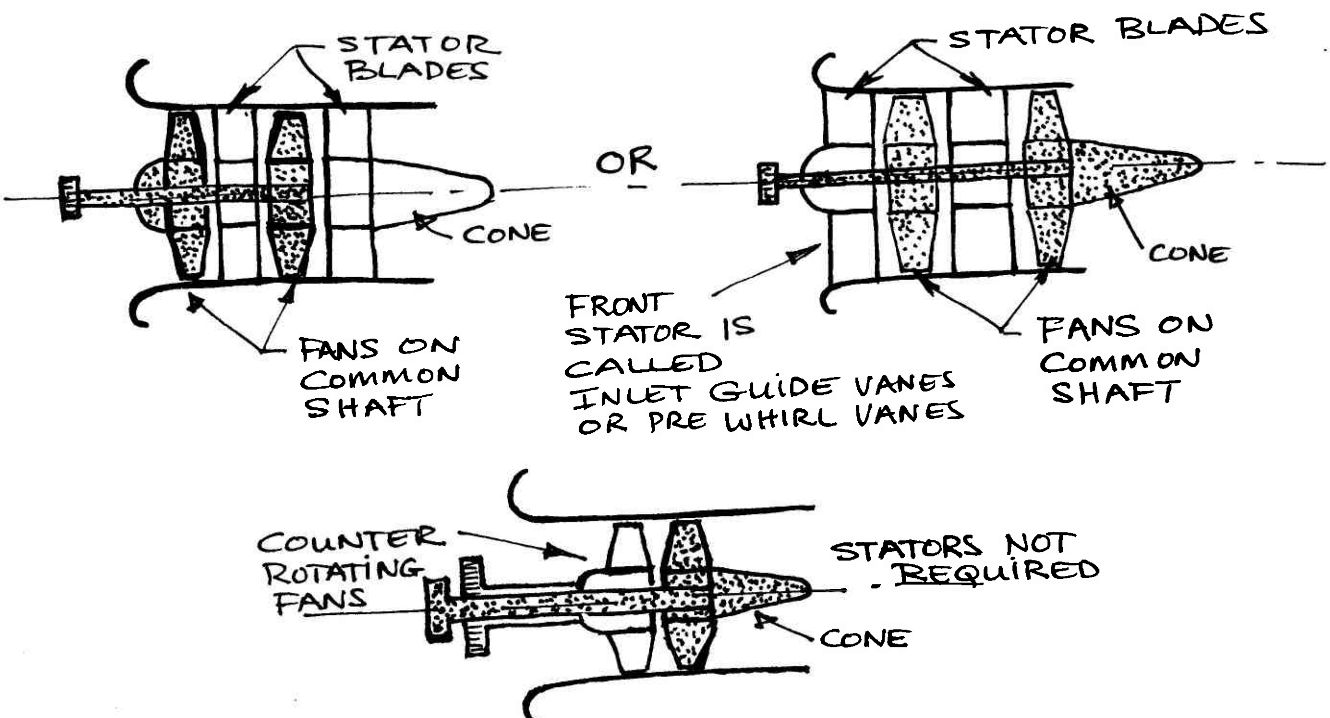


FAN DRAG REDUCES AND WILL SPEED UP



FAN OR PROP DRAG WILL INCREASE AND SLOW DOWN.

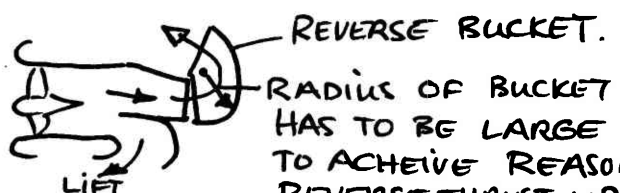
VARIOUS, FAN OR PROP, INLET CONDITIONS:



VARIOUS FAN ARRANGEMENTS:

ALL OF THE ABOVE INSTALLATIONS WILL ABSORB TWICE THE HORSE POWER AS THAT OF A SINGLE FAN AND STATOR AND IS CAPABLE OF PRODUCING TWICE THE THRUST.

NOTE: REVERSE BUCKETS ARE NOT VERY EFFECTIVE BEHIND PROPELLORS. A PROP WILL STALL MORE EASILY THAN A FAN WHEN BACK PRESSURE IS INCREASED.



RADIUS OF BUCKET HAS TO BE LARGE TO ACHEIVE REASONABLE REVERSE THRUST, UP TO 50% OF FORWARD THRUST.

SEE 'CONTROL' PAGE 40.

Very basic craft with low fan power loadings, that is low power with large diameter, do not benefit greatly from refinements such as stators. However, when power per square foot of disc area is above about 5 HP/sq. ft. stators become worthwhile.

There are two methods of manufacturing stator blades in common use:

1) They can be designed by simple momentum theory and made in fiberglass from a mold. Metal blades are possible but fatigue caused by blade flutter is often a problem. Simple curved sheets are quite adequate as aerofoil blade sections are seldom justified.

2) A plastic fan with fully adjustable blades, such as the Breeza, can be used as stators. The correct blade angles are determined by trial and error. With either type of stator, correctly aligned, a thrust gain of 15 - 20% can be achieved. For maximum effect, stators should be accompanied by a fan spinner and a tail fairing. The spinner can be a simple hemisphere in fiberglass covering the hub of the fan although an elliptical profile is slightly more efficient. The tail fairing can be a simple cone -- tests have determined that the cone angle can be up to 17 degrees per side for straight or convergent ducts with a truncation of up to 1/3 of total length (see previous sketch).

Some fans will produce more thrust for a given RPM when operated against a moderate back pressure. This can be achieved by gently contracting the thrust duct towards its outlet. Such things, however, should be calculated.

Fan and duct installations as used in hovercraft contain nothing new, the technology has been with us for more than 50 years.

If one wanted to maintain the same size duct but double the absorbed horsepower, an extra fan can be installed in series with the first. Another set of stators would be required as well. If the fans were made to counter rotate, then the stators could be dispensed with, but the mechanics of this outweigh the simplicity of two stator blade sets.

Propeller installations are less complicated. Propeller selection is made after comparing its horsepower curve with that of the engine.

Stators are not required for props but the thrust duct should be constructed along similar lines as that used for fans. (See previous sketch.)

10.1 Intake Effects

Hovercraft racing in the US has progressed in recent times. Plow-in is still the major concern of most drivers. For light craft which travel fast lift-off is also a concern. Another concern of some drivers is a bogging-down-effect when craft turn in certain directions. This phenomen is believed to be related to fan or propeller inlet conditions. For example on racing craft built by the authors, turns made to the right cause trouble. Also, the same trouble arises if there are strong crosswinds. The present explanation is as follows:

Air coming into the thrust duct from a crossflow direction causes the drag on the rotating fan blades to increase or decrease depending on the incoming flow's direction. Because the lower part of a hovercraft thrust duct tends to be obstructed by the driver, engine, hovercraft body or something else, the unobstructed flow hitting the top portion of the fan has more influence on fan blade drag. When the incoming air is almost in line with the fan blades rotation path the blade lift increases as well as its drag. When the flow comes to the back side of an advancing blade the drag is less and so is the lift. Of course, what is wanted in a turn is maximum thrust so that the craft can accelerate through the corner or turn. This problem is ralated to the fan power curve and engine power curve matchings. (See page 56.) What is believed to be happening is that as the fan drag goes up it slows down or it needs more power from the engine to keep it at the same speed. If the engine power curve is closely matched at the particular fan speed when the fan drag goes up then the engine can't supply more power or energy so the engine slows down and so does the fan. The opposite happens when the air flow comes from the other direction, the fan speed increases. The engine can easily over rev but it is usually prevented from doing so by the driver who throttles down. Engines with flat power curves are not so sensitive to this problem as is the 2-cycle whose power curve almost parallels the fan's power curve. The solution might lie in overpowering the fan or in developing an exhaust system which produces a flat power curve. The penalty is that at low RPM the engine has so little power it cannot accelerate the fan up to speed. Some drivers are trying to overcome this problem by fitting clutches so that the fan is not engaged until the engine has speeded up and is on its power curve, sometimes referred to as on-the-pipe. One other solution which is of interest to the authors is the possibility of variable length exhaust systems. This would give the driver the ability to get more power when the engine starts bogging down. (See page 52.) And still another possibility would be the use of an adjustable pitch fan or prop. This solution, however, would be expensive and could reduce reliability.

11. Control

As we have covered the hovering and thrust processes we should now begin to look at what happens next ... moving! Hovercraft slide along like an ice puck. Their motion is very much influenced by wind, slope of the ground surface, the type of ground surface, and craft trim. Controls on board the machine must be adequate to overcome these external effects and make the craft go in the general direction its operator desires. Such an objective, however, is not always possible when driving hovercraft. More than any other influence is the thrust available. For control this thrust must be directed so as to generate the desired motion in the hovercraft.

