Marine Systems Supplement

Waterjet Propulsion for Marine Vehicles

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The principle of waterjet propulsion has never been seriously considered in the past as a means of propelling large ships because more efficient methods were available. For high-speed ships, and for certain other applications, the interest in the waterjet has been renewed. For the design of an optimum waterjet propulsion system it is necessary to consider all factors that influence the over-all efficiency. These factors are kinetic energy loss in the jet, increased external drag due to duct system, increased external drag due to propulsion system weight, internal pressure losses in the duct system, power required to raise the water from sea level to the jet nozzle exit, and pump efficiency. The relationship between these factors is determined by the internal and the external power balance. The resulting optimum jet velocity ratio, required for minimum shaft horsepower, is given by $(V_j/V_0)_{opt} = C_1 + (C_1^2 \times C_2)^{1/2}$. The constants C_1, reflecting the external losses, and C_2, reflecting the internal losses, can be calculated for a given system configuration without determining beforehand its absolute dimensions. System layouts for high-speed hydrofoil ships and displacement ships are discussed.

Introduction

THE principle of the waterjet, though rather old in concept, has never been considered seriously in the past for the propulsion of ships, since more efficient methods were available. With the introduction of high-speed ships, the interest in waterjet propulsion has been renewed. This is primarily because a more favorable jet velocity ratio V_j/V_0 can be achieved, resulting in a more acceptable value of the ideal propulsive efficiency[1]:

$$\eta_{pi} = 2/(1 + V_j/V_0) \quad (1)$$

Since the installed horsepower required for ship propulsion is of major importance to the success of this mode of operation, it is necessary to consider all factors associated with this propulsion concept and to evaluate their relative influence on the over-all effectiveness.

System Optimization

The thrust of a waterjet can be obtained with various combinations of waterflow rate and nozzle exit velocity. Equation (1) shows that the ideal propulsive efficiency is increased by using a lower jet velocity, which corresponds to a high value of waterflow rate for a given thrust. However, a high waterflow rate requires a ducting system with large cross-sectional areas to achieve acceptable values of internal flow velocity and system pressure drop. For hydrofoil ships, the use of these ducts results in prohibitive values of both external drag and system weight. It is necessary therefore to balance the internal flow losses of a given system configuration against the associated external hydrodynamic drag and system weight, while taking into account the resulting ideal propulsive efficiency. The tradeoff factors that influence the power required and the system configuration are kinetic energy loss in the jet, additional external drag due to duct system, additional external drag due to propulsion system weight, internal pressure losses in the duct system, power required to raise the water from sea level to the jet exit, and pump efficiency. Two methods of system optimization, enabling the determination of the jet velocity ratio to achieve 1) minimum installed shaft horsepower and 2) maximum payload fraction for a given mission are discussed in the following paragraphs.

Minimum Power

This analysis utilizes the concept of a "basic ship," which is defined as a complete vessel carrying the desired payload but without a propulsion system. In the case of a hydrofoil, minimum struts and foils, necessary to accommodate the weight of the basic ship, are included. One can assume that this vessel is being towed at the design speed. The purpose of this approach is to separate the total system into a "basic vehicle" and a propulsion system. Accordingly, as the propulsion system is added, all losses associated with making the vessel self-propelled can be taken into account. The over-all efficiency, defined as the ratio of the productive work rate E_s of the basic ship at velocity V_0 and the power supplied by the prime mover E_{pp} or

$$\eta_0 = E_s/E_{pp} \quad (2)$$

must be a maximum.

The development of the over-all efficiency η_0, as expressed in Eq. (2), is based on the internal and external power balance of the waterjet system. The internal power balance of the system requires that

$$E_{\text{out}} - E_{\text{in}} = E_{\text{pu}} - E_f - E_l \quad (3)$$

which states that the difference in power between the fluid leaving and that entering the system ($E_{\text{out}} - E_{\text{in}}$) is equal to that provided by the pump E_{pu} minus that lost in internal friction E_f and elevation of the water from sea level to the jet

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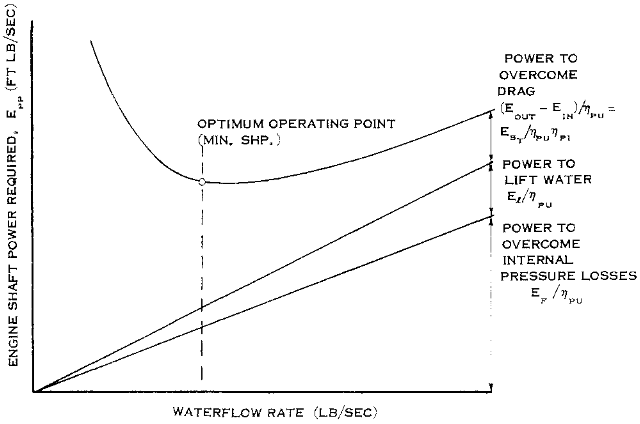

Fig. 1 Internal power balance.

nozzle exit E_l. This also can be written as

$$E_{pp} = E_{pu}/\eta_{pu} = (E_{out} - E_{in} + E_f + E_l)/\eta_{pu} \qquad (4)$$

in which E_{pp} = engine shaft power and η_{pu} = pump efficiency.

