Sevtec Hovercraft

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Technical Data

Now, if one wants more reading on Sevtec craft all one has to do is "Google" up and click on the "groups" button and ask for Sevtec, or alt.rec.hovercraft.Sevtec or other things and just about anything will come up, including some technology discussions, as well as catfights and whatever usually goes on in newsgroups.

This paper, published in the Canadian 1984 International Conference on Air Cushion Technology, Sept 25, 26, 27, at Vancouver, BC may be old, but the numbers are just as valid today. A systems approach was taken to compare the Sevtec design philosophy directly to the design of large surface skimmers (hovercraft) with some surprising results. (A wait may be required for download for dialup.)

LIGHT HOVERCRAFT DEVELOPMENT

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ABSTRACT

Characteristics of several hovercraft of the author's design are described. The comparative straight line performance of the machines is studied through use of a simple numerical model.

The design characteristics of the small machines are then analytically applied to two large existing hovercraft and comparative straight line performance evaluated for the large craft in its original stock configuration and revised configuration.

It is concluded that significant improvements can be made to large machine performance through use of light hovercraft technology as shown in this paper.

INTRODUCTION

Although the hovercraft as we know it has been around for perhaps thirty years, these vehicles seem to have shown little improvement in efficiency except for improvements related to size. As a result the craft are still very powerful for their weight, resulting in high initial and operating costs. The author has been developing small hovercraft for some sixteen years in which emphasis has been placed on low noise levels and efficiency. This paper explores application of the light hovercraft technology to large vehicles in an attempt to improve large hovercraft performance.

ANALYTICAL MODEL

Nothing is particularly unusual in the way the author models his vehicles. "Get it done" practicality is favored over meticulous detailing so as not to hide true model function behind a broad veil of empirical coefficients. It should be appreciated that the ultimate goal is to move a given load at a given speed over a given surface using minimum power, consistent with minimum costs.

THRUST

All of the propellers except a single example on the light hovercraft are two blade, 15 degree, fixed pitch, and performance predictions are based on measured data for a two blade, Clark-Y airfoil, 15 degree three-quarter radius pitch propeller per (1). The single exception was a ducted fan, which was constructed to emulate the ducted fan per (2) as closely as practical without going to the extremes of aerodynamic fairing of the rotor hub and blade roots, and double surfaced duct as shown in the reference.

Propeller static thrust was determined on the vehicles through vehicle static thrust tests. In most cases vehicle static thrust was 85% of static thrust indicated in (1), using full throttle engine data and allowing for a 5% drive loss.

Similar ducted fan static thrust tests did not remotely approach levels in (2). Measured static thrust more closely approached what would be expected using a simple momentum model per (3) with the assumption that flow exits the duct at full duct exit diameter, and parallel to the thruster axis, with a drive loss of 5% and reduced by the 85% factor.

For the purposes of this analysis, it is assumed that the open propeller and ducted fan performance are 85% of (1) and (2), allowing for a 5% drive loss, through the speed range of a vehicle, for lack of a better model. This should not affect the comparative nature of the calculations.

The 15% loss in thruster performance is probably due to obstructions such as guarding, supporting structure, the ground plane and vehicle itself, and cannot be measured with a load cell placed on the thruster shaft. Measurement of the "installation factor" would require the use of a wind tunnel.

SMOOTH WATER DRAG

Drag is broken into aerodynamic, skirt wipe, and wavemaking. Momentum drag is not considered, as additional cushion air flow volume tends to improve vehicle performance probably by virtue of a combination of a reduction in skirt wetted area and reaction thrust of the cushion air, which is primarily expelled rearwards in the author's designs. Vehicle drag is the sum of drag components which was constructed to emulate the

as below:

$$D_t = D_a + D_s + D_w \qquad (1)$$

Aerodynamic

Aerodynamic drag, D_a, is modelled from vehicle frontal area as a function of vehicle base area width, B only. A drag coefficient, C_a, is selected from craft measured performance and aerodynamic drag is calculated as below:

$$D_a = \frac{\rho_a}{2} C_a A_p B^2 V_a^2 \qquad (2)$$

For the purposes of this analysis, A_p is set at a constant value of .3 and C_a at a constant value of .7, which is reasonable in light of the data on automobiles in (4).

Skirt Wipe

It is difficult to separate skirt wipe drag from aerodynamic drag as both build as a function of the square of vehicle velocity. For the purposes of this paper, skirt wipe drag is setat 40% of aerodynamic drag. This is based on some second hand information obtained from a builder of one of the author's designs. More data is needed here.

The builder was reporting 41 miles per hour speeds on smooth ice in calm conditions. Normally such information is ignored as builders tend to exaggerate observed speeds for their vehicles as the vehicle was a 10 horsepower Fan-tastic similar to fig (1), only it had a lowered seat. The builder allowed a 74 pound kid to drive the craft, and during a full throttle run in which speed was being measured using a radar gun, the craft went into a bow up attitude. Calculations indicated that for the bow lift to occur a dynamic pressure of 85% of cushion pressure would be required. The 41 miles per hour speed yielded the correct dynamic pressure.

The 85% of cushion pressure estimate has since correlated with a bow up condition which occurred while the author was making a full throttle speed test with the 54 horsepower Volkswagen powered "Red Machine" shown in fig (2). This craft would normally top out at 45 miles per hour with one or two aboard. During one test with one aboard, the craft was able to pull considerable surface area free of the water and allow speeds of 56 miles per hour, which calculated to be 85% of cushion pressure. A slight bow up attitude and a rear end squat indicated the vehicle was not operating in its normal mode.

Therefore skirt wipe drag is as below:

$$D_s = \frac{\rho_w}{2} C_w B^2 V_w^2 \qquad (3)$$

Skirt drag coefficient, C_w, is set at .00015 in all the analysis of this paper. It is appreciated that skirt wipe drag is a function of the air gap generated by the lift system, which is also a function of vehicle loading. Except for the extreme case mentioned previously, the Red Machine and the larger 56 horsepower "Yellow Machine" showed little sensitivity in top speed as a function of loading, while the smaller craft did show significant reduction in speed at high loads. It should be noted that wavemaking drag as will be discussed, is nil at vehicle top speeds for the small hovercraft.

Fig. 1 Fan-Tastic 8, 10, 11 hp.

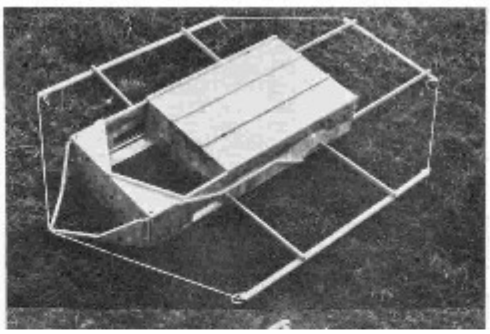
Fig. 2 Red Machine 25, 54 hp.

Wavemaking

As traditional methods of calculating wave drag at hump usually fall far short of reality (5) analysis per (6) (and others) is readily reducible to the form as below: (Planeout Coefficient is 16 for this study.

$$D_h = 1/K_w \, (W \cdot P_c/L) \qquad (4)$$

The hump drag, D_h, is determined from the easily measured values of operating weight, W, cushion pressure, P_c, as measured directly or calculated from operating weight and machine cushion area, and the average cushion area length, determined from cushion area and cushion beam, B. The planeout coefficient, K_w, is measured by determining the maximum load that a particular vehicle can get over hump at full engine power. Care is taken to assure still, deep water, still air conditions, and correct vehicle pitch trim for minimum drag. Craft actual thrust is then determined at a forward speed consistent with a Froud Number of 0.6 based on average cushion length and propeller performance



data per (1) or (2), the propeller data is reduced to .85 of that shown in the references and 5% drive loss is allowed.

Since operation of a hovercraft at speeds just below hump is totally undesireable (except in the specialized area of ice breaking) it is not considered here.

Wavemaking drag over hump is as below:

$$D_w = D_h \ (V_h/V_w)^2 \qquad (5)$$

If it is assumed that the bouyant fraction of vehicle lift is negligible at hump speed the wavemaking drag, D_w, is hump drag, D_h, times the ratio of vehicle hump velocity, V_h, to vehicle overwater velocity, V_w, squared.

HOVERCRAFT EXAMPLES

Examples of the author's hovercraft designs are shown in figs. (1) through (7).

The smallest of the hovercraft is Micro, the folding hull structure of which is shown in fig. (4). The 142lb, 4hp. craft

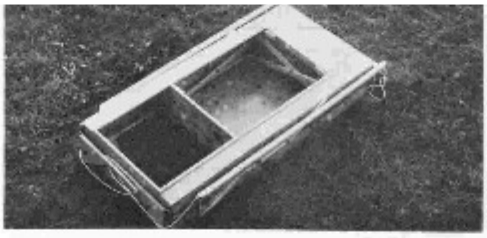


Fig. 4 Micro 4hp.

will plane a 170lb. adult and fold to fit into a closet.

Fan-tastic, fig. (1), was designed to be built by recreational home builders, and about 120 of them were constructed over a period of 1975 to 1983, in various configurations of 8, 10, and 11hp.

Fan-Tastic II is also a kit and homebuilder program, and some 45 have been built, using 16, 25 and 35hp. engines.

Fig. 3 Fan-Tastic II 16, 25, 35hp.

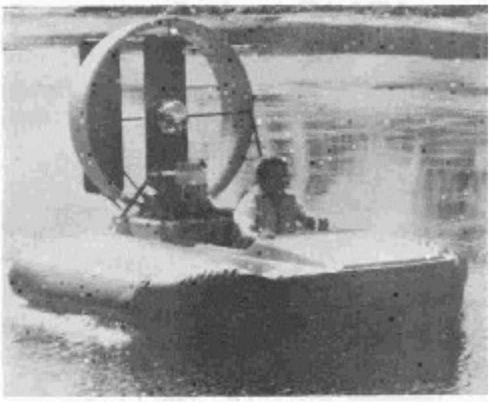


Fig 5 Plastic Fan-Tastic 11hp.

Plastic Fan-Tastic, fig. (5), is the result of a consulting program of the author. It uses fiberglass construction and a a ring guard (not a working shroud) for the propeller. The vehicle is being marketed as of this writing. An 11hp. engine direct drives the lift fan, and propeller drive is supplied by a vee belt, which is "folded" through a right angle, using 2 idlers. The "mule drive" is used in most of the small craft as a light weight replacement for a right angle gearbox.

Fan-Tastic III, fig. (6), was to be a homebuilder program, but it was abandoned as it was felt that its two engine design was simply inferior to single engine craft due to the ease of driving the single engine craft. Fan-Tastic III had one unusual feature, side by side axial fans driven by a single lift engine.

The Yellow Machine, shown with the Red Machine in fig. (7), is the largest of the author's designs, and uses a liquid cooled automobile engine for power. Eight people could be shoehorned into its small cockpit, a strictly S. R. O. proposition, and be planed out in deep water. The 56hp. craft is of sufficient size to be used in such tasks as hauling sand and gravel for its riverfront hoverport, and supplying firewood from the river.

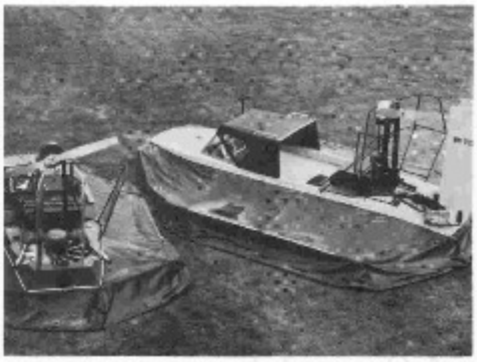


Fig. 7 Yellow Machine 56hp.

Features that are common to all the small vehicles are described below.

Hull Construction

Fir and Mahogany plywood covered Fir wood frame construction is used for craft intended to be built by home builders. A typical wood frame, fig. (8), may incorporate 1.25 lb/ft^3 polystyrene foam for positive flotation, as is shown in the figure.

Fig. 6 Fan-Tastic III 26hp.

The Red Machine uses the same fiberglass structure as the Yellow Machine. As shown in fig. (2), the craft is 2 place and is powered with an aircooled automobile engine of 54hp. The craft is vastly more maneuverable than the Yellow Machine, at the expense of much reduced payload capability. This craft has been operated in seas of up to 4 foot wave height.