With a simple propeller it's just a matter of having two or three rudders behind the prop and possibly a horizontal elevator to help control longitudinal trim. The thrust throttle will be used to do the rest.

With a fan it's almost the same. Craft equipped with thrust reversers (reverse buckets or bow thrusters) have the added ability of stopping, reversing, and crabbing. The normal methods of stopping are: (1) Use the rudder to spin the machine 180 degrees and then apply full throttle such that the total thrust brakes the motion of the machine. (2) Reduce thrust and lower the machine on the surface where the skirt drag will slow the speed but the major braking occurs when the underhull skids make ground contact or the hull meets the water.

Some larger light hovercraft use a system of underhull cables to move the inner skirt attachment line. When this control is applied the skirt changes shape slightly and results in a small movement of the skirt surface contact line. This produces a change in lift area at the extremity of the cushion. The net effect is a movement of the cushion center of pressure and a resulting roll of the machine. Skirt shift, although complicated, is a useful means for trim and control purposes.

Certain larger craft also have air ports that bleed air from the cushion or the lift air ducts. These are referred to as "puff ports" or, when they are fitted close to the bow, "bow thrusters". These are not found on any of today's light machines.

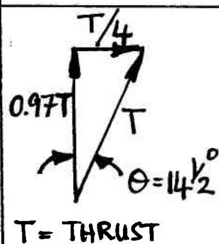
It has been suggested that to counteract side winds and slopes, a control side force of about 25% of the maximum forward thrust is required. There are three main classes of control system capable of generating a side force:

1) Thrust vectoring devices -- rudders, differential thrust, etc.

2) Side thrust devices -- puff ports, thrusters.

3) Cushion tilt devices -- skirt shift, skirt lift.

The table below lists these classes, appropriate yaw angles, and additional power required to generate a side force of 25% of maximum thrust. It is assumed that full thrust power is maintained and not 'siphoned off' for control purposes.

<table>
<tr><th>Control Class</th><th>Yaw Angle</th><th>Loss of Forward Thrust Due to Yaw</th><th>Additional Power Required</th></tr>
<tr><td>1) Propeller or propulsion fan thrust vector</td><td>
</td><td>3.2%</td><td>Approximately 3.2% (neglecting drag due to yaw)</td></tr>
<tr><td>2) Side thrust air ports</td><td>0</td><td>0</td><td>25% (device as efficient as main thrust system)</td></tr>
<tr><td>3) Cushion tilt (lift power 1/2 thrust power & * H = 0.1W)</td><td>0 (YAW MAY OCCUR DUE TO SKIRT DRAG.)</td><td>0
* H = STRUCTURAL CLEARANCE
W = WIDTH</td><td>Approximately 245% (Only 10% of cushion power available for thrust.)</td></tr>
</table>

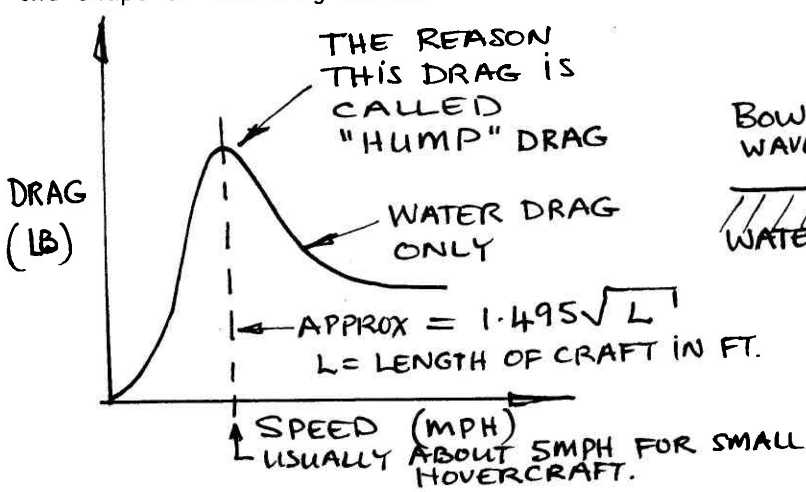
As can be seen, only thrust vectoring from the main propulsion system is efficient in generating appreciable side force, however, this is only true when propulsion power is high. For low speed maneuvers high forward thrust is not possible, except maybe for short bursts, thus puff ports and or cushion tilt is often used despite relatively low side thrust capabilities.

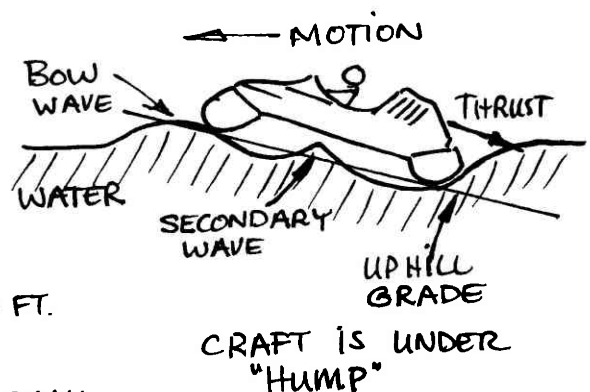
Like skirt technology, the whole area of control and thrust is still in its infancy. Some breakthroughs would be good but more realistically we will probably see only incremental improvements in the existing thrust and control devices already duscussed.

12. Dynamics

In the situation where a hovercraft begins to hover, let's say over water, its cushion pressure will displace the water under the craft to a depth corresponding to the cushion pressure. Of course, the total weight of water displaced will equal the gross weight of the hovercraft.

Now to accelerate; the cushion pressure continues to depress the water under the skirt as it moves along. Much to the surprise of many early researchers, it took considerable energy to move a hovercraft over water. Many early small hovercraft lacked sufficient power to accelerate the depressed underhull water, and, as a consequence, they could not get going. This is one of the more intriguing phenomena of hovercraft. As the speed of the machine increases so does its need for more energy. This is because the water under the craft is depressed downward by the cushion pressure. As the cushion moves forward and depresses the water surface downward it also depresses it forward which results in the tendency for the water to move in the direction of the craft's cushion, resulting in the generation of a standing wave under the craft. In turn, this causes the nose to rise up and the stern to sink. In effect the machine is trying to accelerate uphill! If the motion of the craft is made to continue, standing waves occur at the front of the cushion -- for this reason this drag is sometimes referred to as wave making drag. If more and more power (thrust) is applied the machine will begin to climb this self-created hill whereupon it will eventually reach the top and begin to hover above the water's surface. No sooner does this occur than there is a large decrease in drag and the machine accelerates quickly. This phenomena is common for all water craft, but for hovercraft it is called "hump drag", so named because of the shape of the drag curve.





12.1 Hump Drag

Hump drag depends upon many factors; however, one simple theory, derived by Crewe and Eggington, for a deep water hump wave gives the approximate equation:

$$R = (2PcC/wL)(1 - \cos(Lg/V^2)) \qquad (31)$$

Where R = wave drag in lbs.,

C = all up weight in lbs., also $C = P_c A$

w = water density in lbs./ft.^{3} = 64 for sea water,

P_c = cushion pressure lbs./ft.^{2},

L = cushion length in ft.,

g = gravity = 32 ft./sec./sec.,

A = cushion area in ft.^{2}, and

V = craft speed in ft/sec.

Drag is a maximum when:

$$\cos(Lg)/V^2 = -1 \text{ (or } (Lg)/V^2 = \pi \text{ rad.} = 180^\circ)$$

$$\text{thus, } R(\text{max.}) = (4PcC)/wL = (4Pc^2\ S)/wL \qquad (32)$$

For a rectangular craft of length equal to twice the width, operating in sea water:

$$R(\text{max.}) = 0.03\ Pc^2\ L \qquad (33)$$

These equations show how important it is to keep the cushion pressure as low as possible. Also it can be shown that long narrow craft generate lowest hump drag; for instance, if the width equaled the length then:

$$R(\text{max.}) = 0.06\ Pc^2\ L, \qquad (34)$$

or twice the drag. However, if L = 3W, where W = width in feet, then

$$R(\text{max.}) = 0.02\ Pc^2\ L, \qquad (35)$$

or only two thirds the hump drag.

It should be remembered that other forces, such as skirt and momentum drag are acting and can significantly raise the total thrust required to exceed hump speed.