This relationship is schematically depicted in Fig. 1 where the engine shaft horsepower is plotted vs the waterflow rate. The external power balance of the system requires that

$$\eta_{pi}(E_{out} - E_{in}) - E_s + E_d + E_w = E_{s_t} \qquad (5)$$

This equation states that the net power available for propulsion $\eta_{pi}(E_{out} - E_{in})$ is equal to the power required for propelling the basic ship E_s increased by that required to overcome the additional external drag due to the nacelles, thicker struts, etc., E_d, and by that required to overcome the drag due to the additional system weight E_w, the sum total of which is equal to the total power required E_{s_t}. This relationship is shown schematically in Fig. 2.

At the point where the shaft horsepower required to propel the ship at a given forward speed is a minimum, the external drag and internal flow losses are balanced and the maximum over-all efficiency is achieved. Substitution of Eqs. (4) and (5) into Eq. (2) results in the following expression for the over-all efficiency:

$$\eta_0 = \eta_{pu}\eta_{pi}\{1 - [(E_f + E_l)/E_{pu}] - [(E_w + E_d)/\eta_{pi}E_{pu}]\}$$

In this equation, the term between the brackets involves the various internal and external power losses attributable to the waterjet system and therefore can be considered as a system efficiency η_s, which itself is a function of η_{pi}. Equation (2) then may be written as

$$\eta_0 = \eta_{pu}\eta_{pi}\eta_s \qquad (6)$$

By expressing these efficiencies as a function of the variable jet velocity ratio V_j/V_0, Eq. (6) can be differentiated with respect to this ratio and equated to zero. The resulting optimum jet velocity ratio then is given by

$$(V_j/V_0)_{opt} = C_1 + (C_1^2 + C_2)^{1/2} \qquad (7)$$

in which

$$C_1 = 1 + (klg/V_0^2\bar{V})(D/L)_f + (Cd_a/2\bar{V})$$

reflects the external losses and

$$C_2 = \Sigma(k_t + 4fl/d)\bar{V}^2 + (2gh/V_0^2) - 1$$

reflects the internal losses. In these equations,

k	=	proportionality constant, relating duct volume to duct length and inlet area
$\bar{V}$	=	inlet velocity ratio, V_i/V_0
V_0	=	forward speed
$(D/L)_f$	=	drag-lift ratio of foil system
Cd_a	=	coefficient of additive drag based on inlet area
$\Sigma(k_t + 4fl/d)$	=	duct pressure loss coefficient
h	=	nozzle exit elevation

These constants can be determined for a given system configuration without specifying beforehand its absolute dimensions. Their influence on the over-all efficiency is shown in Fig. 3. The values of the system constants for a 550-ton hydrofoil ship are also indicated.

After calculating the optimum velocity ratio, the following equations can be used to determine the various efficiencies:

Ideal Propulsive Efficiency

$$\eta_{pi} = 2/(1 + V_{opt})$$

Optimum Over-All Efficiency

$$\eta_{0\,opt} = \eta_{pu}/V_{opt}$$

System Efficiency

$$\eta_s = (1 + V_{opt})/2V_{opt}$$

in which $V_{opt} = (V_j/V_0)_{opt}$. The pump efficiency η_{pu} is assumed constant at the design condition. The maximum attainable values of η_s, η_{pi}, and η_0 are shown in Fig. 4 for various values of V_{opt}, assuming a pump efficiency $\eta_{pu} = 0.90$.

The equations used in this analysis are based necessarily on generalized assumptions. It does offer, however, a more correct approach to the problem than those methods whereby, for predetermined water passage dimensions, a balance is found between internal flow losses due to friction and elevation of the water and the power losses associated with the jet velocity. The additional advantage of this type of analysis is that since the equations derived include all losses accountable to the propulsion system, a tradeoff may be made for each part of the water duct. The minimum shaft horsepower for each configuration can be determined, and the best for a particular application thus is defined. Also it enables a valid comparison between various methods of propulsion, utilizing the same "basic ship."

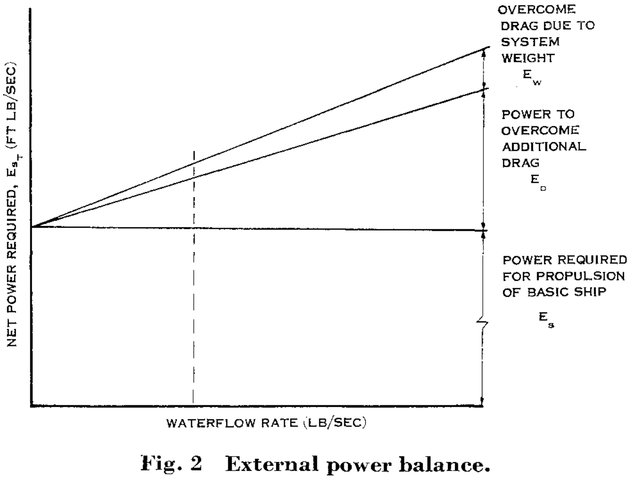

Fig. 2 External power balance.