Fig. 8 Fan-Tastic Hull Frame

The larger craft are built of fiberglass, which is built up within fiberglass molds similar to those used in the small boat building industry. Urethane foam of 4 lb/ft^3 density is used as a core material to stiffen large flat areas of the largely matt-polyester resin parts, and reserve bouyancy is molded in in the form of 2 lb/ft^3 urethane. In spite of very light construction of the order of .6 to 1.5 lbs/ft^2 of skin area the construction has given excellent service.

Skirt

The skirts are usually solvent bonded Vinyl coated Dacron of 10 to 22 oz/yd^2 material weight. Pop rivets are used sparingly in areas of high loading.

Neoprene coated Nylon is used on some craft. The Neoprene proved much tougher than the Vinyl and was considerably superior in weather of below 25 deg. F. However, the buffed mechanical cemented bonds required for the Neoprene were difficult to make, especially in the field, so the vinyl is the preferred material unless cold weather operations are normal.

The skirt configuration is similar to the socalled "bag" of the past except for some important differences. The bag is terminated at the forward quarters of the hull and one to three curtain type skirts are across the forward quarters and bow.

The unique configuration provides increased plough resistance, spray reduction, and a small forward cushion compartment that gives good pitch stiffness to the craft. The forward cushion pressure is controlled by pitching of the vehicle by virtue of variation of the air gap, or is directly controllable through use of cockpit adjustable air valves, in the larger craft.

Due to the high variability of the nose down pitching moment caused by the high thrust line, lightly loaded thrust installations of the small craft, a forward cushion compartment is necessary, except on machines which are small enough that the operator may effectively shift his weight.

It was recognized early on that for any realistic chance at good performance, the bag interior had to be kept to very near to cushion pressure. A Fan-Tastic has some 16 ft^2 of frontal area. Skirt drag, or skirt form drag equal to aerodynamic drag would be caused by less than 3 in^2 of skirt frontal area in the water. Some of the skirts are filled from the fan bay while others are filled from the cushion. All of the skirt bags are vented to the cushion.

A single carefully located drain at the aftmost end of the skirt avoids the

and still be weight competitive with bag finger skirts.

The author cannot make a quantitative judgement as to whether the drag of this type of skirt is above or below that of a finger type skirt. The only examples of finger skirted vehicles the author has driven were clearly short on cushion air flow, and, on a subjective basis, seemed to have much higher smooth water drag.

As the curtain-bag skirt of the author presents a smoother flow surface to rough water, it is suspected that its drag may be lower than a finger skirt. The two largest craft have been through contour mode and into seas of up to 4ft wave height.

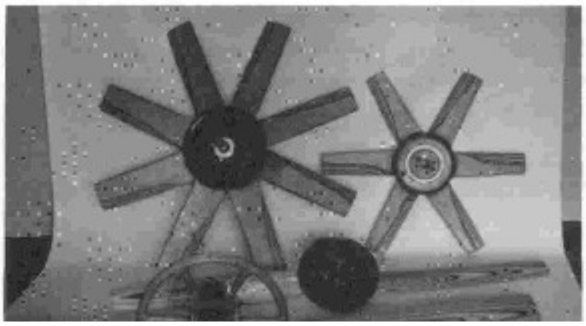
In one interesting experiment, a large portion of the bag was suspended, using many rubber bands. Ride in rough water was greatly smoothed, and, subjectively, drag seemed to be reduced. It should also be noted, though, the tests produced the only case of "mal-de-mer" in the author's experience with the small craft, indicating the need for some form of damping, in addition to the suspension.

Drives

Stock cast iron pulleys and vee belts were usually used on the machines. The use of light alloy pulleys would represent a major weight reduction.

Rotors

Propellers are made of cold molded Birch plywood. Fan blades are similarly molded, and inserted into slots in a Fir marine plywood hub. Typical fans and propellers are shown in fig (9).



flooding problems associated with the old bag skirt. The use of flotation material on the skirt material can virtually eliminate the purge problems associated with craft taking off from a rest period on water.

As a typical bag and finger skirt may have as much as 4 times the surface area than the author's design, the running surface of the bag could be extremely robust

Fig. 9 Typical Rotors

As deterioration of surface finishes is a major problem, the author has begun an aluminum rotor program.

All of the small vehicles use flat pitched axial flow fans. They are designed to not stall and have a full power shutoff pressure capability of the order of 2 1/2 to 3 1/2 times maximum normal operating weight cushion pressure. This is required as the single engine craft have fixed drive ratios, and some of the vehicles may operate at as little as 15% of full power, for operations in tail winds, rivers and tight maneuvering areas.

Larger single engine craft will have to have some sort of mechanism for altering the drive ratio, or variable pitch propellers. A simple speed change device can consist of 2 belt drives placed side by side and that can be clutched into the drive system, allowing the craft operator to select the proper drive ratio for the operating conditions. A varidrive has been used for this application, and these drives are capable of varying drive ratio without operator control (10).

PERFORMANCE, CALCULATED AND MEASURED

Figure (10) is a summary of the light hovercraft configurations and performance, which is calculated from the numerical model in this paper, along with measured performance data.

It should be noted that the speeds achieved are representative of wide open throttle operation under absolutely ideal conditions of smooth water, still air for the vehicles loaded to the design weights as shown. While the craft could get greater amounts of payload over hump as shown from the planed out weights in the "Refusal column, these load levels are impractical as no performance margin is allowed for conditions such as headwinds, shoal or rough water, and maintenance of cushion and reasonable speed when running down wind.

Although the cushion air gap, or hover height do not enter directly into the straight line performance in the analysis, it must be evaluated to determine if a realistic power penalty is being applied to a particular design when it is compared to another design, or equivalent cushion charging is used in comparative studies.

For all calculations in this paper, the fan total efficiency is assumed to be 70% and a 5% lift drive loss is allowed. A "Dumping Loss Coefficient" of 1.5 is used for all cushion systems, and no penalty is applied for machines which pressurize their skirts above cushion pressure. Cushion efficiency is determined as below:

$$E_c = E_f\left(\frac{1}{1 + K_c(A_l/A_f)^2}\right) \qquad (6)$$

The ratio of hover gap leakage area, A_l, to fan throughflow area, A_f, is the primary determiner of cushion overall efficiency, E_c. The loss coefficient, K_c, is a product of the degree of complexity the cushion flow sees as it passes through the cushion system. The fan efficiency, E_f, is determined at the rotor exit and does not include diffusion losses beyond the impeller.

The author has never measured actual cushion performance. It should be recognized that the number resulting from the analysis can be viewed as relative to the

HOVERCRAFT DESIGN DIMENSIONAL DATA							PERFORMANCE (Calculated/Measured)			
HOVERCRAFT	ENGINE (Hp/Make)	THRUST / LIFT	PROPELLER / FAN DIA. (In)	EMPTY WT. / DES. WT. (Lbs)	LENGTH / BEAM (Ft)	CUSHION AREA (Ft²)	HOVER HEIGHT (In)	TOP SPEED (mph)	REFUSAL LOAD (Lbs)	STATIC THRUST (Lbs)
FAN-TASTIC	8/B&S	50/50	48/24	180/380	11/7	54	.67/-	26/25	465/470	36/36
	10/B&S	"	"	200/400	"	"	.73/-	28/-	507/-	42/-
	11/ "	"	"	"	"	"	.78/-	29/-	533/-	45/-
FAN-TASTIC II	8/B&S	50/50	48/24	240/440	13.4/8.5	80	.68/-	21/22	612/612	36/36
	2-8/B&S	"	"	380/720	13.5/8.5	88	.67/-	27/27	860/-	57/-
	16/B&S	60/40	62/32	450/790	13.5/8.5	88	.71/-	31/32	1029/1020	80/-
MICRO	4/B&S	50/50	42/20	142/312	11/7	54	.46/-	19/-	349/312	21/-
FAN-TASTIC III	16,10/B&S	63/37	68/2-32	680/1190	14.5/10	120	.89/-	33/33	1578/1360	119/120
RED MACH.	25/ONAN	60/40	68/32	680/1190	13.5/10	110	.71/-	32/33	1406/-	112/110
	54/VW1600	60/40	68/32	980/1320	14.5/10	120	1.08/-	43/45	2076/-	199/195
YELLOW MACH.	56/DATSUN B210 1400	60/40	82/32	1200/2200	18/12	175	.82/-	38/41	2968/-	231/230
PLASTIC FAN-TASTIC	11/HONDA	50/50	48/24	280/480	11/7	60	.69/-	29/22	589/580	45/42

Fig. 10 Light Hovercraft Dimensions, Performance

other air gap numbers of the other craft, and the characteristics of the vehicles as driven by the author supplies more information than a cushion flow measurement program could supply.

The calculated and measured performance appear to be in reasonable agreement. The model tends toward underestimating the top speed as vehicle size increases. As the Fan-Tastic 8 Hp. design, (7), (8) is the

Drive and rotor weight is also reduced by the proportion of power reduction, even though the rotors are larger and drive ratios are greater for the revised craft, for lack of information in this area. It should be appreciated that the axial flow fans posed in the study are only slightly larger in diameter than the centrifugal fans they replace, in the case of the Voyageur and its equivalent, and clearly many times lighter, especially baseline vehicle for sizeing the empirical part of the model, agreement is good. Fan-Tastic III failed to meet calculated refusal performance possibly due to impatience of the author in allowing time to get it over hump. (Failure to gain hump after a minute is taken as over refusal load.) The low speed of the Plastic Fan-Tastic is probably due to the high drag of its shroud and under performance of its cushion due to use of an industrial fan, rather than a hovercraft fan.

APPLICATION TO LARGE HOVERCRAFT

Two large hovercraft are "system" analyzed using the analysis of this paper. The vehicle is first analysed as it exists, and then a revised version is analysed using a large diameter propeller which is power loaded nearly as lightly as the Yellow Machine propeller, a flat pitch, large diameter axial flow fan, and the author's skirt system.

In the actual analysis, the propellers on the craft are modelled using the performance of the light hovercraft propellers. Although this results in a high blade tip speed no Mach number penalty is assessed. Centrifugal fans are converted to equivalent axial fans by assuming their inlet diameter to be .6 of the fan tip diameter and the equivalent axial fan to be equivalent to the inlet diameter.

since the objective is to move a given payload over a given surface at a given speed, the revised designs are reduced in size to account for loss in gross weight due to engine, fuel, and tankage that is not needed because of economies of power, and 3/4 of the ballast trim fuel and tankage that is not needed due to the pitch trim system used in the equivalent hovercraft. 1/4 of the ballast trim fuel is kept to provide roll trim.

when considering that the centrifugal fans require a more elaborate housing than the axial units. Similar weight economies probably occur when comparing the multiple double suction centrifugal fans to their axial equivalent. The large diameter propellers are structurally almost identical to the propeller on the Yellow Machine and would scale directly in weight using cube scaling. The 20 ft. propeller would weigh around 275lbs., less than its equivalent 4 blade heavily loaded propeller. If variable pitch is required, the plus or minus 15 degree pitch change required could be obtained with a simple mechanism similar to a helicopter tail rotor pitch mechanism.

Performance of the Voyageur and the AP1-88 as represented in this paper along with the revised versions is shown in fig. (11). In both cases, half of the power is removed, large rotors and skirt installed and the useful load and endurance maintained. Speed, hoverheight, and thrust to hump drag ratio have been maintained or slightly exceeded in the equivalent designs. (The thrust to lift power split for the Voyageur was fixed, and the variable pitch propeller should improve the area of performance of thrust over hump drag for the "real" vehicle.)