Also, hump drag will vary depending on the depth of water, due to effects caused by wave reflection off the seabed or river bottom, and there is a critical depth where the hump drag will be at its greatest value. Trim of the machine will also generate effects and salt water hump drag is not the same as fresh water hump drag because of different water densities. On some small hovercraft changing trim as the craft negotiates the hump will minimize the hump drag and give a more rapid rate of acceleration. When starting off, nose-down trim is required. This adds additional thrust; it's like the craft seems to be going downhill and craft nose-down trim probably slightly reduces the water depression toward the rear. But, more importantly, it helps dump water from the rear segments, bags, or jupes and reduces any skirt scooping tendency, i.e., skirt rear drag. Bag skirts must be purged of water before attempting to blast through hump. Just prior to climbing over the hump wave, the nose has to be lifted. Otherwise there is a tendency to submerge the bow; anyway, the machine should then accelerate.

Hovercraft generate maximum waves below hump. Having to be constantly climbing over hump wastes a lot of energy. Because of the hump phenomena craft can be very difficult to control in narrow winding creeks. This is because for safety and control the driver is forced to operate at slow speed and this invariably turns out to be just under or on the maximum hump drag point. It's a little like trying to surf a hovercraft through a narrow and winding gully with odd wind gusts, tree limbs, sand bars, and rocks, to boot. For machines with marginal hump performance there are various tricks, many of which were deployed by early hovercraft salesmen. One is to start on land, accelerate, and arrive at the water above hump; then the machine will go great, but don't slow down!

It's obvious that if we can somehow reduce the water depression under a hovercraft then this would lead to a reduction in the magnitude of the hump drag force.

For satisfactory hump performance under a variety of conditions it is important to have a thrust reserve over calm water hump drag. Reducing weight or increasing cushion area will help; but, whatever the the final configuration, it is essential that the static thrust available is about twice the calm, deep water hump drag. Formula 35 indicates the importance of hovercraft length or shape to minimizing hump drag. Until now we have not mentioned hovercraft shape.

12.2 Shape

Imagine a machine which is three times as wide as it is long. This would be a very poor shape because its hump drag would be excessive. In fact, the least hump drag is achieved with pointed nose streamlined machines. This also happens to coincide with being the best shape for high speed. In this respect we can take our lesson from boats. In fact, long and skinny will have the least hump drag and this is the shape used for fast boats.

For practical reasons the majority of craft are rounded at the front and straight across the back. Sometimes the corners will be rounded or cut off for styling or to facilitate skirt attachment. This shape has more functional advantages overall than does the long and skinny machine. Until now we have avoided discussing cushion lift area.

In equation (5) the lift area was L x W for a rectangular craft. The actual effective lift area is that encompassed by the skirt contact line. For calculations this line is usually guessed at except on a pure jupe skirted hovercraft where it can be calculated with reasonable accuracy. For bag skirted machines use the center of the bag and for segmented skirts use a line just inside the furthermost outward contact point on the bottom of each segment to determine cushion area.

Measure the area as accurately as possible. To determine the lift area of a full size craft make a scale cardboard pattern of the craft cushion area. Measure the length of this cardboard pattern. You should be able to estimate the scale factor, x, by using the length of the full size machine; divide the length of the full size machine, L_{fs}, by the length of the cardboard pattern, L_M:

$$x = L_{fs}/L_M \qquad (36)$$

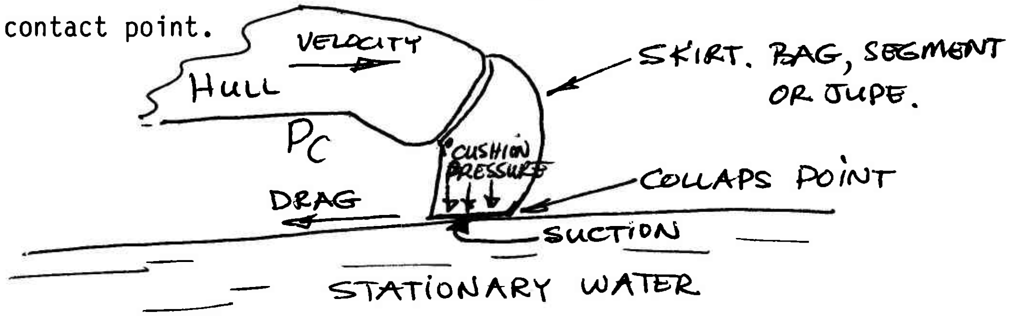
Measure the area of the cardboard pattern accurately. Multiply the area of the cardboard pattern by x^2. This is a quick means of finding the cushion area of the full size craft. The cardboard pattern also contains another useful item of information -- the center of area. Balance the cardboard pattern on a needlepoint. This corresponds with the craft center of area which is also the center of pressure. Scale off the pattern to determine the equivalent center of the full scale machine. The center of pressure of a static machine hovering horizontally will be in line with it's center of gravity.

12.3 Dynamic Effects

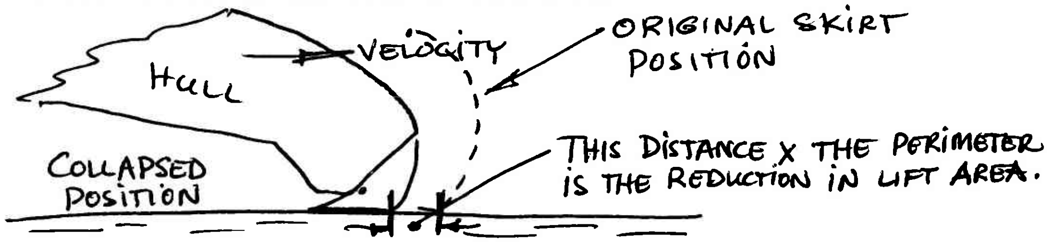
Except perhaps for racing hovercraft, all other craft should be designed to float when sitting in water. They should not turn turtle if passenger or operator move around in the floating craft. Incorporating sufficient polyurethane foam so that 100%+ positive flotation is available to float a fully loaded vehicle is not easy. Present machines use plastic bottles, inflated bags, sealed compartments, urethane or other foams, in an effort to comply with the Hoverclub and Coast Guard floating and safe loading requirements.

All hovercraft, when hurtling along, can plow-in. Plow-in occurs in the direction of travel. If the craft is going backwards or sideways, plow-in will occur in the same direction. Depending on the shape of the underhull, the craft might rotate when the hard structure contacts the water or ground. It is a phenomena where the hovercraft falls off its cushion of lift air. It can also be thought of as instability. It will happen over land or water. There is a similarity between plow-in and aircraft stalling. All aircraft stall, but in reality it is very rare because pilots are taught to avoid those conditions which cause it. Experienced drivers rarely plow-in because they have discovered how to avoid plow-in conditions. Big passenger carryng hovercraft which used to operate across the English Channel rarely plowed-in because the pilots were trained to avoid plow-in conditions. When a hovercraft is travelling fast, above 25 MPH, especially across a smooth water and perhaps even with a tail wind, the crafts speed will increase. The driver begins to feel uncomfortable with the increase in speed and begins to throttle down, thinking that this will slow the hovercraft. In hovercraft which are of the integrated type it is much more of a problem. To slow means that the engine and the fan slow also and cushion air flow diminishes.

Once this happens the volume of air and the pressure of the same air decreases. Looking at Formula 25 and 26 you can see that the air volume drops off in the same proportion as the speed decreases but that the pressure drops off as the speed squared. This means that a slight reduction in fan speed has a much greater effect on the air pressure which drops much quicker. So, now as the cushion pressure drops and the volume flow drops, the effects which now result are thought to be that the air escaping under the skirts (volume flow) is the lubricant so that the lubrication now diminishes. The cushion pressure decreases and the hull or hard structure, which is being supported by the cushion's air pressure, starts to fall. It falls depending on the other forces acting on the hovercraft. If the cushion is not pumped up again the hovercraft continues to fall. Meanwhile the skirts begin to collapse at the water surface contact point.

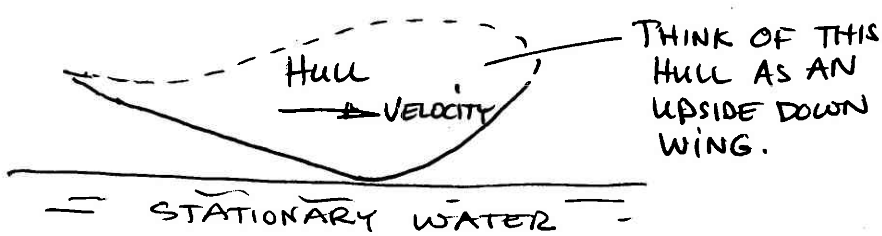


A suction force is generated between the skirt material and the water which is assisted by the cushion pressure. Associated with this suction is a drag force. This drag force pulls more skirt under the hovercraft and so on until the hard structure of the hull makes contact with the water or ground. Notice as the skirt is pulled under the hovercraft how it reduces the cushion lift area.