Maximum Payload

The previous analysis outlined the calculation of the minimum shaft horsepower to propel a ship at a given speed V_0 regardless of the duration of its mission. When the powerplants are matched properly with the power required, the fuel quantity used during such a mission is also a minimum. For a given application this does not result necessarily in a maximum payload, since the system weight, of which the water in the ducts forms a major part, is not of course at a minimum. Ships that perform missions of short duration therefore will achieve a higher payload when the fuel economy is sacrificed partially in order to obtain a lower system weight.

The optimization of a waterjet system with respect to payload for a given ship gross weight and mission requirements can be achieved in the following manner. The basic weight build-up of a ship states that

$$G_t = G_p + G_s + G_f + G_w + G_b \qquad (8)$$

in which

G_t = total weight of ship (const)
G_p = payload
G_s = propulsion system weight
G_f = mission fuel weight
G_w = weight of water in the system
G_b = weight of ship structure (const)

With the exception of the structural weight, each component weight is considered variable in the analysis and can be expressed as a function of the power required and subsequently the jet velocity ratio.

The propulsion system weight G_s is the summation of the weight of engines and accessories, pumps, and ducts

$$G_s = G_{\rm eng} + G_{\rm pumps} + G_{\rm ducts}$$

with $G_{\rm eng} = K_3 shp$, $G_{\rm pumps} = K_4 shp$, $G_{\rm ducts} = K_5(G_{\rm eng} + G_{\rm pump})$, $G_f = K_1 shp$, $G_s = (1 + K_5)(G_{\rm eng} + G_{\rm pumps})$, and $G_w = K_2 l W_w / V_i$, in which l = length of water flow passage, W_w = water flow rate, V_i = inlet velocity, K_2 = proportionality constant, and $K_1 = SFC \times t$.

Equation (8) can be written as

$$\eta = G_p/G_t = a - (1/G_t)(K_6 + K_1){\rm shp} - (K_2 l W_w / G_t V_i) \qquad (9)$$

In this equation, $a = (G_t - G_b)/G_t$ and $K_6 = (1 + K_5)(K_3 + K_4)$.

Expressing the variables in Eq. (9) as a function of the jet velocity ratio V, differentiating this equation with respect to V and equating to zero, results in the following expression for

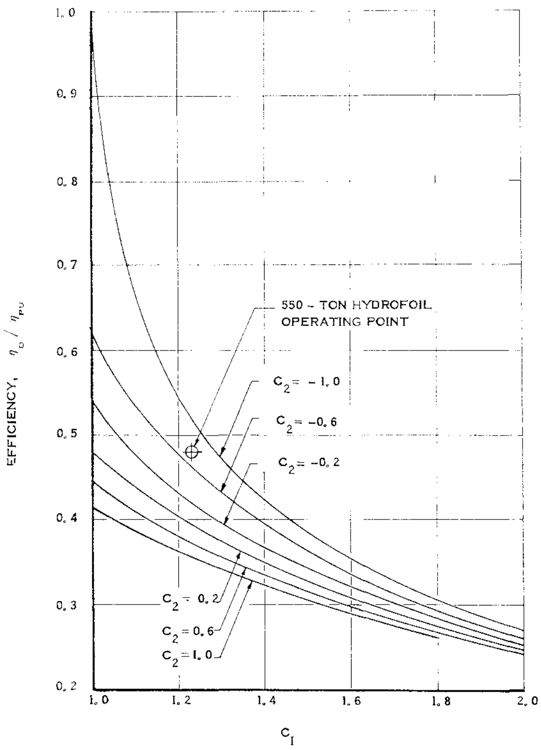

Fig. 3 Optimum over-all efficiency vs system constants C_1 and C_2.

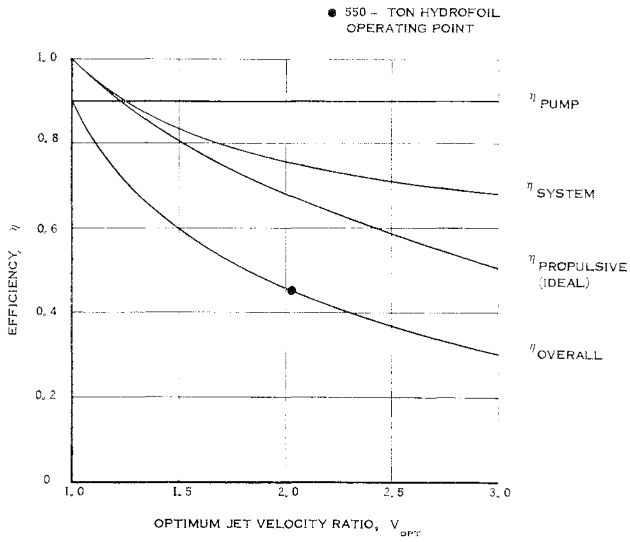

Fig. 4 Maximum efficiency vs optimum jet velocity ratio.