The weight reductions might be questioned for the examples. Not only does machinery, fuel and tankage weight come down, structure and skirt weight also come down as there is less load to support, in the case of the revised designs. Additionally, vehicle overall dimensions come down to 90% of original dimensions as the large rotor design simply results in a much lighter, and therefore smaller craft. Fig. (12) is a breakdown of the weights

HOVERCRAFT DESIGN DIMENSIONAL DATA							PERFORMANCE			
HOVERCRAFT	ENGINE (Hp/Make)	THRUST / LIFT	PROPELLER / FAN DIA (Ft)	WEIGHT (Lbs)	CUSHION LENGTH(Ft) / BEAM(Ft)	CUSHION AREA (Ft^2)	HOVER HEIGHT (In)	TOP SPEED (Kts)	THRUST / HUMP RATIO	STATIC THRUST (Lbs)
VOYAGEUR	2-1300/P&W	65/35	2-9/2-7	91000	64/32	2049	1.24	58	1.09	4763
EQUIVALENT	1-1300/P&W	67/33	2-22/2-7.5	69428	58.3/29.1	1697	1.26	59	1.56	5678
AP1-88	4-500/Deutz	50/50	2-9*/8-2.75	86395	64.8/28	1815	1.02	57	1.1	5559
EQUIVALENT	2-500/Deutz	67/33	2-18/2-7.5	63978	58.3/25.2	1470	1.01	57	1.17	4078

*Ducted Fan Thruster

Fig. 11 Voyageur, AP1-88 Simulated Performance

of original and revised designs.

HOVERCRAFT WEIGHT BREAKDOWN (Lbs/%)					
HOVERCRAFT	STRUCTURE SKIRT	ENGINE MACHY.	CABIN ACCESS.	FUEL-TANKAGE	USEFUL LOAD
VOYAGEUR	29120/32	6670/7	2657/3	18189/20	34398/38
EQUIVALENT	22217/32	3335/5	2657/4	6821/10	34398/49
AP1-88	34558/40	15000/17	6552/8	9520/11	20765/24
EQUIVALENT	25591/40	7500/12	6552/10	3570/6	20765/32

Fig. 12 Weight Breakdown

There is considerable ambiguity in trying to come up with a correct weight reduction model. For instance, the fan shroud may show up in the structure part of one set of data, yet it is clearly in for weight reduction in the form of machinery weight reduction, so these weight models are not referenced. The craft should be taken as similar to the named vehicles.

The fact that the top speed as calculated in the model came up very reasonably close to what is expected of the two large craft may be more due to serendipity than accuracy. The large craft base areas are of much higher length to beam ratio than the light hovercraft, which should result in more skirt drag. As the large craft do not have "open convertible" drag coefficients of the light craft, there should be

CONCLUSION

Power requirements for current technology large hovercraft can be reduced to one-half current levels if large diameter lightly loaded propellers and axial flow fans, and , to a lesser extent, simplified skirt design is employed. The resulting economies achieved can result in the amphibious hovercraft concept making inroads into new markets presently occupied by other forms of marine transport.

NOMENCLATURE

Var.	Definition	Subscript	Definition
A	Area-Ft^2	a	Aerodynamic,air
B	Cushion Beam-Ft	c	Cushion, Dump
C	Drag Coefficient	f	Fan
D	Drag-Lbs	h	At Hump
E	Efficiency	l	Leakage Area
K	Coefficient	p	Projected Area
L	Avg. Length-Ft	s	Water Friction
P	Pressure- lb/Ft^2	t	Total
V	Velocity-Ft/Sec	w	Wavemaking, Water
W	Weight oper.-lbs		
ρ	Mass Density-Slug		

REFERENCES

1. Bierman, D., Hartman, E. F., Tests of Full Scale Propellers· · · ' NASA TR 658

less aerodynamic drag. Therefore the study is primarily comparative. The craft represent equivalents and are not configured as the author might design for similar application.

Some consideration should be given to the aspect that the large propellers of the equivalent craft overhang the outboard of the hulls. In reality, while such a configuration might represent a hazard on a recreational machine, it should be of no problem for vehicles managed by professionals. As the propellers are far overhead they represent almost no danger to bystanders, and, indeed, because of their distributed wash, may be safer than small propellers. A light frame could be built to define the outer limits of the propellers if desired.

It should be noted that the revised AP1-88 design is very similar in useful load, power, and operating weight to the Hovermarine HM2 Mk. 4 sidewall marine propulsion craft, which operates in calm conditions at 34 kts (9). Although it is expected that the AP1-88 equivalent would be slowed by rough weather to a greater degree than the sidewall vehicle, it is clear that the fully amphibious craft has a performance advantage, which would probably result in lower operating costs. The large propellers give the amphibian very nearly the 70% propulsive efficiency of the sidewall craft's marine propellers (5).

2. Mort, K. W., Gamse, B., 'A Wind Tunnel Investigation of a 7 Foot-Diameter Ducted Propeller,' NASA TN D-4142, 8-1967.

3. Wood, K. D., 'Aerospace Vehicle Design Vol. I,' Johnson Publ Co., Boulder, Colo. 1966.

4. Hoerner, S. F., 'Fluid-Dynamic Drag,' Publ. Author, 1965.

5. Mantle, P. J., Ed. 'Air Cushion Craft Development,' DTNSRDC-80/012, 1-1980.

6. Lamb, H., 'Hydrodynamics,' Cambridge Univ. Press.

7. Palmer, B. H., 'Fan-Tastic, A Light Amphibious Surface Effect Vehicle,' AIAA Pacific Northwest Div, Experimental Aircraft Symposium Proceedings, 7-1975.

8. Palmer, B. H., 'Acoustic Characteristics of a Light Amphibious Surface Effect Vehicle,' 1st Int'l Conference On Noise From Recreational Off Road Vehicles (ORV),' University of Montana-USDA-Forest Service 11-1975.

9. Hovermarine Corp, Promotional Literature, Hazel Road, Woolston, Southampton, SO2 7GB England.

10. Windt, B., 'Universal Hovercraft,' Publ. Author, P. O. Box 281, Cordova, Ill.

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Here is another paper, on the radiated noise of an 8hp craft of the author's, showing the overall far field noise, and a breakdown of the constituent contributors, engine, fan, propeller, to the far field noise through narrow band noise analysis.

PROCEEDINGS

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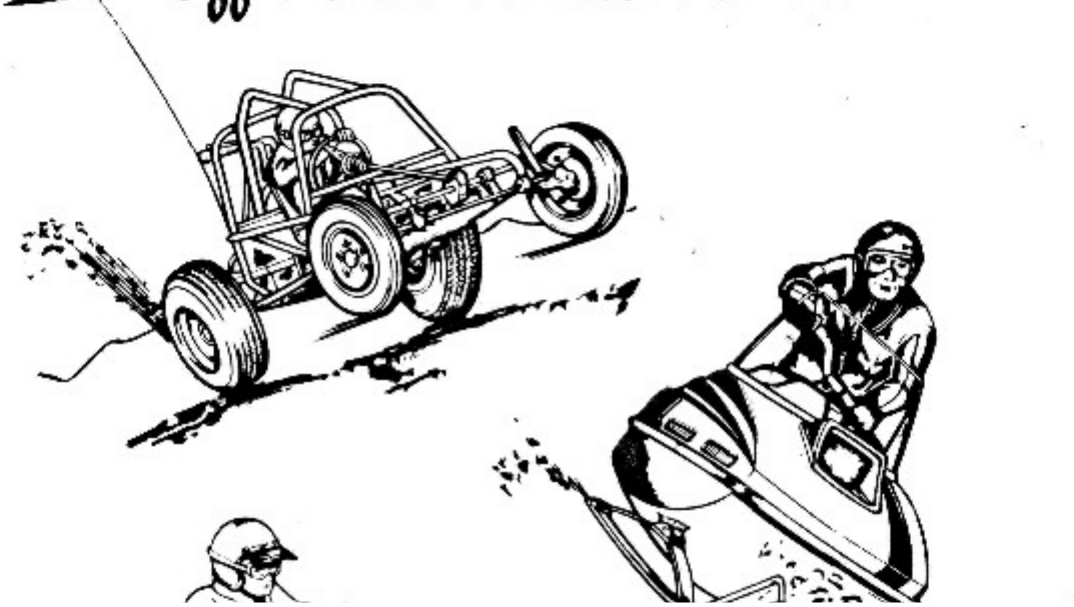
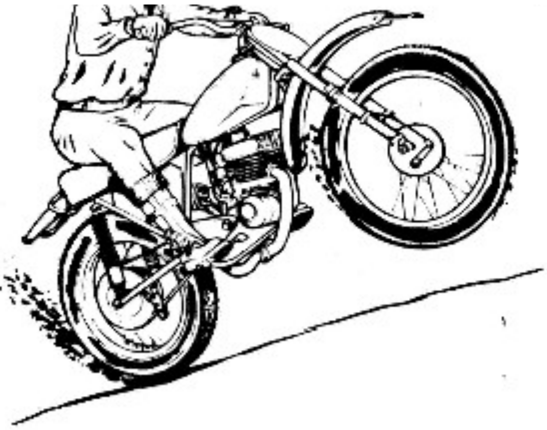
1st International Conference On Noise From Recreational Off-Road Vehicles (ORV)





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ACOUSTIC CHARACTERISTICS OF A QUIET LIGHT AMPHIBIOUS SURFACE EFFECT VEHICLE

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INTRODUCTION

Although the concept is quite old, and patents date back to the turn of the century, air cushion vehicle, or hovercraft, or surface effect vehicle (sev) technology has primarily evolved in the past twenty years. These unique vehicles, while solving unusual transport problems, have generated their own set of problems, principally high initial and operating costs, and rejection by communities due to excessive exterior noise.

A number of small vehicles have been designed to be very quiet, notably the English CC-7 hovercraft. Unfortunately, the low noise level of the CC-7 was achieved through an extreme sacrifice in efficiency. The ten place, 35 knot craft uses a 500 horsepower engine. The extremely high power requirement is caused by the use of small diameter, fully enclosed centrifugal fans for both propulsion and lift.

Fan-Tastic was designed by the author for construction by the amateur builder. In the design, both efficiency problems and noise problems were attacked directly. Performance of the craft is discussed by Palmer in Reference 1. This paper is addressed to the exterior noise aspects of the design and the results achieved. Additionally, the lower practical noise levels of this type of vehicle are explored.

DESIGN ASPECTS OF QUIET SEV'S

The principal noise producing elements of an amphibious sev are the engine, lift fan and propeller. A separate lift fan and propeller of fairly large diameter must be used to achieve high vehicle efficiency.

The engine may be buried within the craft or mounted externally. From acoustics considerations, the buried engine represents the best configuration. Buried engine noise control is similar to noise control of an automobile engine, except that higher continuous engine output is required in the sev application and sev engines tend to be light-weight and air cooled. However, engine noise is controllable if effort is made to enclose the engine, acoustically treat air inlet and outlet ducting, and provide an adequate muffler.

Fan noise is generally characterized by an irregularly shaped pressure pulse, which is produced at the fan blade passing frequency. The pulse shape produces harmonic "spikes" in narrow band Fourier Transform data. Broadband noise is produced which can be the order of 20 dB below the spikes. Fan pulse noise can be minimized by keeping fan blade to stator and support structure spacing large. "A" weighted, or subjective noise levels can be reduced by using fewer blades, which can shift fan pulse rate to lower frequencies. Broadband noise may be reduced by using lower blade tip speeds. The fan may also be buried deeply within the vehicle, and acoustic linings may be used upstream.

Propeller noise is the most severe problem for the sev designer. Trillo's[2] empirical study of propeller noise shows that propeller noise is primarily a function of propeller blade tip speed and secondarily a function of horsepower absorbed by the propeller. Noise characteristics of the propeller are similar to the fan and the same rules for noise reduction apply except that the propeller cannot be buried within the hull.

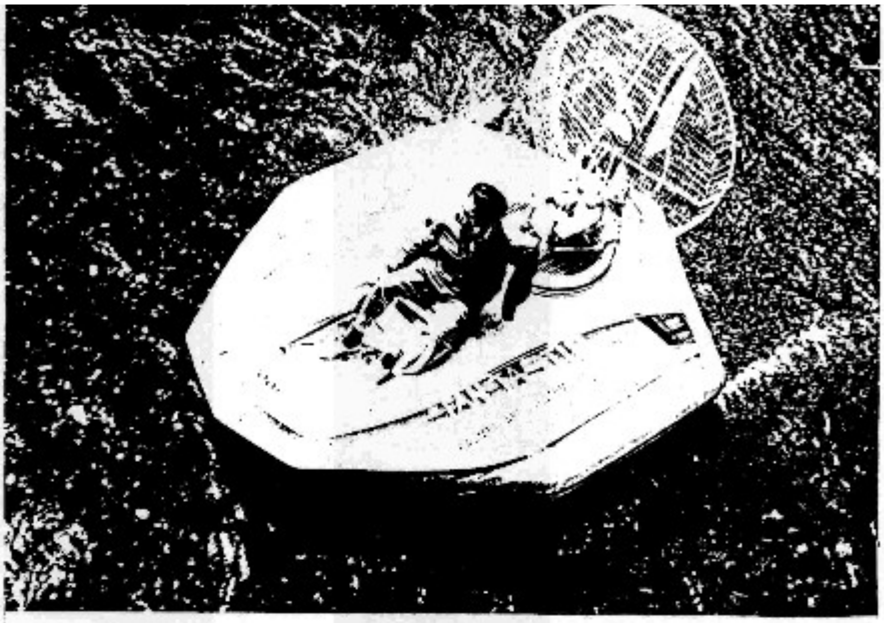
One might expect that a duct could be used on the propeller as an aid to increase propulsive efficiency and reduce noise. Frequently, ducts are used on sev's. However, from aerodynamic considerations, a duct can represent a performance penalty for a sev if the propulsive efficiency is high as is the case for the vehicle to be described.