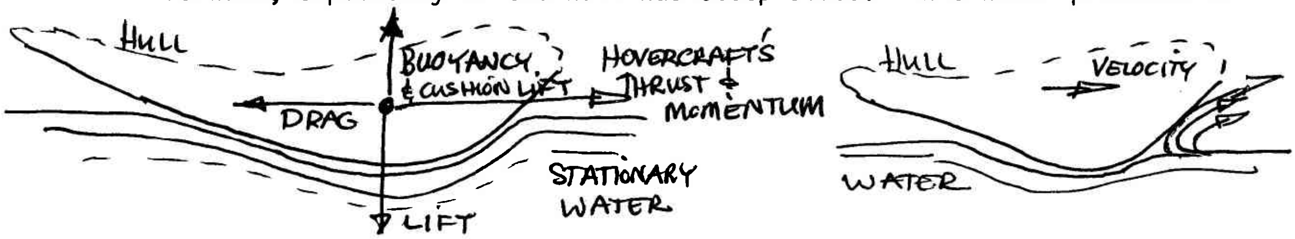
With the hull beginning to fall or roll about the center of lift and the loss of lift which is the cushion pressure times the reduction in lift area further exaserbates the cascading of effects until hull contact with the surface, whereupon a massive increase in drag occurs instantaneously. If you are not strapped to the hovercraft or hanging on with all your mite you will be rocketed through the air before tumbling on the ground or d iving into the water. For this reason small hovercraft are equipped with kill switches and lanyards which should be attached to the driver's body. Otherwise your machine drives off without you!

The name given to skirt collapse is 'tuck under'. Actually plow-in only occurs when the hull contacts the surface. This phenomena is believed to be similar to that of how an aircraft wing derives lift.



Most hovercraft hulls are shaped very much like the wing depicted here so that they are very efficient at developing considerable lift. The more lift the more drag and it's the drag which decelerates the hovercraft and causes the craft to roll in the direction of the plow-in.

Another effect which occurs is that a proportion of water is forced forward, especially if the hull has steep sides. This water proceeds to



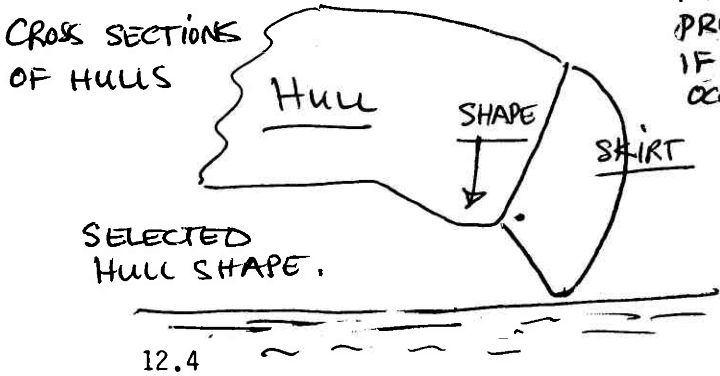
get caught by the skirts, if the craft is fitted with segmented skirts, and it has so much energy it snaps the skirt ties or blows the skirt(s) off. This now adds yet another effect: That of releasing whatever cushion pressure was trapped by the skirts and makes any recovery by speeding the fan up impossible.

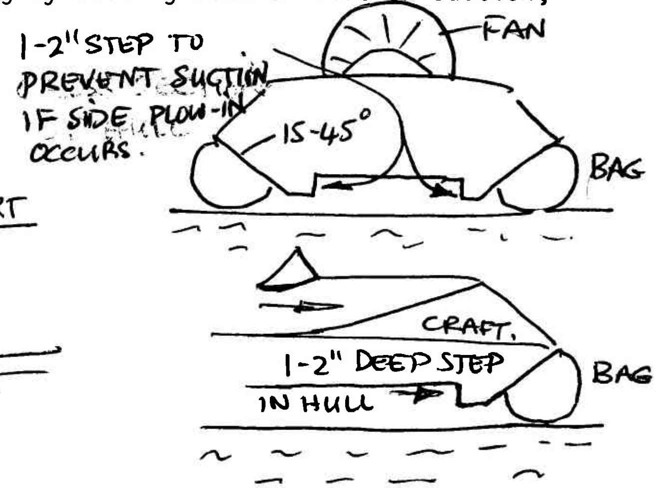
The solution is to design a hull which has low lift and not too much drag. The authors have experimented with a limited number of shapes and in the absence of any supporting research funds have settled on the following shape. This shape is replicated around the entire perimeter of the underside of the hull. (SEE NEXT PAGE)

A lot more work remains to be done before entirely satisfactory solutions are found. The best approach for right now is to select lift systems which stay pumped up under all situations. Even though integrated hovercraft still plow-in easily this new hull shape offers the advantage of reducing the surface drag so that the experienced driver has time to power up and recover from the normal cataclysmic series of events wherein the driver and hovercraft are separated.

For drivers of existing hover craft there are no obvious solutions, only preventatives. For example, always run the machine with nose up trim -- not very desirable for a high performance racing machine because this increases the drag. Next, pump as much air into the front of the lift cushion as is possible. Further, use adjustable trim elevators so that nose up trim can be applied, especially useful when going down wind; thrust reversers will also work; so do high pressure bag skirts; a long, pointed nose on the craft is good; smaller craft having increased cushion pressure also do good; and, lastly, design the hull so that when a plow-in does occur it is very gentle and the craft decelerates slowly.

As a point of interest you might have noticed that the shapes used by hydroplane racing boats and sea planes have a lateral step in the hull, supposedly this reduces drag by cutting down on lift or suction, it s the same phenomena.





12.4

Lift Off

Light hovercraft begin to fly at speeds above 50 MPH. It occurs when the free stream dynamic head equals the cushion pressure. Racing machine drivers can often be observed leaning way forward in an effort to prevent the machine from flipping backwards. Several members of the Hoverclub of America, Inc., have flipped machines when travelling at high speeds across ice or from wind gusts, fortunately with little serious effect to the passengers or craft. Racing craft which are about to lift off will do so if overtaken by a faster machine should they get caught in the thrust air blast of the passing machine.

In an effort to combat this difficulty some craft are made smaller so that their cushion pressures are increased. This has the effect of increasing the forward speed at which the front skirt gets blown inward when the dynamic head equals the cushion pressure. Forward horizontal wings have been tried but were found to be unworkable since they are too difficult to control.

Becoming airborne doesn t seem to be the problem it might at first appear. In practice few craft actually flip. Usually the driver will automatically reduce thrust and the craft will smoothly settle back down. It does seem however, that this represents the upper speed limit for small hovercraft. Hovercraft racing on courses will not exceed the 50 - 60 MPH lift off limits unless craft become much heavier. It is quite common to see craft lift sideways -- sometimes to almost 90 degrees and for many drivers this is a most effective means of completing a sharp turn, rapidly decelerating, having a heart attack! Racing craft occasionally roll over but as of this date it has not proved to be that dangerous. Besides, it adds considerably to the high level of excitement offered by this relatively new and safe sport.

13. Structures

13.1 Hull Structures

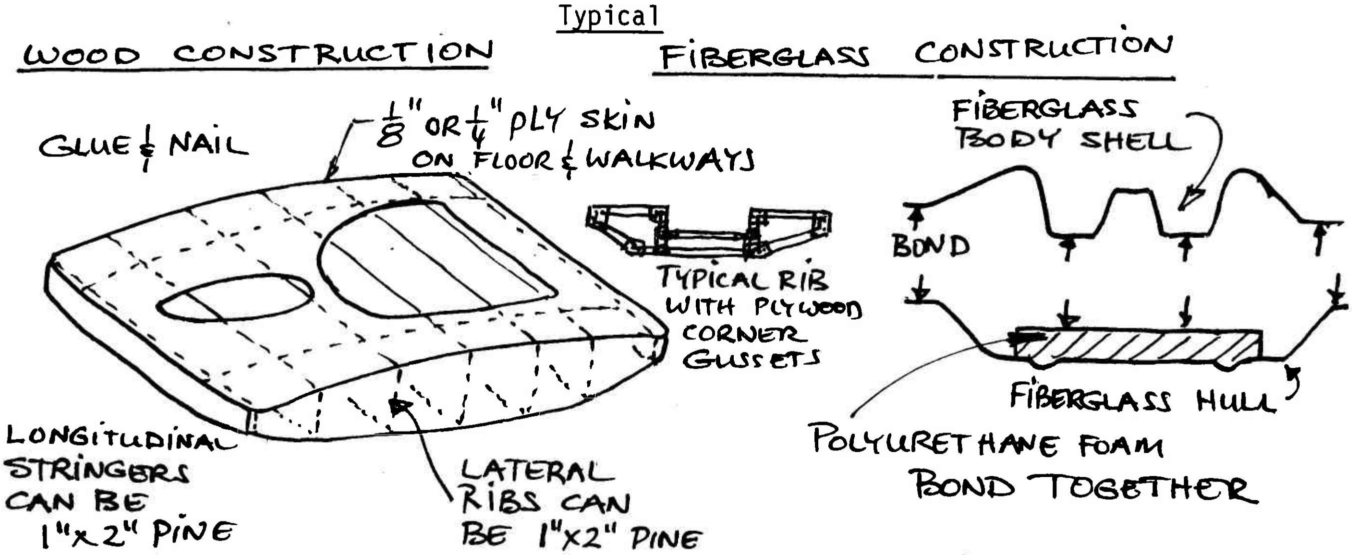
With many years of light hovercraft experience behind us it is difficult to recall a single instance where a craft suffered a serious hull structural failure. There are various light hovercraft structures built and operating; few have been structurally designed. Actually, it is quite difficult to make a hovercraft hull structure light enough to where it will fail. This is especially so as these structures are mostly built to withstand footprint pressure on at least some part of the structure and this, in turn, means it will also be capable of carrying the dynamic loads.