the optimum jet velocity ratio:

$$V_{\rm opt} = \frac{V_j}{V_0} = \left(1 + \frac{Cd_a}{2\bar{V}}\right) \pm \left[\frac{Cd_a}{\bar{V}} + \frac{Cd_a^2}{4\bar{V}^2} + \Sigma_i\left(K_i + \frac{4fl}{d}\right)\bar{V}^2 + \frac{2gh}{V_0^2} + \frac{2K_2 lg\eta_{pu}}{\bar{V}V_0^3(K_6 + K_1)}\right]^{1/2} \qquad (10)$$

Figure 5 shows the variation of optimum jet velocity ratio as a function of the mission time for a 550-ton hydrofoil ship. Insertion of the expression for $V_{\rm opt}$ given by Eq. (10) into the relationship previously derived, the component weight fractions associated with this jet velocity ratio are given as

$$G_p'/G_t = a - [V_0(K_6 + K_1)(D/L)/\eta_{pu}]V_{\rm opt}$$

$$\frac{G_f'}{G_t} = \frac{K_1(D/L)V_0}{\eta_{pu}}\left[V_{\rm opt} - \frac{K_2 lg\eta_{pu}}{\bar{V}V_0^3(K_6 + K_1)R}\right]$$

$$\frac{G_s'}{G_t} = \frac{K_6(D/L)V_0}{\eta_{pu}}\left[V_{\rm opt} - \frac{K_2 lg\eta_{pu}}{\bar{V}V_0^3(k_6 + K_1)R}\right]$$

$$G_w'/G_t = K_2 gl(D/L)/\bar{V}V_0^2 R$$

in which $R = V_{\rm opt} - (Cd/2\bar{V}) - 1$. Figure 6 shows these component weight fractions for the 550-ton hydrofoil ship for various values of mission duration.

Results of the two methods of system optimization applied to the forementioned ship for a mission time of 6.5 hr indicate

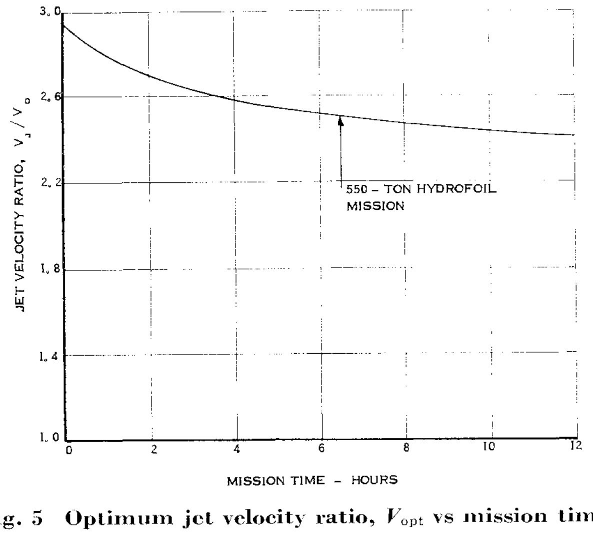

Fig. 5 Optimum jet velocity ratio, $V_{\rm opt}$ vs mission time.

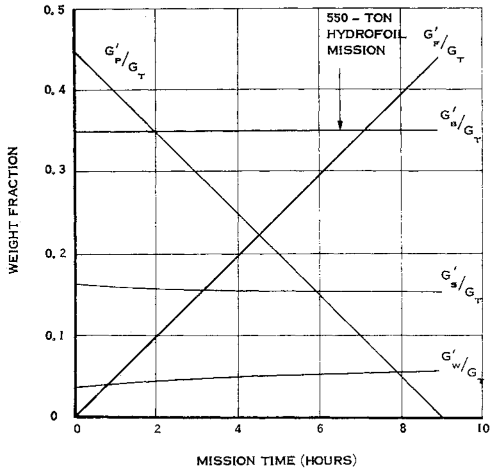

Fig. 6 Weight fractions vs mission time.

that the payload fraction can be increased from 10 to 12% of the gross weight by optimizing the system for maximum payload. However, the required shaft horsepower also will be increased.

Thrust Vectoring and Control

To use the installed shaft horsepower more effectively, the jet thrust vector should be inclined downward to provide a vertical lift component. Thereby the effective ship weight and foil drag are reduced for a small decrease in net horizontal thrust. The optimum thrust deflection angle can be found from the balance of horizontal and vertical forces acting on the ship.

Horizontal force equilibrium requires that during steady-state operation

$$D = aL + D_0' = T \cos\theta \qquad (11)$$

in which

D = total drag
a = local slope of lift/drag curve
L = total lift
D_0' = "zero lift" drag
T = gross thrust
θ = deflection angle

For vertical equilibrium,

$$L + T \sin\theta = W \qquad (12)$$

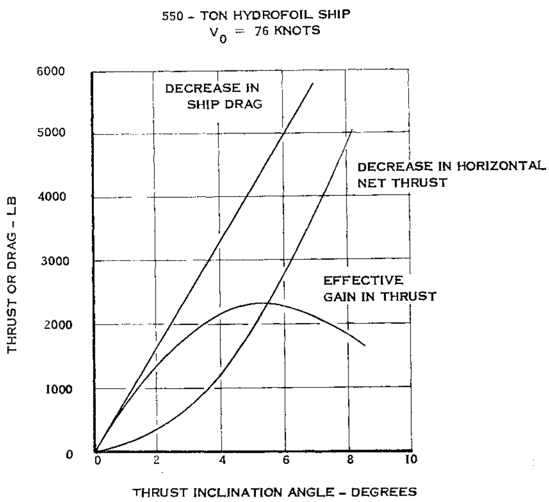

Fig. 7 Effect of exit thrust inclination.