VEHICLE DESCRIPTION

Fan-Tastic is a single place, single engine amphibious sev. An overall view of the vehicle and its specifications are presented in Figure 1.

The vehicle is designed around an 8 hp (at 3600 rpm) Briggs and Stratton vertical shaft diecast aluminum garden equipment engine. A 24-inch diameter, six blade lift fan is directly driven by the engine. The fan hub to engine shaft adapter serves as a drive pulley for the 48-inch diameter two blade propeller. The propeller vee belt drive is folded from the horizontal plane of the fan to the vertical plane of the propeller via a "mule drive", using two idler pulleys. The engine exhausts directly outboard on the starboard side through a small muffler.

The engine to propeller nominal drive reduction is 2.2/1. However, under the static thrust conditions of the noise tests, the operating



SPECIFICATIONS

Gross Weight	440 LB	Top Speed Water	25 mph
Useful Load	260 LB	Top Speed Land	30 mph
Empty Weight	180 LB	Fuel 18 mph Water	34 mpg
Power	7 HP	Test Engine Operating Speed (Static)	3080 rpm
Length	11 FT	50 ft Passby Maximum Noise Level	83 dBA
Beam	7 FT		

FIGURE 1 VEHICLE OVERVIEW

drive ratio proved to be 2.35/1, corresponding to a 7 percent belt "creep".

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TEST PROCEDURE

The vehicle was anchored in the middle of a grass field. Two sidelines were established 25 feet from the vehicle centerline. The vehicle was operated at full power and data was direct recorded on a tape recorder while the recorder operator walked the sidelines. A pistonphone calibrated 1/2 inch condenser microphone was used. The static vehicle, moving measurement point was used as vehicle full power operation would cause excessive speed problems and reduce data integration time in the small field available for the tests. Also, the static vehicle near field propeller, lift fan and engine exhaust acoustic signatures, which were recorded, could be related to far field narrow band noise data.

Data was reduced to octave band and 4 Hz narrow band presentation.

TEST RESULTS

From a noise standpoint, Fan-Tastic proved to be extremely complex. There were obvious differences in spectral content even to an aural observer as he walked around the craft. The noise radiation was obviously asymmetric about the vehicle centerline, no doubt due to the asymmetries of the exhaust, engine valve train location, and rotor rotation. A distinct pulse note was easily observable all around the vehicle. An extremely sharp edge pulse was observed in the aft arc on the starboard side of the vehicle. The source of this noise was probably an engine exhaust gas-propeller interaction.

Highest sideline A weighted noise levels were observed directly abeam the vehicle, as this represented the point of closest approach. (Moving vehicle tests done in the past indicated maximum noise levels in the aft arcs.) Octave band spectral content is shown in Figure 2 for a 50-foot sideline distance.

The high A weighted level shown in the starboard (exhaust) passby data is caused by the high frequency noise content of the engine valve train and exhaust noise. The propagation direction is directly outboard in the direction of exhaust gas flow, although no doubt there is some direct valve noise radiation through the engine structure itself.

The starboard noise levels could be reduced to the port radiation levels if the engine exhaust was ducted down through the hull, and a metal cover were placed over the valve area of the engine (allowing room for cooling air exhaust).

Although the low frequency content of the starboard radiated noise is also above the port side radiation, it does not contribute significantly to A weighted levels.

Sideline exterior noise levels of Fan-Tastic could be easily reduced to the 78 dBA 50-foot sideline level of the port side if the aforementioned improvements were incorporated.

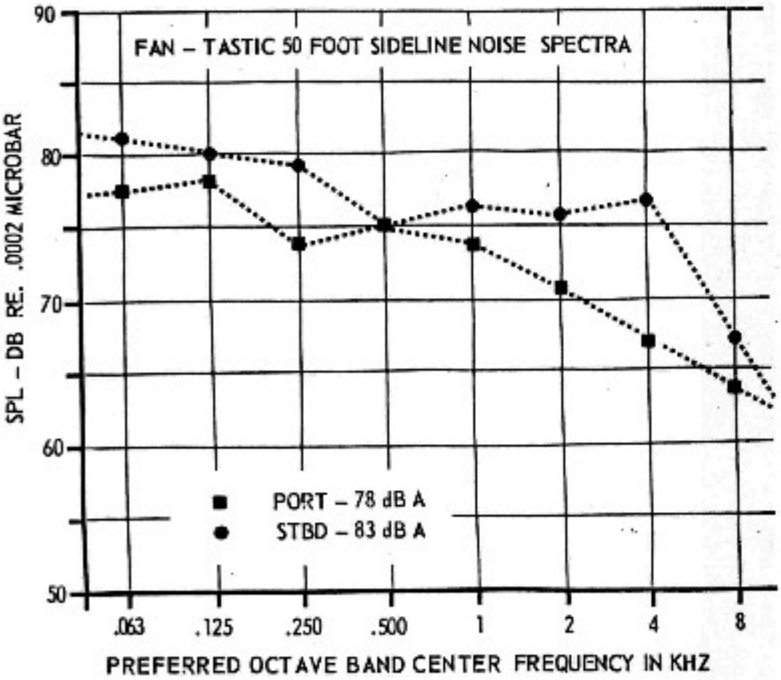


FIGURE 2 VEHICLE 50 FOOT SIDELINE PASSBY MAXIMUM NOISE LEVELS

Ultimately, after engine noise is reduced the vehicle rotors themselves must be considered for noise reduction.

Fan-Tastic rotor noise was ascertained by recording near field signatures of the lift fan, propeller and engine exhaust to separate engine broadband noise from rotor noise.

Narrow band reductions of fan, propeller, and engine exhaust signatures are shown in Figures 3, 4 and 5. Blade passing and engine firing fundamentals and harmonics are noted in the figures.

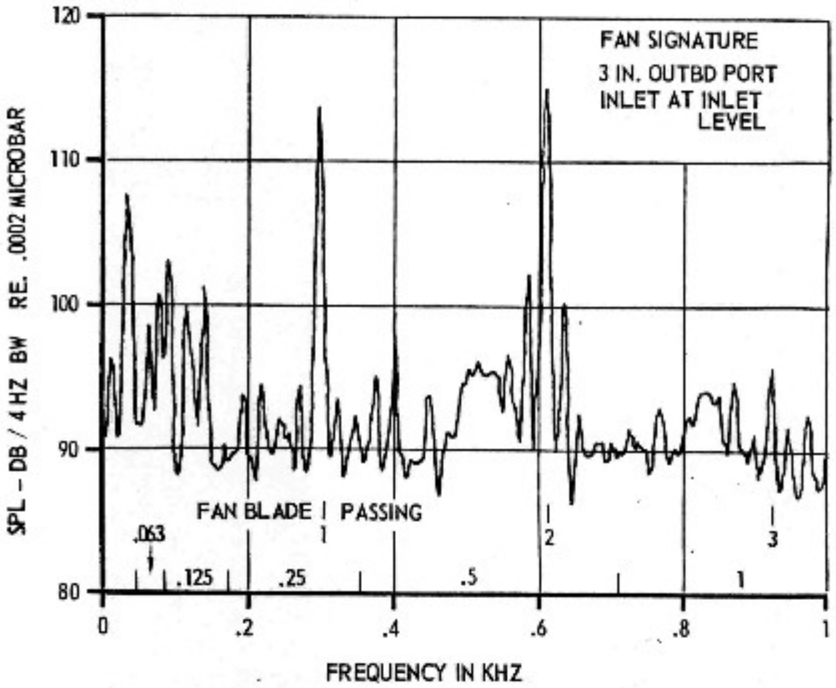


FIGURE 3 FAN SIGNATURE

The fan signature consists of two harmonics which are the order of 25 dB above broadband noise levels, and additional harmonics that barely appeared above the broadband levels. The data suggests a wave train (inverse Fourier Transform) of a sine wave with maxima and minima dimpled. However, the wave train is altered as it projects to the far field, as harmonic content in the far field was considerably modified. Unfortunately, engine broadband noise could not be adequately rejected due to the close proximity of the fan to the engine.

The descending in echelon harmonics of the propeller signature suggests a wave train of sharp edged, short duration pulses, as would be expected from the low solidity propeller.

Engine noise rejection was good, as the microphone could be held well away from the engine and yet close to the propeller blade tips. The fundamental spike is over 30 dB and the "skirts" of the narrow band filter used come together before broadband noise is encountered.

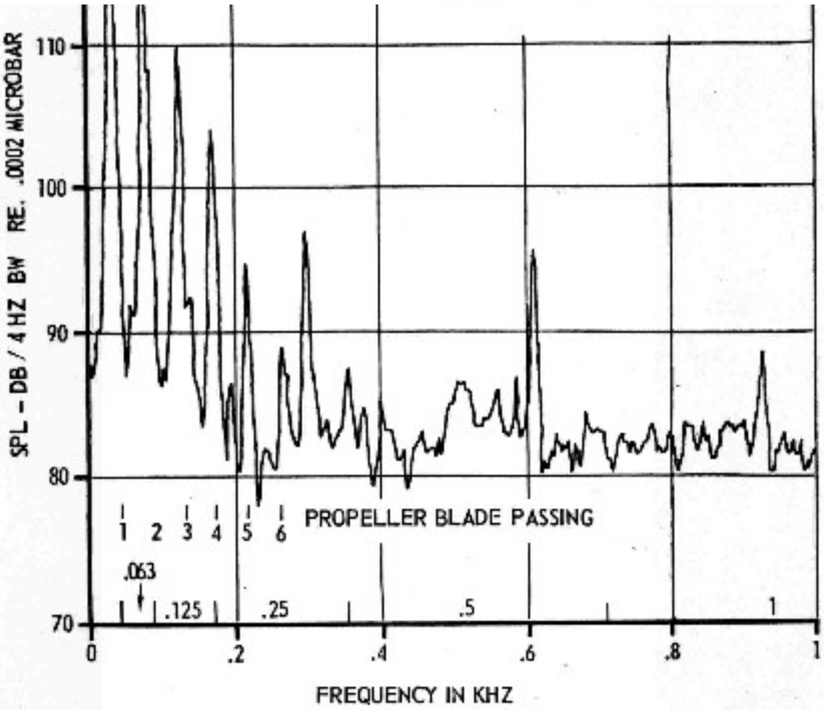
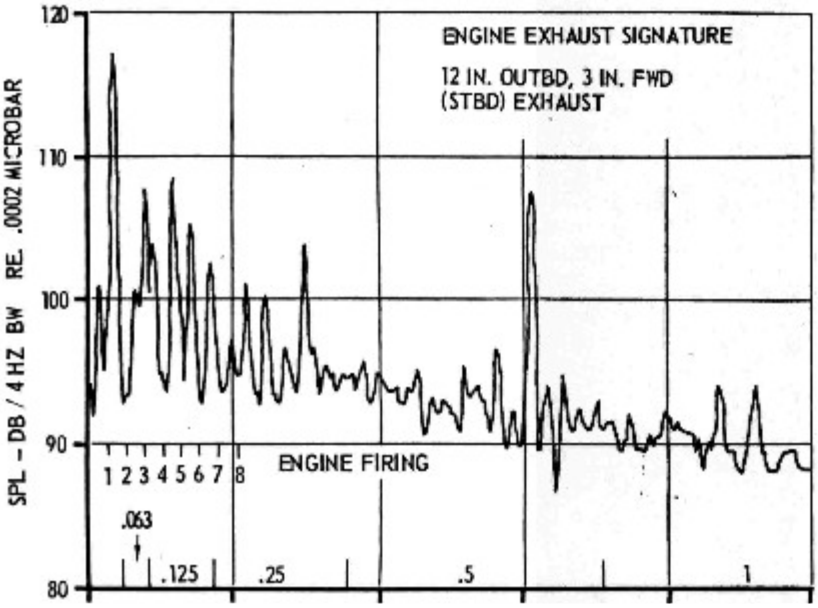


FIGURE 4 PROPELLER SIGNATURE

The engine exhaust signature was well buried within the propeller noise levels, and only the fundamental is well defined. It should be appreciated, however, that it was obvious, from a subjective standpoint, that there is considerable high frequency noise content in the exhaust, and even the most minute variations in exhaust wave train shape will destroy the high number harmonics in the exhaust, and produce high frequency broadband noise.