Early machines were constructed of wood. The majority of US homebuilts still use various pine woods and birch plywood. Most production machines are fiberglass, both hand laid and chopper gun. Many are composite while a few are aluminum or a combination of all three. In the US thermoplastics and urethane foam are also used in production machines. Most European racing and cruising machines are fiberglass. One company used to manufacture a series of models, before going out of business, which employed inflated structures similar to that of the inflated boat.

Wood and fiberglass compare favorably with respect to weight, but wood requires more maintenance.

Probably the greatest challenge with the hovercraft structure is its size. It is bulky, hence costly; and, it is expensive to ship and to produce because cost is a function of surface area and volume. Because hovercraft will always require a large structure they will always be more expensive than similar but smaller competing vehicles such as snowmobiles and water toys.

Typical



13.2 Machinery Structures

Unlike the hull, machinery structures on hovercraft are subject to occasional failure. Fortunately, such failures are seldom dangerous, merely inconvenient; however, the potential exists for serious injury if simple safety precautions, like adequate fan and propeller guards, are not observed. Apart from propellers and fans, probably the most common machinery failure involves engine mounts and, especially, high performance 2-cycle engine mount frames.

To gain some idea of why this is so, consider the acceleration forces acting on a hull structure compared to an engine mount. Various measurements have shown that hull accelerations seldom exceed twice the value due to gravity or 2g in normal operations and 4g is considered a very rough ride indeed. By comparison, accelerations on a 2-cycle engine test mount support were recorded at over 200g (resonant condition). This, of course, is a result of engine vibration, not fan thrust or any other steady load condition.

Standard engine mount frame design procedure considers loads generated by weight, thrust, torque, crash conditions and maybe gyroscopic effects for large propellers or fans -- vibration is seldom considered as a limiting condition. The reasons for such a design omission are obvious -- accurate vibration analysis is complex, the required design data is scarce, and even the measurement of vibration strains requires very special equipment and skill. The traditional engineering approach in such cases is to apply large safety factors on steady state loads and trust to 'good engineering judgment' for the doubtful areas. Good judgment includes the provision of very soft (low natural frequency) machinery to hull failsafe mounts and the use of fatigue resistant steel, rather than aluminum alloys, for engine frames.

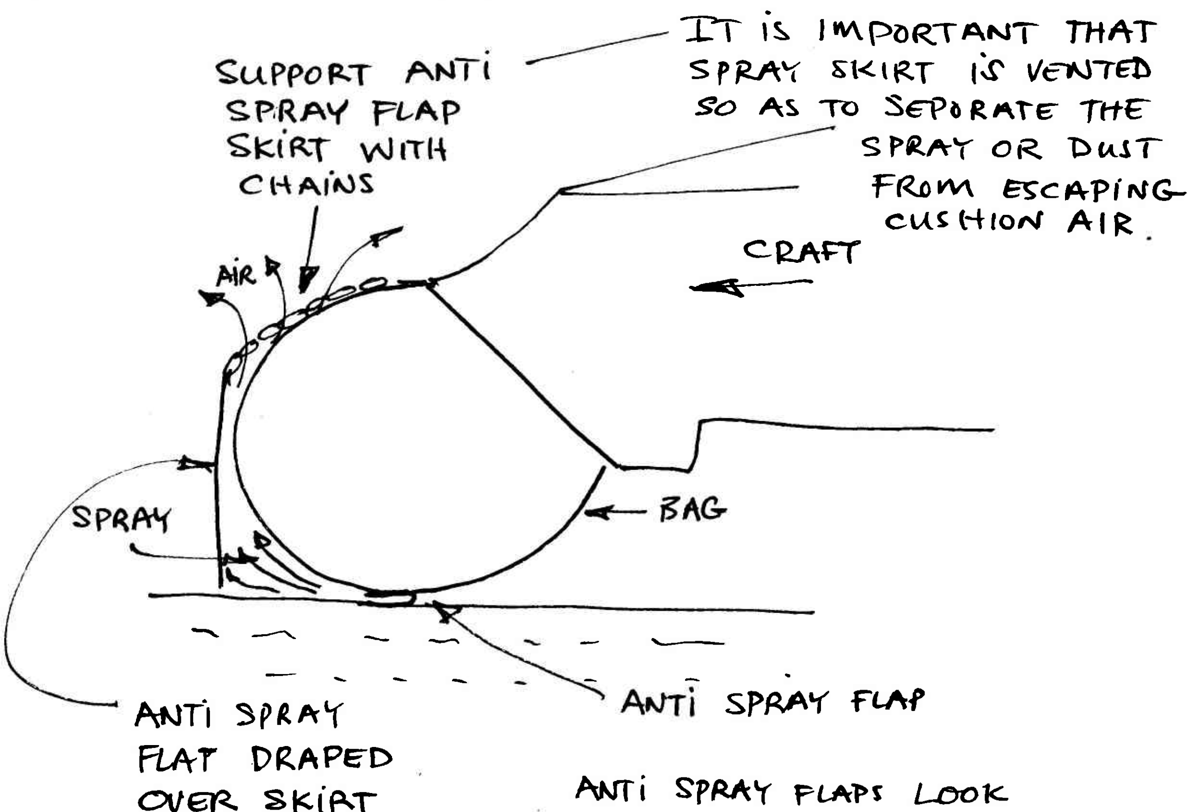
It is interesting to note that most fatigue failures have occurred with 2-cycle snowmobile type engines. The 4-cycle automobile engine rarely causes short term fatigue problems with mounts adequate for steady loads -- no doubt this is due mainly to their much greater weight or damping mass.

14. Dust and Spray

One great drawback to hovercraft, apart from the noise they make, is the dust and spray which are kicked up by the air escaping from the cushion. Of the available skirts, the segmented skirt produces the least dust and spray, probably because it lets the least cushion air escape. Some craft are equipped with simple spray skirts, usually a piece of skirt material loosely draped outside the skirt or a deflector stitched to the side of a bag.

This is an area ripe for new ideas. Most hovercraft drivers are forced to grit their teeth in dust while trying to smile with salt water spray and dust in their eyes. Apart from the driver and passengers such an environment is devastating to power plants and machinery.

This problem can be kept within bounds through judicious operation. Proper vehicle trim ensures the egress of particles toward the rear and low application of lift power in dusty conditions or powdery snow is helpful to minimize dust and spray.



ANTI SPRAY FLAPS LOOK UGLY, ADD WEIGHT & EXPENSE. THEY ARE FAIRLY EFFECTIVE AND CAN BE FITTED TO BAG, SEGMENT OR JUPE SKIRTS.

15. Engines

The lack of engines specifically developed for hovercraft use has been, and continues to be, a serious impediment to the production of low cost, reliable, high performance hovercraft. Some types of engines are more suitable than others, but all have been adapted and thus all types have 'problems' when used in hovercraft.