in which W = total ship weight. Combining Eqs. (11) and (12) gives

$$L = (T \cos\theta - D_0')/a \qquad (13a)$$

or

$$T \cos\theta + aT \sin\theta - aW - D_0' = 0 \qquad (13b)$$

Taking the partial derivative with respect to T and θ and equating to zero results in

$$\tan\theta = a = (D - D_0')/L$$

which, in words, states that the tangent of the optimum deflection angle is equal to the local slope of the drag-lift relationship of the complete ship.

For the 550-ton vehicle, this angle is approximately 5.5° to the horizontal. Figure 7 shows that this inclination results in the maximum excess of horizontal net thrust over total drag. A further development of jet deflection makes use of the jet thrust for steering and thrust reversing. This allows the elimination of drag producing appendages such as the rudder while providing equal or better turning capability. An advanced concept studied by Lockheed and shown in Fig. 8 is the vectored thrust principle employing two jet nozzles. Simultaneous deflection will give pitch control, whereas differential deflection will give a powerful roll control couple. Outward deflection of the jet in the horizontal plane will give yaw control. Location of the jets in the bow will have a distinct advantage since the yaw force partially provides the required centripetal force while at the same time inducing a proper heeling moment. Thrust reversal is accomplished with clamshells at each nozzle exit.

Propulsion System Design and Integration

General Design Considerations

The internal flow system must perform several functions. The flow must be inducted into the system, diffused, turned, manifolded into the pumps, raised in pressure, collected from the pumps, and finally discharged overboard as shown schematically in Fig. 9 for both a displacement and a hydrofoil ship. The layout of the internal flow ducts has a major influence on the over all performance of the vehicle. For example, in the case of the 550-ton hydrofoil ship, a 1.0 psi loss in total pressure in the duct system is equivalent to a loss of approximately 260 hp during cruise operation. To reduce the weight of the water captured in the system, the flow path should be as short as possible using local flow velocities dictated by the internal-external loss tradeoff while preventing flow cavitation. Furthermore, existing structure should be used to minimize additional system weight and external drag. The design of important system components is discussed below in general terms for application to a hydrofoil ship.

Inlets

The location and type of inlet used in waterjet propulsion systems is of great importance. The location should be such

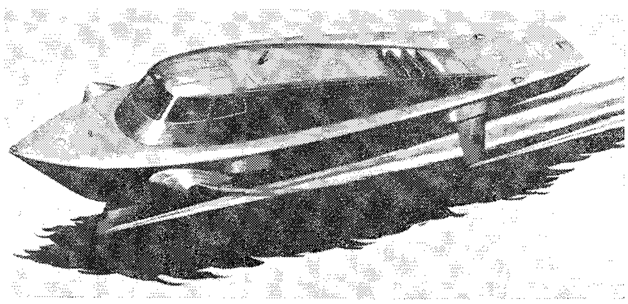

Fig. 8 Hydrofoil test craft with thrust vector control.

that full advantage is taken of the submergence level of other necessary structure such as oils and struts. It should not interfere, however, with the flowfield of either component, nor should it increase the draft of the ship. On the other hand, the inlet flow field should not be distorted by that of the strut or foil regardless of angle of attack or yaw. In addition, a high inlet total pressure is mandatory, and no flow cavitation or separation should occur anywhere in the system. In meeting these requirements the use of a ram-type inlet in a nacelle located at the strut-foil intersection offers distinct advantages. Since a faired body is required at this junction to minimize interference drag, the location of the inlet and nacelle at this point will cause only a minimum increase in form and friction drag. Locating the inlet plane well forward of the strut and foil minimizes the influence of the upwash due to the foil. An inlet total pressures ratio P_{t1}/P_{t0} on the order of 0.99 can be achieved[2] at inlet velocity ratios between 0.5 and 1.0. This inlet velocity ratio V_i/V_0 is selected by considering both the external and the internal flow. To prevent cavitation on the nacelle internal lip, a value close to unity is desirable. By having an inlet velocity ratio less than unity, the velocity of the flow entering the nacelle is reduced efficiently, thereby minimizing the flow turning problems in the nacelle-strut elbow. For the 550-ton hydrofoil ship design study, a base vented nacelle with a ram inlet having an inlet velocity ratio of 0.68 during cruise operation was selected since a compromise was necessary to meet the takeoff condition without having to resort to auxiliary inlets. The DTMB 4162 profile[3] is used for the internal lip contour, because internal flow system tests showed that, at high values of inlet velocity ratio, as occurs during low forward speed, this profile shape is superior to a lemniscate with the same contraction ratio and contributes to achieve a uniform velocity distribution. Figure 10 shows a $\frac{1}{10}$ scale model of the 550-ton hydrofoil inlet to be used during testing of the internal-external flow.