It can be surmised from the propeller data that propeller broadband noise levels are very low. Therefore, an octave band spectrum of the propeller can be generated using the propeller maximum harmonic levels alone. The



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FREQUENCY IN KHZ

FIGURE 5 ENGINE EXHAUST SIGNATURE

octave band spectrum constructed from the harmonics is shown in Figure 6. A propeller alone noise level of 66 dBA at 50 feet was determined from the narrow band spectrum as recorded in the far field. The spectrum is constructed from narrow band presentation of the 25-foot sideline data, rather than the signature data so that it is truly representative of far field data.

Although fan signature broadband levels were high due to the fan location being next to the engine, it is likely that fan alone broadband levels are low as in the case of the propeller, as fan and propeller blade tip speeds are similar. Also, the fan harmonics have been observed to be extremely sensitive to engine mount structure location. Although the fan fundamental is aurally obvious, moving the fan down the engine shaft only 3/4 inch, increasing the fan to engine mount spacing to 2-1/2 inches eliminates subjective recognition of the fan fundamental.

The far field fan alone spectrum, estimated in an identical manner as the propeller spectrum, is also shown on Figure 6.

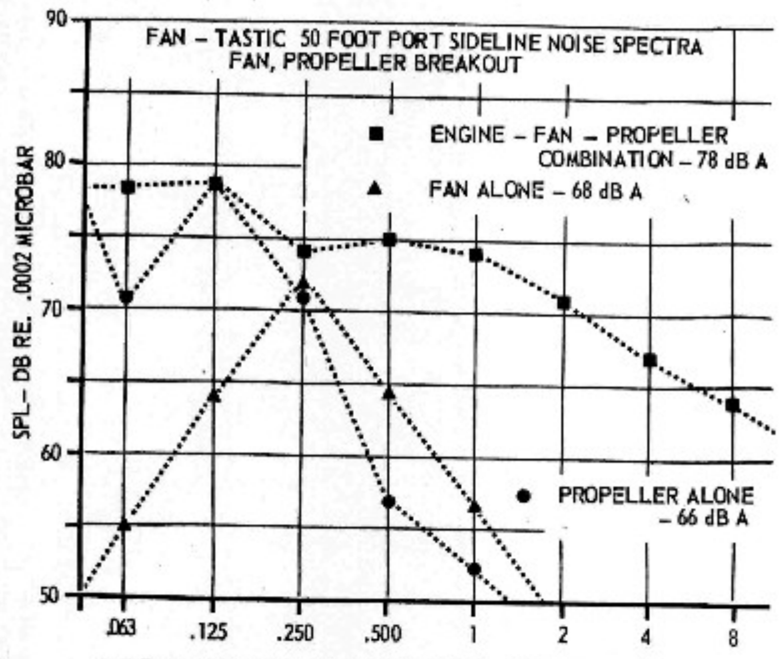

FIGURE 6 FAN, PROPELLER NOISE BREAKOUT

CONCLUSIONS AND RECOMMENDATIONS

The Fan-Tastic light amphibious sev produces a relatively low average 50 foot passby sideline noise level of 81 dBA over grass at full power. The vehicle is engine noise dominated.

Combined lift fan and propeller noise level is in excess of 10 dBA below the engine noise level. The low noise level of the rotors is a product of design for high efficiency in addition to low noise production.

As vehicle size increases, rotor noise will increase. But if high efficiency design philosophy is used, vehicle noise levels may still be engine dominated. For instance, based on Trillo[2], and the author's analytical design procedures, the propeller noise for an efficiently designed 100 maximum total horsepower, eight place, 45 mph top speed sev, (Fan-Tastic would be a one-half scale model) would be only 11 dBA above the Fan-Tastic propeller noise level.

As engine noise of large vehicles should be easier to control than is the case for small vehicles, it is likely that vehicles of the order of ten place can be built with exterior noise levels within 10 dBA of a single place vehicle.

It should be relatively easy to reduce the Fan-Tastic 50-foot sideline noise levels to below 75 dBA by burying the engine exhaust in the hull and acoustically shrouding the engine. Therefore, it is recommended that target exterior 50-foot sideline noise levels, for manufactured vehicles, as measured at full power over a grass reflecting surface, should be 75 dBA for one place vehicles, and graduate upwards to 85 dBA for a ten place craft. These noise levels are consistent with current noise levels of snowmobiles, motorcycles and pleasure boats, as reported by the Environmental Protection Agency.[3] As the sev industry develops lower levels then may be achieved.

It should be appreciated that the sev rotors do present an ultimate noise floor and as noise levels of other types of vehicles are reduced through development, the light sev may not be able to do likewise. It should be recognized that the light sev possesses a potential for exceptionally low environmental impact in other ways, as it applies no forces to the terrain, nor does it excessively disturb water surfaces or submerged terrain.

REFERENCES

1. B. H. Palmer, "Fan-Tastic, A Light Amphibious Surface Effect Vehicle," AIAA Pacific Northwest Section, Experimental Aircraft Symposium Proceedings, 66-72, (1975).

2. R. L. Trillo, "An Empirical Study of Hovercraft Propeller Noise," J. Sound Vib. 3, 476-509, (1966).

3. U. S. Environmental Protection Agency, "Report of the Administrator of the Environmental Protection Agency," U. S. Government Printing Office, (1972).

And here is still another paper showing the most fundamental analysis of a small sev.

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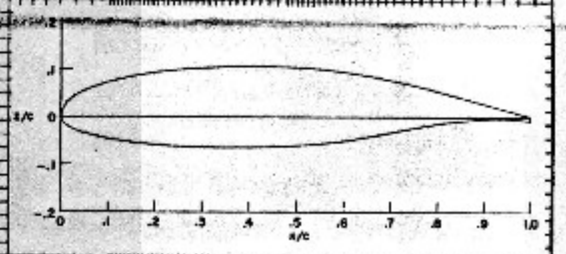

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TIME VALUE

FAN-TASTIC, A LIGHT AMPHIBIOUS SURFACE EFFECT VEHICLE

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Abstract

Methods are discussed for achieving high efficiency and reliability, while at the same time obtaining a low noise level from a light amphibious surface effect vehicle. An operating prototype high-efficiency vehicle is described and its performance and design are related to vehicles of more conventional design philosophy.

NOMENCLATURE

A Cushion area, ft^2

A_{ex} Cushion underflow leakage area, ft^2

A_f Cushion fan throughflow area, ft^2

I. INTRODUCTION

Although there have been a substantial number of attempts to manufacture a light surface effect vehicle (sev) and there has been some activity by amateur builders since the mid-1950's.

D	Vehicle wavemaking drag, lb
d	Open propeller diameter, ft
H_c	Cushion pressure head, ft of water
K	Fan dumping loss coefficient
K_w	Wave drag coefficient
L	Cushion length, ft
P_f	Cushion fan power, ft-lb/sec
P_t	Thruster power, ft-lb/sec
V	Vehicle velocity, ft/sec
V_{ax}	Fan throughflow velocity, ft/sec
W	Vehicle operating weight, lb
ρ	Air weight density, lb/ft^3
η_a	Fan aerodynamic efficiency
η_f	Cushion system overall efficiency
η_p	Propulsive efficiency

only large English craft have achieved a degree of success.

Most attempts at producing a truly viable light sev have resulted in vehicles which are either excessively noisy, inefficient, or unreliable. In some cases all three problems can be associated with a single vehicle design.

"Fan-tastic" is the outgrowth of a program to eliminate the principal problems associated with light sevs and at the same time provide a basis for the design of efficient, quiet, and reliable light amphibious sevs. The vehicle is illustrated and major specifications summarized in figure 1.

It should be realized that vehicle configuration selection is more of an art than a science. The practical designer must work with existing materials (and sometimes complete assemblies, such as engines) and therefore practical decisions must sometimes be made at the expense of theoretical optimums.

A complete theoretical treatment of amphibious sevs can be found in Williams.[1] It is the intent of this paper to bridge the gap between theory and practicality.

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Fan-Tastic
Single-Place Amphibious Sev
(Specifications)

Gross weight	440 lb
Useful load	260 lb
Empty weight	180 lb
Power (Briggs and Stratton four-cycle) rated 8 hp at 3600 rpm	7 hp at 3300 rpm
Power split, thrust/lift	50/50
Max power loading	63 lb/horsepower
Length	11 ft
Beam	7 ft
Cushion area	54 ft^2
Fuel consumption, 18 mph normal cruise, sea level still air	34 stat miles/U.S. gal
Refusal gross weight (maximum weight over hump, still water, sea level air)	470 lb

2.1 PROPULSION

For the purposes of this discussion, propulsion will be limited to air jet reaction, since it appears to be the simplest system for amphibious sevs.

Fan-tastic was designed so that the average homebuilder could construct and maintain it. Therefore, the open or unconfined propeller was selected as the propulsor, as it was felt that maintenance of the tight blade tip clearances and construction of a large diameter duct would be difficult for the amateur.

Assuming incompressibility and using the basic momentum considerations, and assuming one-half the momentum increase in the air passing through the thruster occurs ahead of the propeller:

$$\frac{P_t}{d^2} = \frac{\pi\rho V^3}{2\eta_p^2}\left(\frac{1}{\eta_p} - 1\right) \qquad (1)$$

Propulsive efficiency for the open propeller is entirely a function of propeller disc loading, P_t/d^2, and vehicle forward speed, given the independent variable of air density.

As can be seen by the equation, either vehicle forward speed must be high or propeller diameter must be large for a given horsepower for high propulsive efficiency.

Obviously, as propeller diameter increases, the total propulsion system of drive, rotor, rotor support, and rotor guard increases in weight and, therefore, at some diameter the increased propulsion system weight may impose an overall vehicle penalty greater than the advantages obtained from increased propulsive efficiency. A baseline weight for the propulsion system at some specific diameter must be estimated and modeled geometrically to give a suitable numerical model with which an optimum diameter may be selected.

Propulsive efficiency, η_p, as a function of propeller disc loading, P/d^2, and vehicle forward speed, V_v, are plotted in figure 2.

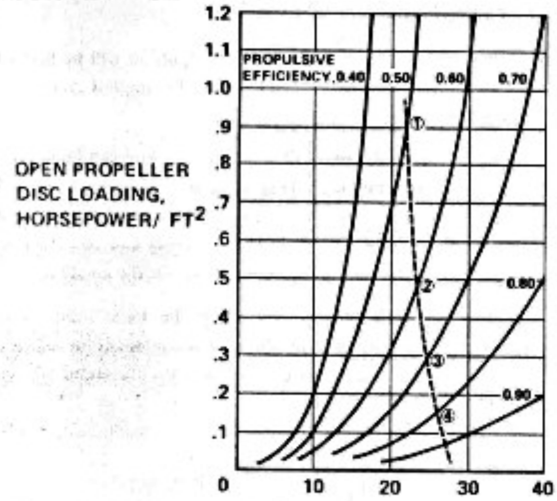
Figure 1. Overall View of Fan-Tastic and Specifications

2. VEHICLE CONFIGURATION

Although the vehicle elements are categorized in this paper, it should be realized that they are interdependent and each element should be evaluated as to its effect upon the overall system.

A propulsion system is modeled numerically, using the final weights achieved on the Fan-tastic vehicle propulsion system. The effect on Fan-tastic vehicle top speed is also plotted in figure 2.