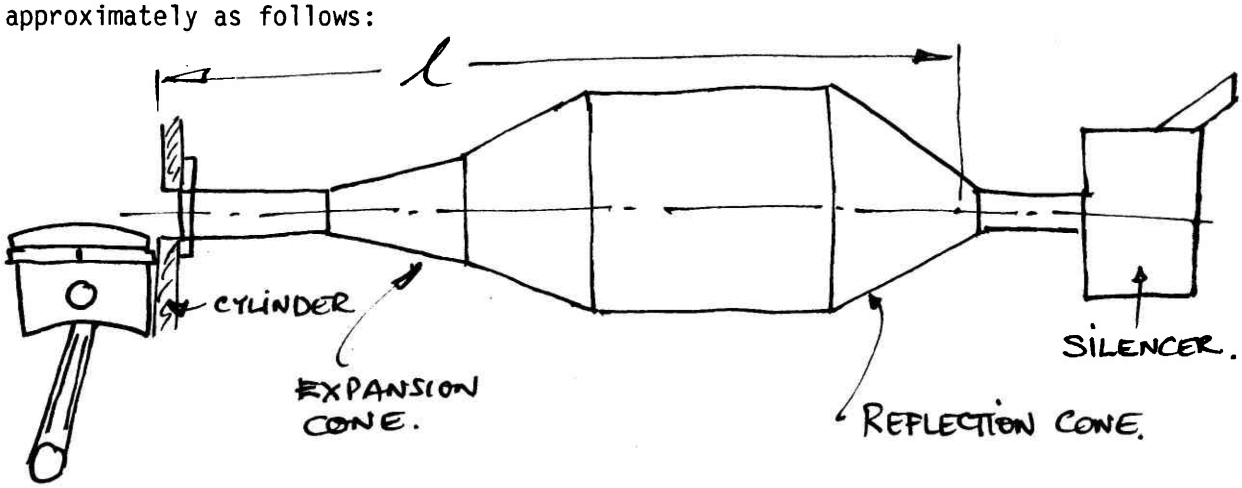
15.1 Two-Cycle Gasoline Engines

Without argument, segmented skirts and the availability of low weight, high power, fairly inexpensive, and dependable 2-cycle engines have allowed the sport of light hovercrafting to evolve as it has today. Most modern small hovercraft use one or more 2-cycle engines. We have to thank the snowmobile industry for the evolution of these high power-to-weight units.

Motorcycle engines have never proved themselves for hovercraft use.

Despite the advent of the "CDI" ignition -- a great boost to the performance and reliability of the 2-cycle -- 2-cycle engines are still a tinker's dream. They tend to be temperamental and require sensitive operation if the maximum performance is to be extracted with any semblance of dependability. Two-cycles are also fuel hogs, running with about twice the specific fuel consumption of comparable 4-cycles. They vibrate like stone crushers and make similar noises. Despite all of these things they have high peak power-to-weight and are small and compact. The evolution of this sport, in large part, owes itself to the availability of such engines.

High performance 2-cycle engines depend upon a tuned exhaust system to achieve their remarkable peak power levels. A typical system looks approximately as follows:



The theoretical tuned length:

$$l = EVs/N \quad (37)$$

where

l = tuned length in inches,

E = exhaust open period in degrees,

Vs = speed of sound in gas in ft./sec., and

N = engine rev./min.

Ideally this calculation will provide a system where the partial vacuum behind the exhaust pressure pulse scavenges the cylinder on port opening, and also returns a strong pressure pulse just before port closing to block loss of the fresh cylinder charge through the exhaust system. In practice difficult to predict factors, such as gas temperature, will vary 'l', thus a certain amount of trial-and-error experimentation is required to achieve optimum results.

Unfortunately this 'boost' effect only works well over a fairly narrow range of engine speeds and the power output at speeds not 'on-the-pipe' can be truly pathetic. The following fan/engine match plots illustrate the situation. The 2-cycle engine has ample power over about 2600 fan RPM (5000 engine RPM) to push the fan to full power revolutions but there is a problem at about 2400 fan RPM (4500 engine RPM). By comparison the 4-cycle VW engine has abundant power at all speeds below the peak. Thus, it is obvious why a slight out-of-tune condition in a 2-cycle engine can be absolutely devastating to craft performance whereas the 4-cycle can often be fairly 'sick' and still work satisfactorily.

Several solutions to this 2-cycle problem have been proposed, such as centrifugal clutches, variable geometry exhausts or even variable port timing, but a simple low cost solution has yet to be offered by engine suppliers. Some of the more recently constructed homebuilt craft are using clutch arrangements which only engage once engine has passed through 4-5000 RPM range.

15.2 Four-Cycle Gasoline Engines

Four-cycle gasoline engines of all types have been used in hovercraft since the very early days. They have been generally noted for low noise and vibration and greater reliability than the high performance 2-cycle. There is, however, some doubt on durability if operated continuously at speeds and power levels beyond their usual operating limits. Purchasing and running costs can be quite reasonable due to high production numbers, but relative weights are often very high. These automotive engines are usually of the large capacity variety, 4-8 cylinders with up to 250 HP output, but they are quite heavy with power-to-weight ratios of .36 HP/lb., compared with the 2-cycle's .8 HP/lb.

Four-cycle lift engines of the lawn mower variety are widely used in the US, but in Europe lift engines are usually small 2-cycles because of their common availability.

15.3 Diesel Engines

Over the proceeding several years air-cooled diesel engines have found favor. Their main attraction being low noise, low specific fuel consumption, low maintenance, and high dependability and safety, which, when summarized, make good economical sense. Like everything, however, they have a monumental drawback which is their tremendous weight, power-to-weight ratio of .1 HP/lb. Light hovercraft fitted with diesel engines will never be good performers.

15.4 Aircraft Engines

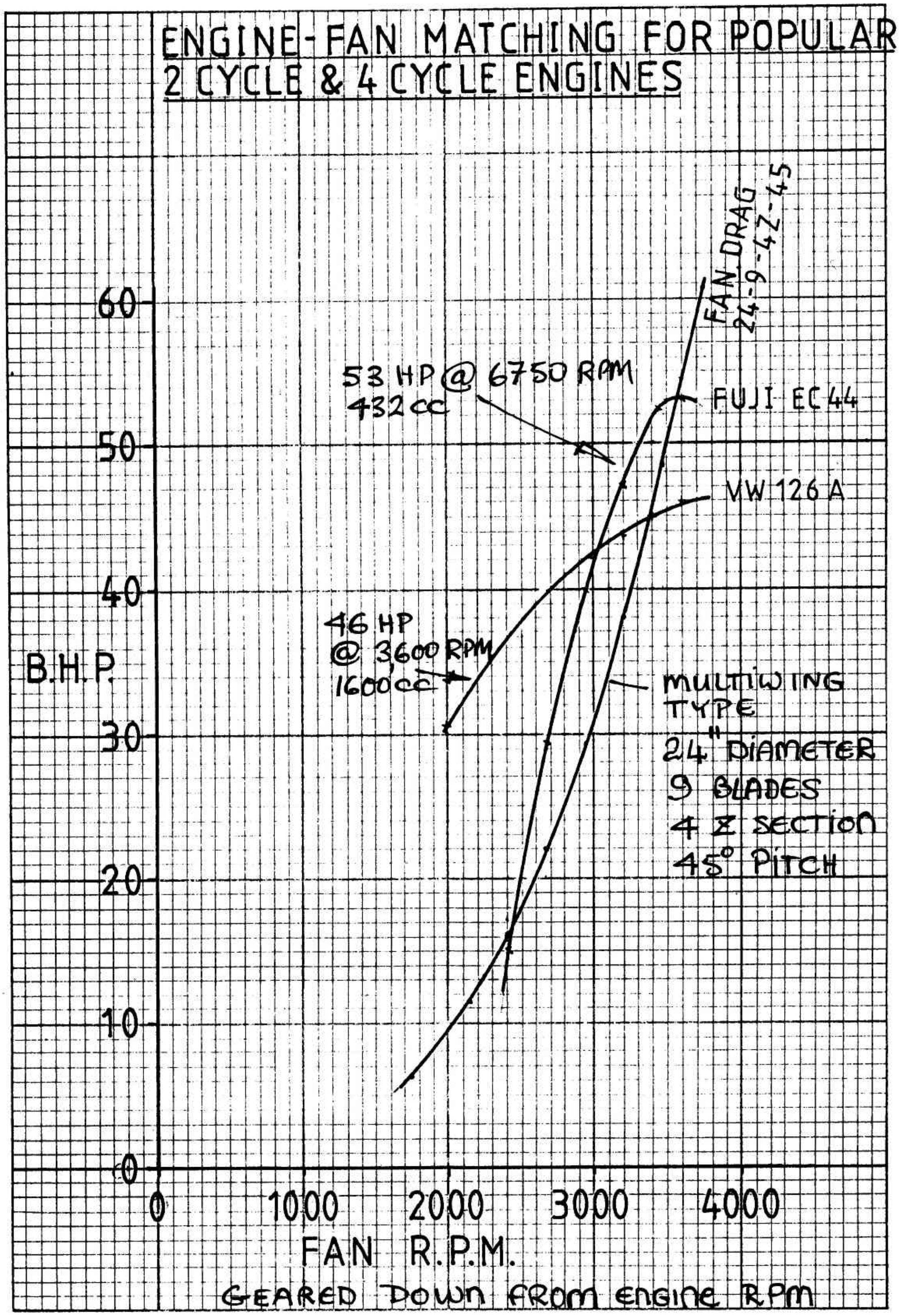
Both reciprocating gasoline and gas turbine engines have been used in hovercraft. However, extreme purchase costs and sometimes cooling and corrosion problems usually exclude these engines from serious consideration for light hovercraft. Their power-to-weight ratios of about .5 HP/lb., while not as good as high performance 2-cycle ratios, give an idea of what is achievable with the medium sized 4-cycle engine.