Nacelle Diffuser

The inlet should be followed by a cylindrical duct with a length of approximately one inlet diameter to dampen irregularities in the velocity close to the duct wall. Downstream of this section a diffuser, either conical or exponential, can be used to reduce the flow velocity to an acceptable value before it enters the nacelle elbow.

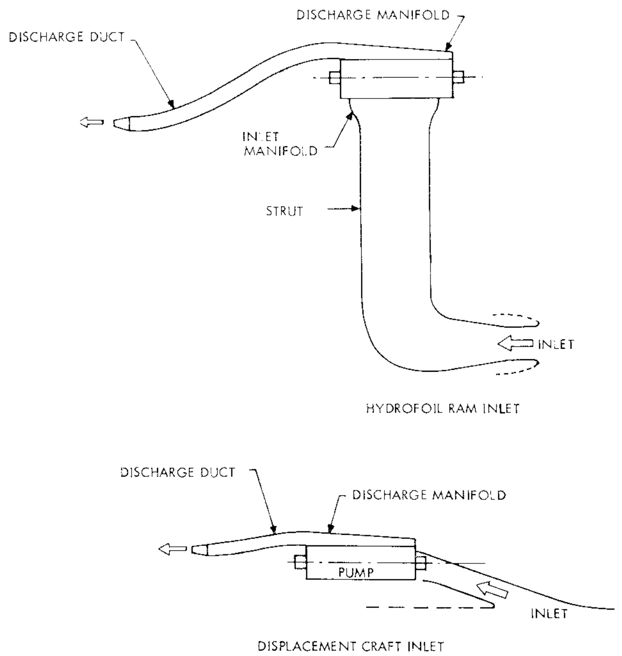

Fig. 9 Schematic duct configurations.

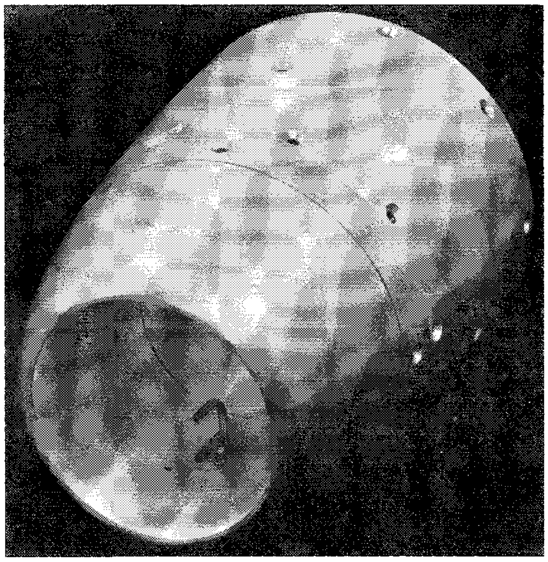

Fig. 10 Model of 550-ton hydrofoil inlet.

Nacelle Elbow

This system component poses a design problem since it is used not only to turn the flow through 80° to 90°, but also is used to change the shape of the duct from circular to essentially rectangular so as to be compatible with the strut shape. To prevent flow separation at the inside of the bend, it is necessary to employ turning vanes as well as an area contraction that creates a favorable pressure gradient due to the acceleration of the flow. Since the effect of either method is limited in any practical application, the inside radius of the bend should be made as large as possible without undue distortion of the external contour. These design considerations should lead to an outlet flow with a uniform velocity profile and a high total pressure. During the internal flow test program, special attention was given to this duct component whereby the number of turning vanes as well as their location was investigated systematically. Based on these test results, the design of the $\frac{1}{10}$ scale model, to be used during the internal-external flow tests, incorporates an elbow section with two turning vanes and an area contraction ratio $A_{in}/A_{out} = 1.38$ as shown in Fig. 11.

Hydrofoil Strut

The strut can be utilized to reduce the flow velocity to achieve compatibility with that required by the pump. This diffusion process can take place gradually over the entire strut

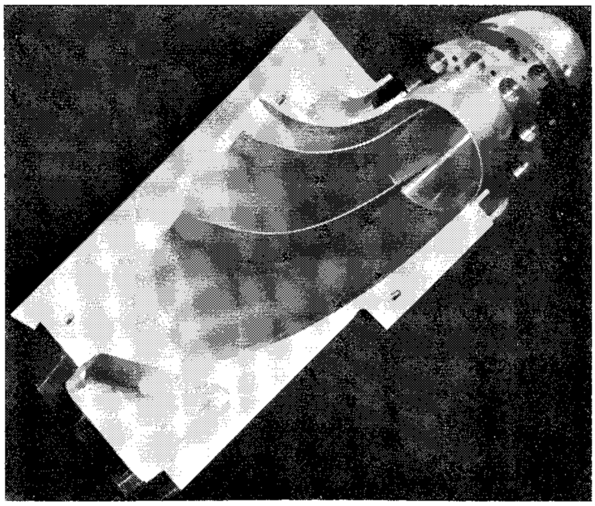

Fig. 11 Model of the 550-ton hydrofoil nacelle duct.