Obviously, as propeller diameter increases, the craft's top speed increases if a simple model of drag is employed, assuming the drag is proportional to the craft's forward speed squared. However, since the simple drag assumption does not account for vehicle weight which is of significant influence (as will be seen later), vehicle top speed continues to rise as the propeller diameter approaches infinity.



CASE	PROPELLER DIA (FT)	GROSS WEIGHT (LB)	USEFUL LOAD (LB)
①	2	350	170
②	3	400	220
③	4	440	260
④	6	500	274

Figure 2. Effect of Propulsor Propeller Diameter on Vehicle Performance

Because the effect of vehicle weight upon vehicle top speed is quite intractable to analytical procedures (as will be seen later), a better picture of the effect of propulsor diameter on overall vehicle performance can be observed if vehicle gross weight is increased relative to the propulsor's ability of planing the vehicle out or accelerating the vehicle over hump speed. ("Hump" speed will be discussed later.) The vehicle payload can then be broken from the baseline model, and it can be shown that both top speed and vehicle payload increase even when the propeller exceeds 72 in., an impractically large diameter.

The payload increased by only 14 lb and the top speed increased by less than 2 mph in going from a 48-in. rotor to a 72-in. rotor. It was therefore decided that the performance benefit derived through use of the larger rotor was not significant enough to outweigh problems of construction, overhead clearance, handling, and trailering a vehicle with a very large diameter rotor, and the propeller diameter was held to 48 in.

Rotor shaft speed selection is also an important factor in propulsor design. If the shaft speed is too high, the blade pitch angle becomes too low, and the rotor operates at low aerodynamic efficiency. Analyses by Wood[2] and others using the same assumptions as in equation (1) have shown that blade pitches flatter than 8°, as measured at three quarters of the blade radius, result in significant reductions in propeller efficiency below that which would be obtainable from a propeller using the same airfoil but at a pitch of the order of 10° to 12°. Also, losses due to flat pitch are aggravated by low airfoil efficiency. Since the average homebuilder is apt to produce airfoils of lower efficiency than a manufacturer, a 12° angle was selected. Selection of a higher pitch angle resulted in excessive drive bulk and weight because of the lower shaft speeds required.

An increasingly important consideration in propulsor design is noise. Trillo,[3] in an empirical study of a large number of propellers, shows a general trend of noise production as primarily a function of propeller blade tip speed and secondarily a function of rotor horsepower. Extrapolations of the Trillo information to the Fan-tastic rotor resulted in noise levels of the 300 ft/sec cruise tip speed propeller being more than 10 dB(A) below the 85 dB(A) at 50-ft noise level of the engine.

Another benefit of low propeller tip speeds is that the blade erosion problem is reduced markedly, and wood or fiberglass leading edges have been found to be more than adequate for Fan-tastic.

2.2 LIFT

The primary consideration in lift fan design is minimization of power consumed for cushion charging. Cushion power is absorbed by fan aerodynamic inefficiency, pressurization of the steady flow of air needed to replenish the cushion, and losses resulting from inefficiency in recovering the throughflow velocity energy of the air passing through the fan and into the cushion. The fan throughflow velocity loss can be lumped with the cushion pressure term as follows:

$$P_f = \frac{W}{A} + K\rho \frac{V_{ax}^2}{2g} \qquad (2)$$

The coefficient K is a function of the flow geometry through the fan and into the cushion and may be as high as 2 for the simplest ducting arrangements (e.g., the simple rounded fan inlet with no exit duct used in the design of Fan-tastic).

From equation (2), it can be seen that if practical restraints dictate a given complexity in the cushion charging flow path by such things as engine mounts, and the engine location in the case of Fan-tastic, alternatives for reducing the apparent total downstream pressure are a reduction in vehicle gross weight, an increase in cushion area, or a reduction in fan throughflow velocity.

Vehicle gross weight was fixed by the requirement that relatively available, nonexotic, and heavy materials had to be used in consideration of the home builder. A heavy engine was selected for reliability and the capability of direct driving the fan (as will be seen later). The useful load selected for the 180-lb empty weight craft was 260 lb.

Cushion area was determined by vehicle planeout capability and a desire to minimize frontal area for top speed considerations.

Reduction of the fan throughflow velocity, V_{ax}, can be obtained at the cost of increased fan diameter and weight.

As can be seen from equation (2), the "dumping" loss is a function of the fan axial flow dynamic pressure. The cushion pressure term in equation (2) can be expressed as the dynamic pressure of the discharge flow. Since continuity of the fan cushion system must be maintained, the fan throughflow loss can be expressed in terms of the cushion underflow leakage in terms of the ratio of fan throughflow area to skirt underflow leakage area, and the efficiency of the overall system can be expressed as follows:

$$\eta_f = \eta_a\left(\frac{1}{1 + K(A_{ex}/A_f)^2}\right) \qquad (3)$$

Since the skirt underflow leakage area, A_{ex}, is usually fixed because of practical considerations, it can be seen from equation (3) that cushion charging efficiency is a function of the fan aerodynamic efficiency and the ratio of the skirt underflow area to the fan throughflow area.

Equation (3) is plotted in figure 3 for a fan aerodynamic efficiency of 70% and loss factors of 0, 1.0, 1.5, and 2.0, which is the range of expected loss factors for simple fan throughflow geometry.

In the case of Fan-tastic, it was decided to compromise fan throughflow area and attempt to drive the fan directly with the 3000- to 3600-rpm engine shaft, for increased simplicity of construction and reliability of the finished product. Fan flow volume has not been measured, and a locus of operation is shown as a function of cushion "daylight" flow or cushion underflow leakage area expressed in terms of an average skirt-to-surface clearance. Volume flow, shaft speed, and required pressure rise dictated use of an axial flow fan, from specific speed considerations as shown in Shepherd.[4]

As in the case of an open propeller, the tangential discharge velocity components are low in the flat pitch fan design used in Fan-tastic and diffuser vanes were not required.

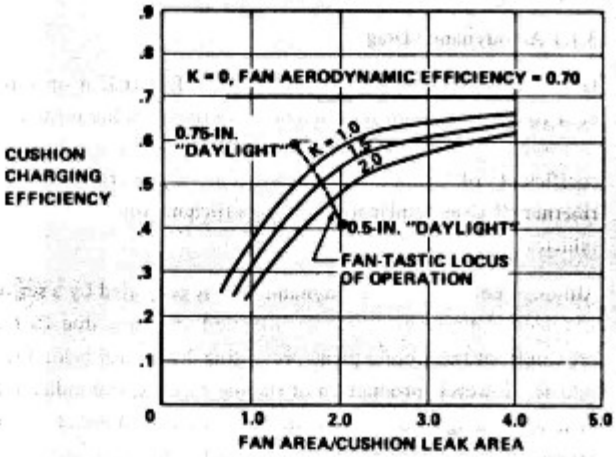


Figure 3. Cushion Charging Efficiency

2.3 POWER

Since Fan-tastic was to be a recreational vehicle, adherence to stringent design performance specifications was not necessary. The vehicle was designed to have the capability to plane out an adult and youngster of 250 lb combined weight, using an 8-hp Briggs and Stratton engine. Vehicle top speed and rough terrain capability were of secondary consideration. The particular engine was selected on the basis of its low cost, and the fact that it was the highest powered die cast aluminum garden equipment engine available at the time. As most small sevs of the same payload capability are powered with 20- to 50-hp lightweight two-stroke engines, the project was undertaken with the knowledge that there was considerable uncertainty of successful completion.

The engine weighs 44 lb dry and is limited to 6.8 hp at 3600 rpm by a manufacturer-supplied governor.

Early in the design, it was decided that the power would be divided equally between the cushion fan and thrust propeller. The vehicle engine installation as matched to the current propeller and fan design produces 7 hp at 3300 rpm. (The governor had been removed.)

3. PERFORMANCE ESTIMATES

3.1 DRAG

Vehicle drag can be broken into the components of aerodynamic body drag, momentum drag, and skirt drag. When the vehicle is operated over water, the skirt drag can be broken into two components of induced and parasitic drag.

3.1.1 Aerodynamic Drag

Due to the abrupt shape of a sev and the fact that it operates next to a surface with its attendant interference, the form drag of a sev is quite high. Elsley and Devereaux[5] suggest a drag coefficient of around 0.5 based on vehicle frontal area. Hoerner[6] gives similar form drag coefficients for wheeled land vehicles.

Although considerable aerodynamic lift is generated by a sev or wheeled land vehicle, there is little induced drag due to the proximity of the ground plane preventing downwash behind the vehicle. However, production of trailing vortices, and indication of induced drag, is obvious in the case of wheeled vehicles with excessive exhaust emissions. It is probable that the condition also exists for sevs, although it has not been observed.

3.1.2 Momentum Drag

Assuming that a moving sev ingests cushion air which was formerly stationary and expels it equally around the vehicle, a net drag is encountered because of the air being accelerated to vehicle speed and expelled with zero average momentum.

In Elsley and Devereaux[5] it is suggested that momentum drag be calculated directly from vehicle speed and cushion fan mass throughflow rate. However, it has been the author's experience with Fan-tastic and its unique skirt design that flow from the cushion forward is almost halted, while the majority of the expelled air is directed to the sides and aft. The sharpness of the lower edge of the vehicle's bow skirt results in a lower flow discharge coefficient than exists at the sides and aft. The vehicle ram dynamic pressure is significant when compared to cushion pressure (1.6 lb/ft^2 as compared to a typical operating cushion pressure of 6 to 8 lb/ft^2). Operating experience has shown the possibility of running a vehicle with a specially tailored skirt with the bow skirt much nearer the water surface than is normal with light sevs. With flow leakage all but eliminated from the bow and forward quarters of the craft, it is possible to have a negative momentum drag; that is, cushion charging power can be recovered in the form of a net thrust (which is at lower efficiency than the main propulsor efficiency) with appropriate skirt design and vehicle operation.

3.1.3 Skirt Drag

3.1.3.1 Overland. As long as no extreme irregularities are encountered, overland skirt drag over most surfaces without vegetation is low enough to be insignificant.

However, if vegetation, discrete separate boulders, or a porous surface is to be traversed, the skirt tends to fill in leakage paths between salient surface projections. If the projections are significantly higher than the "daylight" clearance of the skirt, and the skirt is incapable of deforming the projections, skirt drag can be high enough to arrest the vehicle forward progress completely.

A practical minimum for daylight clearance for a recreational vehicle is an average 5/8 in., which is the case for Fan-tastic.

3.1.3.2 Overwater. Calculation of overwater friction drag is quite difficult as a definition of skirt wetted surface is required. Operating experience with Fan-tastic has shown that skirt friction drag is high in very smooth water, drops to lower values in a 1- to 2-in. chop, and then rises again as seas build. No numerical information is known in this area, although the author has estimated skirt wetted area as being between 1 and 4 ft^2 under various operating conditions by calculating a vehicle drag breakdown to yield a friction drag quantity. Friction drag is quite sensitive to vehicle loading as daylight clearance is altered.

Wave, or planeout, or "hump" drag is similar to the induced drag in airplanes. Solutions for this drag have been worked by Lamb[7] and others. All the solutions are reducible to the form below for the highest wavemaking drag, which occurs just before planeout:

$$\frac{W}{D} = K_W \frac{L}{H_c} \qquad (4)$$

where the constant K_W may vary depending upon vehicle planform effects.

The author finds that if a K_w of .15 is selected, a design vehicle static thrust can be selected on the basis of the lift-to-drag ratio, W/D, at hump determined from equation (4).

The vehicle velocity at which the maximum wave drag occurs can be determined from momentum considerations of the water flow underneath the vehicle as in reference (7). However, it usually suffices to assume that maximum wave drag occurs at a Froude number of 0.6, assuming the "hull" length to be the length of the air cushion. Wave drag for Fan-tastic at speed is less than a pound.

3.2 VEHICLE PERFORMANCE

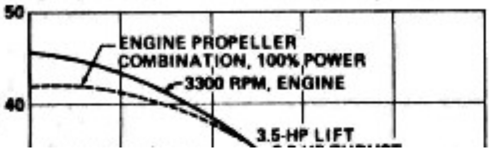
Vehicle performance was measured using a simple procedure. First, vehicle static thrust was measured along with engine shaft speed at maximum power. The vehicle was run to top speed in still air and engine shaft speed was again noted.