16. Waves

A frequent question is "How high waves can hovercraft handle?" This is a complicated question. Generally waves are produced by wind. There is a common marine scale for defining wind force which is called the "Beaufort" Scale.

Beaufort No. or Force No.	Miles per hour	Name
0	1	Calm
1-2	1-7	Light breeze
3	8-12	Gentle breeze
4	13-18	Moderate breeze
5	19-24	Fresh breeze
6-7	25-38	Strong wind
8-9	39-54	Gale
10-11	55-75	Whole gale
12	Greater than 75	Hurricane

The ocean tends to produce twice the height of wave under gale conditions compared with a shallow water bay. Both the ocean & shallow bays produce approximately the same wave height up to about Force 5 which is about a 5 ft. wave height. The ocean, however, tends to produce long waves which are better for hovercraft than the short pitch waves usually found on shallow bays. Large boats, speed boats, and barges also produce waves. As a general rule hovercrft do not handle waves or wind with any enjoyment. The skirt drag usually is so high that the craft will not go fast. If the hard surface starts plowing into the waves then the craft is usually brought below hump speed. A hovercraft's ability to handle waves depends on its direction of travel with respect to the wave as well as wind direction and on its comparative size. One of the 4-passenger craft developed by the authors performs well, fully loaded, across a 2 1/2 ft. wave system with 15 MPH wind. Its hoverheight is 9". It works better downwind in the direction of the waves.


ENGINE-FAN MATCHING FOR POPULAR
2 CYCLE & 4 CYCLE ENGINES
FAN DRAG
24-9-4Z-45
53 HP @ 6750 RPM
432 cc
FUJI EC 44
VW 126 A
46 HP
@ 3600 RPM
1600 cc
MULTIWING
TYPE
24" DIAMETER
9 BLADES
4 Z SECTION
45° PITCH
B.H.P.
60
50
40
30
20
10
0
0
1000
2000
3000
4000
FAN R.P.M.
GEARED DOWN FROM ENGINE RPM

17.

Noise

A topic of increasing interest to the general public and hence important to hovercraft enthusiasts is noise, or more accurately the reduction of the perceived loudness of the sound they produce.

Much confusion can exist when the readings of simple sound level meters are used to assess the acceptance or otherwise of a sound if the assessor does not have an understanding of what is being measured.

Most simple sound level meters record sound intensity in decibels -- this is not a linear scale but a logarithmic one.

$$N = 10 \text{ Log}_{10} \ (J_1/J_2) \qquad (38)$$

which is the difference N in decibels between two sound intensities J_1 and J_2.

For a variation of 1 decibel, the sound intensity ratio, J_1/J_2= 1.26 (approximately). In practical terms to reduce the sound level by 1 dB we must reduce the intensity reaching the meter or your ear by about one quarter. If 10 dB is the reduction sought, J_1/J_2= 10. This represents a truly formidable problem in noise reduction.

To complicate things further, the human ear does not recognize all frequencies of sound as of equal loudness even though the sound intensity may be the same. Frequencies around 4000 Hertz are perceived as the loudest, thus simple sound level meters are weighted to give maximum sensitivity in this region. This is the A scale or dB(A). However people, and their ears, vary in sensitivity, thus loudness is subjective and can neither be accurately measured nor precisely defined.

The components in hovercraft most likely to prove noisy are fans or propellers, engines and their exhausts, vibrating body panels, and other structure such as guards.

Tip speed is often quoted as the most important factor in fan or propeller noise generation so any design that reduces tip speed can be expected to reduce the noise level. Such modifications are: increase the number or chord of blades; fit a well designed duct; or, reduce the power loading -- large diameter props running at slow RPM.

Engine exhausts can usually be muffled sufficiently with careful design without major loss in power but mechanical noise is harder to reduce, expecially in high RPM 2-cycle engines. Placing an insulated box around the engine can help if cooling problems permit. Parts that can vibrate, such as loose exhaust retaining springs, should be stiffened.

Sealed cockpits can reduce internal noise levels as can cabin insulation. Tests on a popular homebuilt design revealed a reduction from about 89 dB(A) to 86 dB(A) at ear level by adding sound insulation inside the cockpit.

A typical sound level plot for a tethered integrated craft is shown below. Of interest is the distribution of sound levels around the craft. The lobe-like peaks at each side of the front of the machine are typical of the 2-fan design being tested. A spectator standing in front and to one side of the craft would probably think it much noisier than a spectator standing directly behind.

The maximum permissible sound level should not exceed 87 dB(A) at 50 feet from the center of the craft measured four feet above flat grassland with engine(s) at maximum throttle. Cruising craft should not exceed 80 dB(A) at cruise engine settings.

Consult SAE noise specifications for further study:

A) SAE J192A -- Exterior sound level for snowmobiles

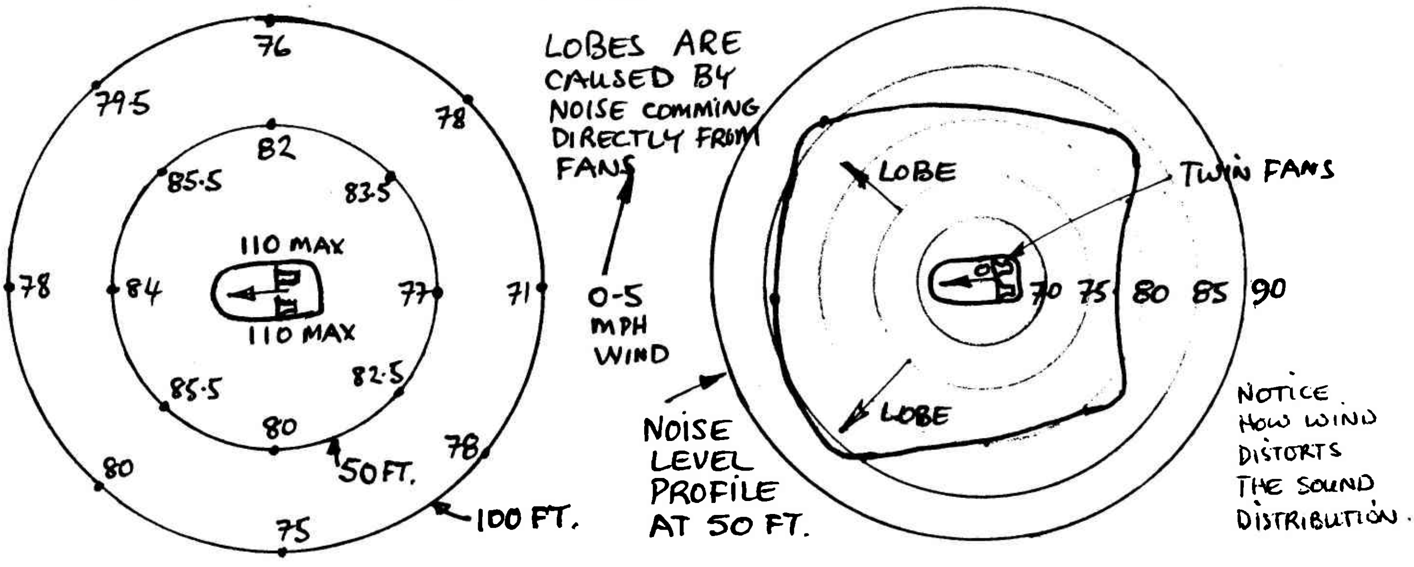
B) SAE J1160 -- Operator ear sound level measurement procedure for snow vehicles

C) SAE H1161 -- Operational sound level measurement for snow vehicles

These specifications can be modified to fit hovercraft. Also, they will give a general outline as to a measurement procedure. When quoting a sound level the applicable SAE or other standard to which the measurements were taken should be given.

NOISE LEVEL SURVEY OF NEOVA 1 HOVERCRAFT 29 JULY 1973

AIR TEMP. 14°C, WIND 0-5 MPH, WEIGHING NETWORK dB(A), TERRAIN OPEN MUDFLAT, CRAFT FAN RPM 2,700. BACKGROUND SOUND LEVEL 50-56 dB(A), INSTRUMENT BRUEL & KJAER 2205.



18. Scaling

Once a workable machine has been perfected it is a straightforward matter to design larger or smaller versions through the judicious application of scaling laws and in particular a scaling factor .