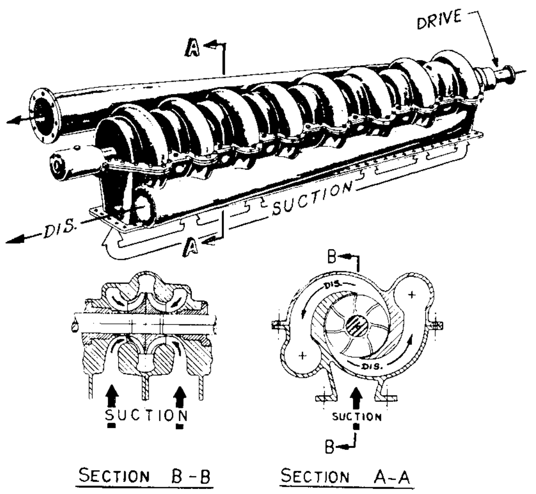

Fig. 12 Multielement pump.

length or can be limited to that part of the strut which normally will be above the water level during cruise operation. The area of the strut-hull intersection requires some attention since flow cavitation during takeoff should be prevented. Furthermore, because most applications require strut retraction to enable foil inspection, a duct seal should be designed such that no flow obstruction will occur during operation of the system. A possible configuration would be a circumferential seal that is recessed when the foils are retracted and then inflated by water pressure from the duct discharge to provide sealing during foilborne operation.

Pump Inlet Manifold

This component has the task to duct the water flow from the strut and distribute this evenly to the various pumps located in the hull. Besides having low pressure drop characteristics, it should have a low volume in order to reduce the system weight.

Pump and Prime Mover

Turboshaft engines with a free power turbine are most attractive because of their flexibility in output power and rotational speed. The air intake and exhaust system requires careful attention since turbine engines are very sensitive to inlet total pressure loss and turbine back pressure. A plenum chamber-type inlet may be required to separate the ingested water. The use of an exhaust ejector reduces the turbine back pressure to a value below that of ambient while at the same time providing a ventilating air flow through the machinery space. The remaining exhaust gas momentum flux should be directed aft to take advantage of the residual jet thrust.

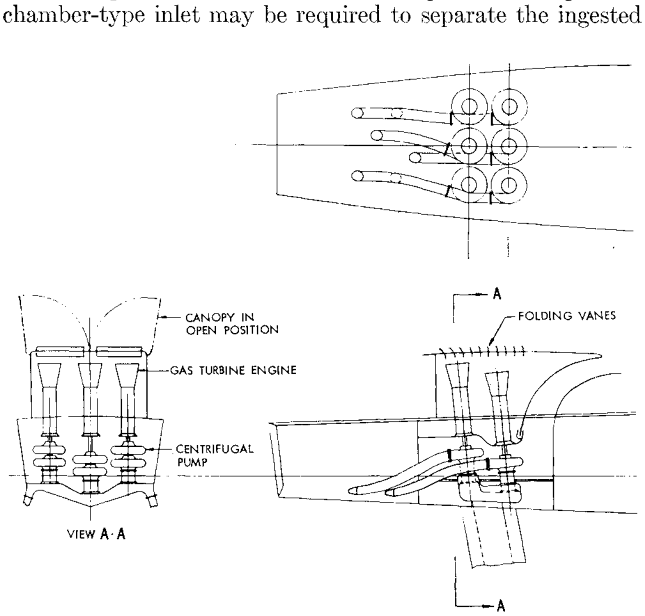

Fig. 13 Schematic of vertical engine pump installation.

Water Pumps

It is evident that it is most desirable to drive the pump at the same speed as the prime mover, thereby eliminating the heavy reduction gear that would otherwise be required. For a fixed value of the pump suction, specific speed is given by[4]

$$S = n(Q)^{1/2}/H_{s_v}{}^{3/4} \tag{14}$$

in which

n = rotational speed, rpm
Q = flow rate, gal/min
H_{s_v} = net positive suction head, ft

The only independent variable is the flow rate per pump element since both the pump speed and the net positive suction head are dictated, respectively, by the engine speed and by the duct geometry and the mode of operation of the ship. When a centrifugal flow pump is used, the total flow rate can be divided in parallel among several pump impellers mounted on a common shaft. In this way the flow rate handled by each element can be reduced to the value given by Eq. (14). This pump arrangement has been utilized in the past for commercial application and results in pump dimensions that are compatible with the available space and water flow path.

Figure 12 shows the eight-element pump used in the 550-ton hydrofoil ship study and designed according to standard commercial practice. In this application the six pumps are directly driven by Pratt & Whitney FT4A-2 gas turbine engines. Each of the pumps has the characteristics shown in Table 1. Improvement in the pump suction specific speed to values in the order of 30,000 and higher by the use of inducers will allow a reduction in the number of elements. Figure 13 shows a possible arrangement of the engine pump combination. In this manner, an extremely compact and accessible powerplant installation can be obtained with a substantial reduction in system weight.