Assuming that the calculated design thrust for the propeller with the vehicle at speed was correct and that the propeller was operating at its best design performance, giving the slope of the thrust curve from analytics, a propeller thrust curve could be constructed for a given engine shaft speed. A complete family of propeller thrust curves could then be generated using turbomachinery affinity laws.

70

The vehicle was then operated at a given weight and engine speed, and the speed obtained was measured with a wind meter.

The vehicle drag is shown in figure 4. It should be noted that a small increase in gross weight has a marked effect on the hump in the drag curve, yet little effect on the top speed. In practical operations where wind and seas are involved, the reduction of daylight clearance at the higher loading has a definite effect on top speed, and a 3-in. chop could slow the vehicle 7 mph at a 250-lb payload loading, yet speed up the craft 2 mph at the 160-lb payload loading.



tip speeds are as high as 900 ft/sec. Frequently, leading edges of the propulsor are protected with steel.

Most lift fans used in these craft are small diameter plastic commercial axial flow units, but occasionally a centrifugal fan is driven by way of a belt reduction.

Figure 5 shows a sampling of these vehicles, taken from the author's personal records.

Vehicle (no. of places)	Thrust	Lift	Power
	English Manufactured Craft		
• Hoverhawk (one plus)	Two dir dr duct prop	1 indr dr cent	Three 2-cycle 48 tot hp
• Crossbow	One split flow dir dr		One 2-cycle

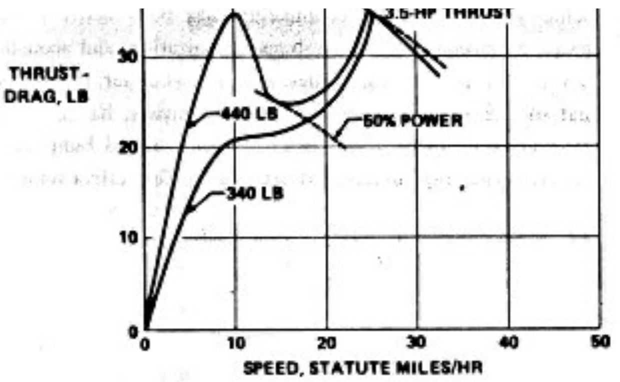


Figure 4. Estimated Thrust-Drag

A more exact picture of overall vehicle performance would require the use of tow tanks and wind tunnels of civilian and military agencies. Such data from more sophisticated tests could yield good drag breakdowns to provide baseline data for larger craft, but at this time interest in small sevs by such agencies is on the ebb.

4. RELATION TO EXISTING CONCEPTS

The current trend in these vehicles is to use multiple two-stroke engines of high power to separately direct drive lift and propulsion rotors. Occasionally, flow from a single direct drive rotor is ducted for both lift and thrust. Total horsepower for the vehicles, which are usually one place with limited capability with two aboard, ranges from 3 for nonplaning vehicles upward to over 50 total installed horsepower. However, the full horsepower of the engines is seldom used because of limitations posed by direct drive rotors.

The propulsors for these machines are generally of considerably smaller diameter than the 48-in. rotor used on Fan-tastic, and

Personal experience and the experiences of others have indicated poor reliability of these vehicles, principally caused by somewhat temperamental engines. Extreme noise levels caused by both engine exhausts and high rotor tip speeds are generally present.

5. CONCLUSIONS

The light sev can be built with considerably lower power requirements than has heretofore been assumed, if careful consideration is given to analytical aspects of design.

It is hoped that the success of such vehicles as Fan-tastic will rekindle interest in Government agencies which have the facilities for more rigorous practical investigation.

REFERENCES

(1) G. H. Williams, *Homebuilt Hovercraft*, Illiffe Transport Publications Ltd., 1967

(2) K. D. Wood, *Aircraft Design*, Johnson Publishing Company, Boulder, Colo., 1966

(three)	axial flow fan		135 hp
North American Manufactured Craft			
• Eglen Hoverbug (one plus)	One dir dr duct prop	One dir dr axial fan	Two 2-cycle 56 tot hp
• Air cycle (one plus)	One split flow axial flow fan		One 2-cycle 55 tot hp
• Hoverover (one plus)	Two dir dr duct prop	Two indir dr cent fan	Three 2-cycle 51 tot hp
• Spectra (one plus)	One dir dr prop	Two indir dr axial fan	Two 2-cycle 45 tot hp
• Airscat (one plus)	One indir dr duct prop	One indir dr axial fan	One 4-cycle 55 hp
English Homebuilt Craft			
• Caliban 3 (one)	One dir dr prop	One dir dr axial fan	Two 2-cycle 33 tot hp
• Crested Wren (one plus)	One dir dr prop	One dir dr axial fan	Two 2-cycle 32 tot hp
North American Homebuilt Craft			
• Dobson Air Dart (one)	One split flow indir dr axial fan		One 2-cycle 10 to 20 hp
• Fan-Jet Skimmer (one) (nonplaning)	One split flow indir dr axial fan		One 2-cycle 10 hp
• Bartlett Flying Saucer (one) (stationary platform)		One dir axial flow	One 4-cycle 3 hp

Figure 5. Thrust, Lift, and Power Plant Data for Contemporary Sevs

(3) R. L. Trillo, "An Empirical Study of Hovercraft Propeller Noise," *Journal of Sound and Vibration*, 1966

(4) D. G. Shepherd, *Principles of Turbomachinery*, The MacMillan Co., New York, 1957

(5) G. H. Elsley and A. J. Devereaux, *Hovercraft Design and Construction*, Cornell Maritime Press, Inc., Cambridge, Maryland, 1968

(6) S. F. Hoerner, *Fluid Dynamic Drag*, published by S. F. Hoerner, 1967

(7) Sir Horace Lamb, *Hydrodynamics*, Cambridge University Press

BIOGRAPHY

Barry Palmer, a graduate of the University of California at Berkeley in mechanical engineering, has been active in the design of turbomachinery, systems optimization, and acoustics in various aerospace companies. As a homebuilder, he was the first of the Rogallo wing hang glider activists, having flown these craft in 1961, and has since designed and built many powered parawing aircraft, airboats, and surface effect vehicles.

It's in the Numbers

Below is a numerical spread sheet model of the straight line performance of a surface skimmer.

SEV ANALYSER, PALMER, 11-93

WITH ALTITUDE COMP

WORST CASE

1.42 561

SEV ANALYSER INPUT09-94		
NO PROPELLERS	1	
NO FANS	1	
SKIRT WIPE DRAG COEF.	.000150	
SEV AERO DRAG COEFF.	0.8	
POWER SPLIT	0.52	
TOT SEA LEV POWER	11.0	HP
PROPELLER DIA	48	IN
SEV OPERATING WEIGHT	470	LB
CUSHION WIDTH	5.5	FT
HULL LENGTH	10	FT
FAN DIAMETER	20	IN
THRUST INSTLL. FACTOR	.98	
FAN LOSS COEFF.	1.5	

OVERALL PERFORMANCE

GEN'L PERF

CUSH PERF

LOW COMP

HIGH COMP

COMP PLOT

WT BAL CALC

WT BAL DWG

DIRECTORY:

WT BUDGET AT K1
DRAG COMP AT K28
PRELIMS AT 19
CUSHION AT 30
PERF AT 49
PLOT AT 108
HULL SIZE AT L66

ALT	0 FT
TEMP	68 DEG F
.00239	DENS
C POW	11.0 HP

UPDATED 09-94 15DEG ULTRA 3 BL 1438 PRPM,FAN 2930 RPM

VANGUARD SEV 18HP, 7 X 14

CALCULATED VALUES					
SEV POWER LOADING	42.6	LB/HP	FAN POWER	5.2931	HP
PROPELLER POWER	5.7342	HP	SEV BASE AREA	46.215	FT^2
TOTAL STATIC THRUST	56.5	LB	SEV CUSHION PRESSURE	10.2	PSF
PROPELLER SHAFT SPEED, 15 DEG	1890	RPM	SEV HUMP SPEED	7.0	MPH
DISC LOADING	0.46	HP/FT^2	FAN THROUGHFLOW AREA	1.85	FT^2
PROPELLER BLADE TIP SPEED	396	FT/SEC	SEV CUSHION PERIPHERY	29.1	FT
AERO FRONT AREA	9.075	FT^2	CUSHION EXIT VELOCITY	92.4	FT/SEC
DRAG AREA	7.26	FT^2	BOW LIFT SPEED	58.452	MPH

WEIGHT BUDGET

STRUCTURE	
	HULL
	DECK
	SKIRT
POWER	
	ENGINE
	DRIVE
	DRIVE FR.
	ROTORS I
	GUARD
	BATTERY
MISCELLANEOUS	
	GAS TAN
	SOFT TOI
	CONTROL
	RUDDERS
	FIRE
	WINDSCR
	ANCHOR
PAYLOAD	
	USEFUL
	USEFUL
	FUEL

CUSHION PERFORMANCE

CUSHION EFF	VOL FLOW (CFS)	THROUGH V FT/SEC	THROUGH Q LB/FT^2	REQ'D AERO EFF.	HEIGHT IN
30	86	46	3.84	41	0.38
32	92	49	4.36	46	0.41
34	97	52	4.92	50	0.43
36	103	56	5.51	56	0.46
38	109	59	6.14	61	0.49
40	115	62	6.81	67	0.51
42	120	65	7.50	73	0.54
44	126	68	8.23	80	0.56
46	132	71	9.00	87	0.59
48	137	74	9.80	94	0.61
50	143	77	10.63	102	0.64
52	149	80	11.50	111	0.66
54	155	83	12.40	120	0.69
56	160	86	13.34	129	0.72
60	172	93	15.31	150	0.77

RETURN

EMPTY CENTER OF
LIGHT WT CENTER
WEIGHT BUDGET

STRUCTURE	
	HULL
	DECK
	SKIRT
POWER	
	ENGINE
	DRIVE
	DRIVE FR.
	ROTORS I
	GUARD
	BATTERY
MISCELLANEOUS	
	GAS TAN
	SOFT TOI
	CONTROL
	RUDDERS
	FIRE
	WINDSCR
	ANCHOR

SEV STRAIGHT LINE PERFORMANCE

THRUST/DRAG AT HUMP= 1.42

REFUSAL GROSS WEIGHT= 560.58

SPEED	ADVANCE	THRUST	PROP	THRUST	TOTAL	AERO	WIPE	WAVE	AERO	DRAG (LB)

MPH	RATIO	COEFF	EFF	LB	DRAG	DRAG	DRAG	DRAG
7.0	.081	.131	.171	52.9	37.2	0.9	0.7	35.552
0	.000	.140	.000	56.5	0.0	0	0.0	0.0
1	.012	.139	.026	56.0	0.0	0.0	0.0	
2	.023	.137	.052	55.5	10.3	0.1	0.1	10.2
3	.035	.136	.077	55.0	15.6	0.2	0.1	15.3
4	.047	.135	.101	54.5	21.0	0.3	0.2	20.4
5	.058	.134	.125	53.9	26.4	0.5	0.4	25.5
6	.070	.132	.149	53.4	31.8	0.7	0.5	30.6
7	.081	.131	.172	52.8	36.8	0.9	0.7	35.2
8	.093	.129	.194	52.3	29.0	1.2	0.9	26.9
9	.105	.128	.216	51.7	24.0	1.5	1.2	21.3
10	.116	.127	.238	51.1	20.5	1.9	1.4	17.2
11	.128	.125	.258	50.5	18.2	2.3	1.7	14.2
12	.140	.124	.279	49.9	16.7	2.7	2.1	12.0
13	.151	.122	.298	49.3	15.8	3.1	2.4	10.2
14	.163	.121	.317	48.7	15.3	3.7	2.8	8.8
15	.175	.119	.335	48.1	15.1	4.2	3.3	7.7
16	.186	.117	.353	47.5	15.2	4.8	3.7	6.7
17	.198	.116	.370	46.8	15.5	5.4	4.2	6.0
18	.210	.114	.386	46.2	16.0	6.0	4.7	5.3
19	.221	.113	.402	45.5	16.7	6.7	5.2	4.8
20	.233	.111	.417	44.8	17.5	7.5	5.8	4.3
21	.244	.109	.431	44.2	18.5	8.2	6.4	3.9
22	.256	.108	.445	43.5	19.6	9.0	7.0	3.6
23	.268	.106	.458	42.8	20.8	9.9	7.6	3.3
24	.279	.104	.470	42.1	22.0	10.7	8.3	3.0
25	.291	.102	.481	41.4	23.4	11.6	9.0	2.8
26	.303	.101	.492	40.6	24.9	12.6	9.8	2.5
27	.314	.099	.501	39.9	26.5	13.6	10.5	2.4
28	.326	.097	.510	39.2	28.1	14.6	11.3	2.2
29	.338	.095	.518	38.4	29.9	15.7	12.2	2.0
30	.349	.093	.526	37.7	31.7	16.8	13.0	1.9
31	.361	.091	.532	36.9	33.6	17.9	13.9	1.8
32	.373	.090	.538	36.2	35.6	19.1	14.8	1.7
33	.384	.088	.543	35.4	37.6	20.3	15.7	1.6
34	.396	.086	.547	34.6	39.7	21.5	16.7	1.5