Usually one starts out with a model craft having a length of l_M. We want to design a fullsize machine with a length L_{fs}; hence, scaling factor:

$$\lambda = (L_{fs})/(l_M) \qquad (39)$$

Reference R. L. Trillo, Marine Hovercraft Technology, Leonard Hill, London, 1971, p. 67.

Basis - Constant Froude No.

$$F = (V)/\sqrt{gl}, \text{ and}$$

Constant Dynamic head coefficient

$$H_q = (1/2\rho V^2)/P_c$$

Fan characteristic Slope

$$dp/dQ_{fs} = \lambda^{-1.5}\, dp/dQ_M \qquad (40)$$

Angular Acceleration

$$W_{fs} = \lambda^{-1}\, W_M \qquad (41)$$

Angular Velocity

$$W_{fs} = \lambda^{-.5}\, W_M \qquad (42)$$

Frequency

$$Hz_{fs} = \lambda^{-.5}\, Hz_M \qquad (43)$$

Rev/Minute

$$N_{fs} = \lambda^{-.5}\, N_M \qquad (44)$$

Power Loading

$$Pl_{fs} = \lambda^{-.5}\, Pl_M \qquad (45)$$

Linear Acceleration

$$A_{fs} = \lambda^{0}\, A_M \qquad (46)$$

EXAMPLE IN THE USE OF THESE FORMULARS. MODEL IS 3 FT. LONG, 2 FT. WIDE, WEIGHT IS 30 LB. It has A 1 HP ENGINE. 5 lb/ft² CUSHION PRESSURE. THE VOLUME FLOW IS 3000 cfm. We want to design a 12 FT LONG CRAFT WITH SIMILAR CHARACTERISTICS.

From(39) $\lambda = \frac{12}{3} = 4$

From (60) $P_{fs} = 4^{3.5} \times 1 = 128$ HP.

From (54) $Q_{fs} = 4^{2.5} \times 3000 = 96{,}000$ cfm.

From (51) $P_{fs} = 4^{1} \times 5 = 20$ lb/ft²

From (52) $S_{fc} = 4^{2} \times 6 = 96$ ft²

From (59) $W_{fs} = 4^{3} \times 30 = 1{,}920$ lb.

CHECK USING FORMULAS 5 & 6

$L \times W = A$

OR $W = \frac{96}{12} = 8$ FT WIDE.

$P_c \times L \times W = C$ OR W_{fs}

$20 \times 12 \times 8 = 1{,}920$ lb.

THESE RESULTS APPEAR TO BE CORRECT.

Density

$$\rho_{fs} = \lambda^{0} \rho_{M} \quad (47)$$

Note that Linear Acceleration and Density, (formulas 46 and 47) are independent of scale.

Time

$$t_{fs} = \lambda^{.5} t_{M} \quad (48)$$

Period

$$t_{fs} = \lambda^{.5} t_{M} \quad (49)$$

Linear Velocity

$$V_{fs} = \lambda^{.5} V_{M} \quad (50)$$

Length

$$l_{fs} = \lambda^{1} l_{M} \quad (36)$$

Pressure

$$P_{fs} = \lambda^{1} P_{M} \quad (51)$$

Area

$$S_{fs} = \lambda^{2} S_{M} \quad (52)$$

Heave Stiffness

$$Kh_{fs} = \lambda^{2} Kh_{M} \quad (53)$$

Volume Flow

$$Q_{fs} = \lambda^{2.5} Q_{M} \quad (54)$$

Mass Flow

$$W_{fs} = \lambda^{2.5} W_{M} \quad (55)$$

Heave Damping

$$Ch_{fs} = \lambda^{2.5} Ch_{M} \quad (56)$$

Volume

$$U_{fs} = \lambda^{3} U_{M} \quad (57)$$

Force

$$F_{fs} = \lambda^{3} F_{M} \qquad (58)$$

Weight

$$W_{fs} = \lambda^{3} W_{M} \qquad (59)$$

Power

$$P_{fs} = \lambda^{3.5} P_{M} \qquad (60)$$

Torque

$$T_{fs} = \lambda^{4} T_{M} \qquad (61)$$

Moment

$$M_{fs} = \lambda^{4} M_{M} \qquad (62)$$

Work

$$W_{fs} = \lambda^{4} W_{M} \qquad (63)$$

Pitch Stiffness

$$K_{p_{fs}} = \lambda^{4} K_{p_{M}} \qquad (64)$$

Roll Stiffness

$$K_{r_{fs}} = \lambda^{4} K_{r_{M}} \qquad (65)$$

Pitch Damping

$$C_{p_{fs}} = \lambda^{4.5} C_{p_{M}} \qquad (66)$$

Roll Damping

$$C_{r_{fs}} = \lambda^{4.5} C_{r_{M}} \qquad (67)$$

Moment of Inertia

$$I_{fs} = \lambda^{5} I_{M} \qquad (68)$$

Of these formula numbers 59 for weight, 50 for velocity, 60 for power, 52 for area, and 51 for pressure will be of considerable use.

Such laws can be helpful providing you do not venture too far from your existing model or full scale machine.

19. Costs

The cost of a hovercraft is an arbitrary matter. Large amounts of capital are required to establish a production operation -- not less than $300,000 - 500,000 US at today's values. Capital recovery comes about through sales of hovercraft units. Such operations become profitable only when sufficient numbers of machines have been sold to cover the break even cost. This cost point for a $300,000 - 500,000 operation is around 300 units over a two-year period. No European undertaking has yet achieved such levels of sales. Several US companies, however, have produced several thousand units. More recently one US company with a capital of $5.5 million US has produced over 2,000 units, but have as yet to become profitable. In addition, none of these undertakings have recovered the cost of product development. The author's company in the US, for example, has invested in excess of $1 million US in light hovercraft product development over a 15-year span and has yet to realize a good return.

What this tells about the present light hovercraft products market is that it is heavily subsidized and craft sales prices do not actually reflect true costs. Investors make up these differences between sales income and production costs. Certain investors gladly embrace this challenge because they are enthusiasts and for the slim chance of a long-term payoff. Eventually the industry should exceed its breakeven costs and gradually become viable.

As to development cost recovery, this might never eventuate. This predicament is not widely appreciated by the community en masse. In Europe hovercraft production is very much a cottage industry and builders who achieve low overheads survive indefinitely but usually without making any profit. With today's business environment a hovercraft company cannot grow to become a viable mass production operation by slowly increasing sales. Big infusions of capital are necessary. Such capital usually derives from astute inventors who require profitability as per planned projections. Much failure so far has been their reward. Until recently North American companies which adopted this large capital expenditure approach have ended in failure. Product purchase price, therefore, has little relation to real craft cost. Price is usually set at whatever the market will bear.

Customers naturally compare hovercraft to other similar, mass produced vehicles. Consequently, the price of trail bikes, motor cycles, ultralights, small power boats, small sports cars, snowmobiles, and water toys shape a customer's product value decision.

Unfortunately, present product value judgments are well below the real cost of craft production. Such is not quite true for the over 6-passenger market where a greater value is acceptable but this is still a very limited market. Investors in the hovercraft industry are, therefore, highly adventurous. Few stand to profit, but their involvement is vital; without them we would have no future.

Cost of homebuilt craft is entirely different. The builder frequently does not try to place a value on the labor portion of construction. Material costs, however, are easier to appreciate. It is usual for the homebuilder to invest $2,000 - 4,000 US in materials. Material costs are limited by cunning scrounging and the use of used parts and scrap materials. Some present day approximate sales prices for various manufactured hovercraft are:

2 seat	$4,000 - $10,000
4 seat	$15,000 - 30,000
6 seat	$30,000 - 60,000
10 seat	$80,000 - 150,000

Kits, where available, are usually about 25% less.

20. Conclusions

Today's light hovercraft design is largely a simple, practical science. Too many examples exist of perfectly satisfactory designs for any serious designer to waste time with involved theoretical studies. It should be possible to design a successful light hovercraft from the information given in these notes. Hovercraft technology is still in its infancy. Much research and development relating to the management of noise, dust and spray, improved control means, engines, and solutions to dynamic problems of plow-in and lift off remain as interesting projects for the amateur and professional alike. The sport of hovercrafting, once in your blood, becomes for many an obsession. It has that something about it like a constant adventure or an endless source of challenges that need imaginative solutions.

In the US hovercraft are still practically unknown by the average person, and this represents the greatest challenge to manufacturer and enthusiast alike. All activity, especially designing and homebuilding your own hovercraft, aids in the promotion of this fascinating sport. The authors wish you all the very best of luck and success with your project.

21. For Further Information or Questions

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- -

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Name ______________________________

Address ______________________________

City, State, Zip ______________________________

Telephone _____-______-______________

Enclosed please find $25 US, drawn on US bank or international money order for one year's membership.

____

Signature Date