Pump-Engine Operation

During cruise conditions, the pump will operate at its maximum efficiency point at a flow rate and pressure rise dictated by the system optimization calculations. The engine is operating at cruise power setting. During the take-off mode, which occurs at a forward speed of 30 to 40 knots, the system is very prone to cavitation. To alleviate this condition, the pump flow rate is reduced with a subsequent increase in pump pressure rise to meet the thrust requirements. The engine delivers the take-off power under this condition at increased rotational speed. Figure 14 shows the pump operating points under these conditions. The anticipated take-off procedure of the 550-ton hydrofoil with respect to power management

Table 1 Characteristics of pumps

	Cruise	Takeoff
Waterflow rate, ft^3/sec	149.6	135
NPSH, available at pump, ft	248	72
Pump, rpm	3,340	4000
N_s, specific speed	1,870	...
S, suction speed	3,790	10,700
Impeller diam, in.	16.5	...
Length, over-all, in.	179	...
Weight, wet, lb	10,400	...
Pump efficiency	0.88–0.90	0.84

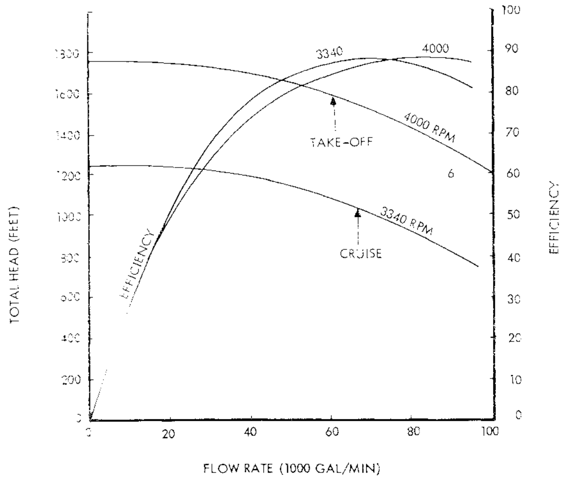

Fig. 14 Operating characteristics of pump during take-off and cruise.

is as shown in Fig. 15. At zero forward speed, all six engines are started and brought up to idle. Gradually, two engines are advanced to take-off power as the forward speed increases. When a certain speed is reached, two other engines are gradually brought up to full power followed by the remaining power plants until full power on all engines is obtained. In this way, a take-off with a sufficient margin of acceleration can be achieved without system cavitation and associated loss of thrust.

Exit Nozzle

To obtain the variation in pump operating conditions at cruise and take-off, the nozzle exit area has to be adjustable for efficient performance. This feature also can be used to unload the engine-pump combination during engine starting. In practice, ariable nozzle geometry can be accomplished with an adjustable plug, moveable nozzle leaves, or nozzle wall. Incorporation of thrust vectoring for control purposes makes this component more complex. However, swivel nozzles and thrust reversers built for aircraft engines have been developed into dependable and light units.

Preliminary Design Study of an 80-Knot 550-Ton Hydrofoil Ship

At the beginning of the study, the following design criteria were developed.

1) The entire machinery concept should be within the state of the art. Developmental components such as pump inducers are beyond the scope of this study.

2) Gear reduction between the engines and pumps should be eliminated if at all possible.

3) Pumps should be self-priming such that no auxiliary power is required for starting.

Several preliminary studies were initiated to determine the best arrangement of the six Pratt and Whitney FT4A-2 engines within the physical limitations of the hull. The six multipath centrifugal pumps are located in horizontal planes directly aft of the prime movers. The pumps are mounted at various elevations within the hull with two pumps being below the hullborne waterline for self-priming capability.

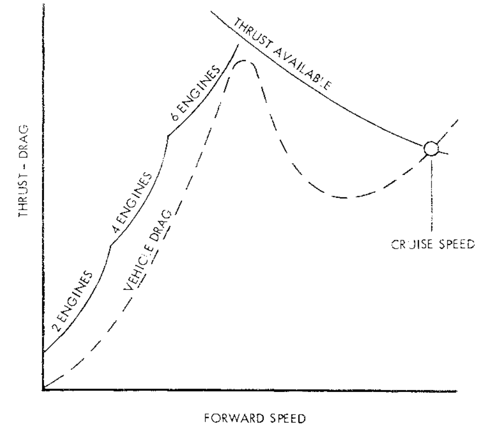

Fig. 15 Graph of available thrust for engines.

The engines are rated at 20,000 shp for maximum continuous operation at 30,000 shp for the intermittent takeoff mode on an 80°F day. The total net thrust at 76 knots is 270,750 lb, whereas the net thrust associated with the takeoff speed at 40 knots is 400,000 lb. The weight of the propulsion system, including entrained water, is estimated at 126 tons. The effect of this weight can be significantly reduced by thrust deflection and by further development of the pump. A value of the power coefficient, $P.C. = (F_n \times V_0)/(550 \times \text{shp}) = 0.53$, is obtained at the design cruise speed.

Conclusions

The results of the analysis and experiments to date indicate that waterjet propulsion, using state-of-the-art components, is feasible entirely for both hydrofoil and displacement ships. Large reductions in system weight can be obtained by improvements of the pumps and more specifically of the inducer allowing a higher value of suction specific speed. It is believed that, with continued emphasis on system tradeoff studies and refinements of component design, efficient application of waterjet propulsion for marine vehicles will be possible in the very near future.

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