RETURN

ED (S PAYLOAD

USEFUL

FUEL

SEV DRAG COMPONE

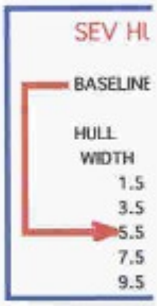
SCOUT 5.5 X 10 12HP

SEV O

VANGUAI

STILL DE

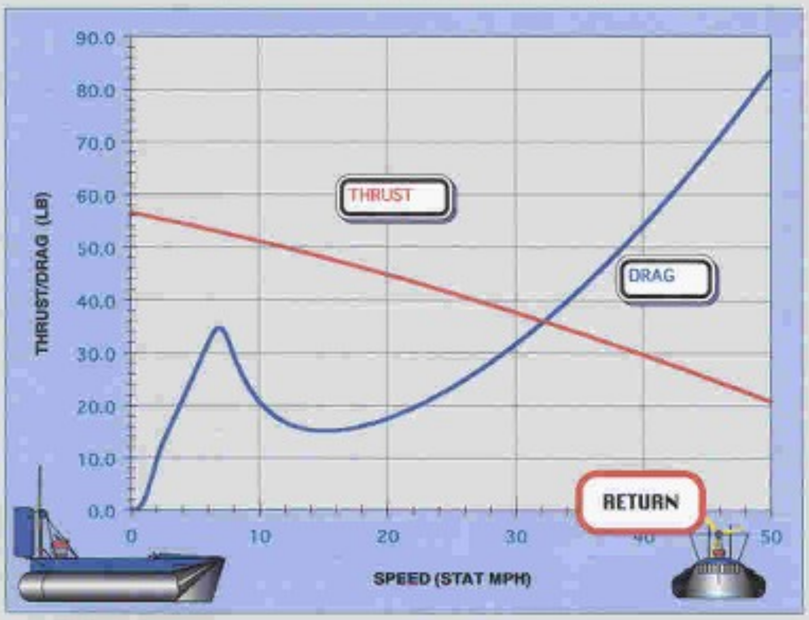
DRAG (LE



RETURN

STRAIGHT LINE PERFORMANCE

VANGUARD SEV 18HP, 7 X 14



The spreadsheet was generated from the equations shown in the first paper. The upper left section is the input file, (for the Sevtec Scout) where the surface skimmer is defined in the simplest of terms. The items backgrounded in yellow are absolutes, while the blue areas are input generated through test experience with the craft being studied or from experience from past craft. (To the right are "buttons" for navigating through the spreadsheet, which extends well beyond what is shown here, and have nothing to do with the analysis.) The blue block just below the input file is the results of calculating various overall surface skimmer parameters as generated by the input file data. The next block down shows the cushion performance. The red horizontal line is positioned at the fan maximum expected efficiency to pick up a daylight height under the skirt running surface. (A more realistic place to put the line is just below 70% giving a lesser height than shown.) This number is a relative number, or it is used to compare craft, as there are other functions involved, (such as under skirt discharge coefficient) and is not an absolute measurement of the actual daylight under the skirt. The last block is thrust and drag breakdown, and a plot of propeller thrust and surface skimmer drag is shown. The top smooth overwater speed is where thrust crosses over the drag curve. This is only one of the spreadsheets used by the author to design craft. More of the spreadsheet (for Sevtec Vanguard prototype) follows. Decisions involving propeller and fan sizing, cushion size and craft powering can now be juggled with weight and trim analysis and lots of experience in designing, building and operating some two dozen different craft.

WORST CASE

EMPTY CENTER OF GRAVITY AT STATION 108 IN 72.1 PERCENT
GROSS WT CTR OF GRAVITY AT STATION 91 IN 60.8 PERCENT

WEIGHT BUDGET			PCT GROSS WT		STATION	MOMENT	GRP LOC
STRUCTURE		137		.18			84
HULL	92		.32		84	7728	
DECK	18		.06		84	1512	RET
SKIRT	27		.09		84	2268	
POWER		132		.18			138
ENGINE	74		.25		133	9842	
DRIVE	20		.07		144	2880	
DRIVE FRAMES	19		.07		144	2736	
ROTORS FAN/PROP	12		.04		144	1728	
GUARD	7		.02		140	980	
BATTERY	0		.00		0	0	
MISCELLANEOUS		22		.03			82
GAS TANK	4		.01		100	400	
SOFT TOP, SEATS	8		.03		65	520	
CONTROLS	3		.01		40	120	
RUDDERS	4		.01		155	240 230 220 210	
FIRE	3		.01		50	150	
WINDSCREEN	0		.00		0	0	
ANCHOR	0		.00		0	0	
PAYLOAD		458		.61			80
USEFUL FRONT SEAT	210		.28		65	13650	
USEFUL AFT SEAT	210		.28		92	19320	
FUEL	38		.05		100	3800	
EMPTY WEIGHT		291		1.00			
GROSS WEIGHT		749					

EMPTY CENTER OF GRAVITY AT STATION 108 IN 72.1 PERCENT
LIGHT WT CENTER OF GRAVITY AT STATION 92 IN 61.4 PERCENT

WEIGHT BUDGET			PCT GROSS WT		STATION	MOMENT	GRP LOC
STRUCTURE		137		.29			84
HULL	92		.32		84	7728	
DECK	18		.06		84	1512	RETURN
SKIRT	27		.09		84	2268	
POWER		132		.28			138
ENGINE	74		.25		133	9842	
DRIVE	20		.07		144	2880	
DRIVE FRAMES	19		.07		144	2736	
ROTORS FAN/PROP	12		.04		144	1728	
GUARD	7		.02		140	980	
BATTERY	0		.00		0	0	
MISCELLANEOUS		22		.05			82
GAS TANK	4		.01		100	400	
SOFT TOP, SEATS	8		.03		65	520	
CONTROLS	3		.01		40	120	

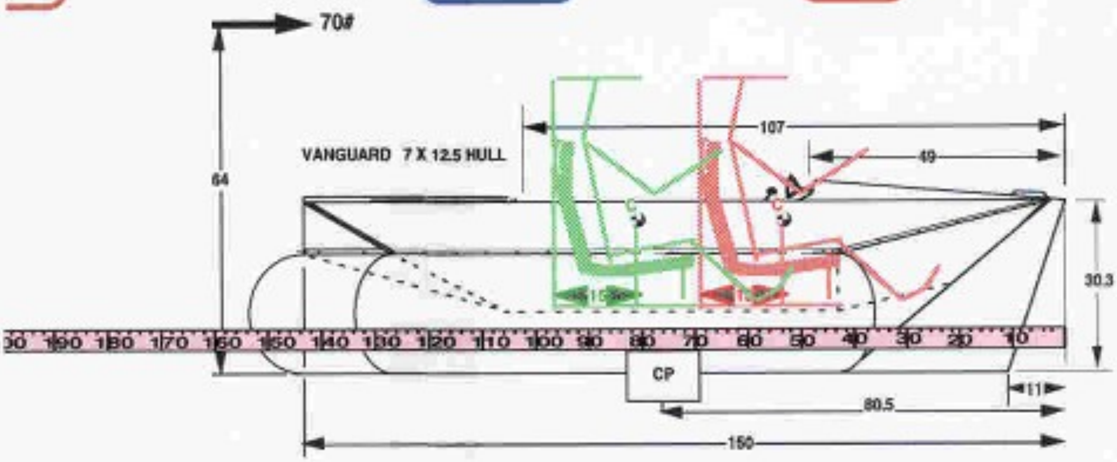
	RUDDERS		4		.01		155	620
	FIRE		3		.01		50	150
	WINDSCR EEN		0		.00		0	0
.B)	ANCHOR		0		.00		0	0
PAYLOAD				175		.38		6
	USEFUL	FRONT SEAT	160		.34		62	9920
MPONE	FUEL		15		.03		100	1500
2HP		EMPTY WEIGHT		291				
		LIGHT WEIGHT		466				

SEV OVER WATER DRAG COMPONENTS

VANGUARD SEV 18HP, 7 X 14 AERO DRAG

TION

RN WORST CASE RETURN

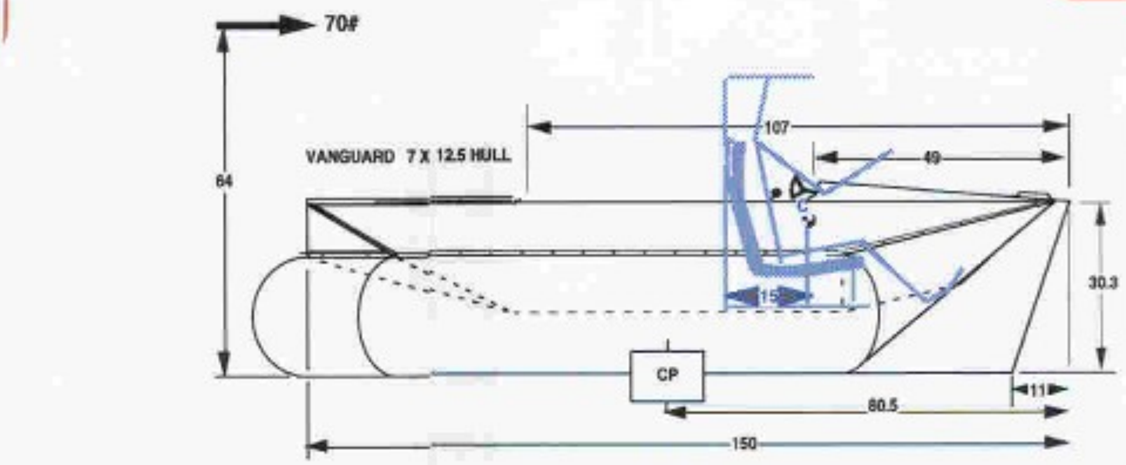


MODIFY BALANCE FOR FULL STATIC THRUST

THRUST (LB)	VERTICAL (IN)	MOMENT	MOMENT/WEIGH	CP	APPAREN BALANCE	DELTA
70	64	4480	006	80.5	85	-5

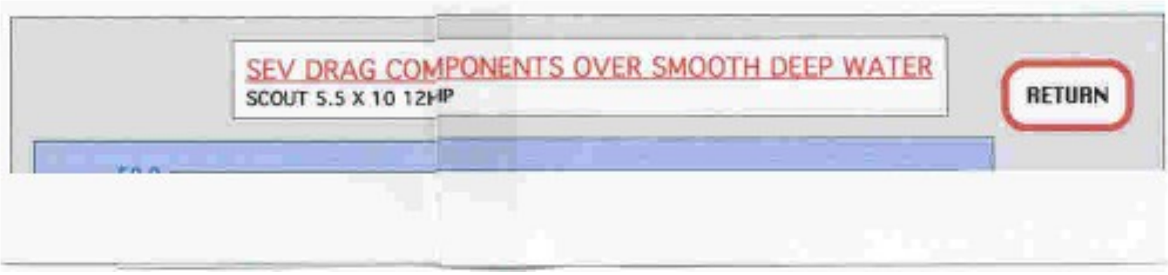
TION

RETURN



MODIFY BALANCE FOR FULL STATIC THRUST

THRUST (LB)	VERTICAL (IN)	MOMENT	MOMENT/WEIGH	CP	APPAREN BALANCE	DELTA
70	64	4480	010	80.5	82	-2


SEV DRAG COMPONENTS OVER SMOOTH DEEP WATER
SCOUT 5.5 X 10 12HP
RETURN