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Integrated Ducted Propulsor Concept

by
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Frank B. Peterson
Daniel T. Valentine

Presented at the Symposium of Propellers/Shafting 1991
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The Integrated Ducted Propulsor (IDP) is a new concept in marine propulsor design that proposes to integrate the propulsor with the ship's stern. This concept is different from conventional design in which the propeller is designed as an add on device to a specified hull. The principal purpose of this paper is to present the IDP concept by describing a proposed design procedure. The results of calculations of power requirements and cavitation performance are presented to illustrate the feasibility of the IDP concept. The IDP is presented as a challenge to the marine propulsor design community to advance significantly existing design technology.

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INTEGRATED DUCTED PROPULSOR CONCEPT

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ABSTRACT

The Integrated Ducted Propulsor (IDP) is a new concept in marine propulsor design that proposes to integrate the propulsor with the ship's stern. This concept is different from conventional design in which the propeller is designed as an add on device to a specified hull. The principal purpose of this paper is to present the IDP concept by describing a proposed design procedure. The results of calculations of power requirements and cavitation performance are presented to illustrate the feasibility of the IDP concept. The IDP is presented as a challenge to the marine propulsor design community to advance significantly existing design technology.

INTRODUCTION

There has always been an interest in finding efficient surface ship propulsors with increased cavitation inception speed. One new concept which has been proposed recently is the Integrated Ducted Propulsor (IDP). The IDP is a design concept that considers the propulsor as an integral part of the hull. Within the framework of the IDP concept, the propulsor designer is assumed to be at liberty to suggest stern shape modifications that show hydrodynamic improvements. This is different from the conventional approach to propulsor design.

The IDP consists of a large shroud (duct) enclosing multiple sets of blade rows (rotors and stators). The shroud is designed to control the flow, in some sense, over the ship stern. The shroud inlet is shaped to ingest the hull boundary layer upstream of the propulsors. The shroud external shape is designed to minimize both wave drag and skin friction. The internal flow passage and asymmetric stators are designed to provide circumferentially uniform flow into the propulsor's rotors. One possibile shape for the IDP is shown in Fig. 1.

There is a dearth of experience in the marine engineering literature on the design of *asymmetric* propulsion devices including integrated ducted propulsors. If a designer is asked to design an *axisymmetric* propulsor, the basic geometry or general shape of the propulsor is understood; in fact, they have names, *e.g.*, open propeller, contrarotating propeller, ducted propeller, etc. If the designer is asked to design a waterjet propulsion system, the general shape of the system, which includes an inlet (flush or ram type), a circular piping system, a pump, and a discharge nozzle, the basic geometry is also understood. Hence, for the devices just described, *i.e.*, for conventional devices, although the actual size and airfoil shapes are not known at the outset of a design project the general shape *is* known. However, the general shape of the IDP *is not* known at the outset of a design project. How does the designer start to draw or design an arbitrarily shaped shroud? One approach is proposed in this note.

Two items are presented. In the next section a method is proposed that gets the designer started in his or her deliberations in designing an arbitrarily shaped shroud for an integrated propulsor. In the subsequent section an overview of some of the benefits of an IDP in comparison with the conventional shaft and strut system are discussed.

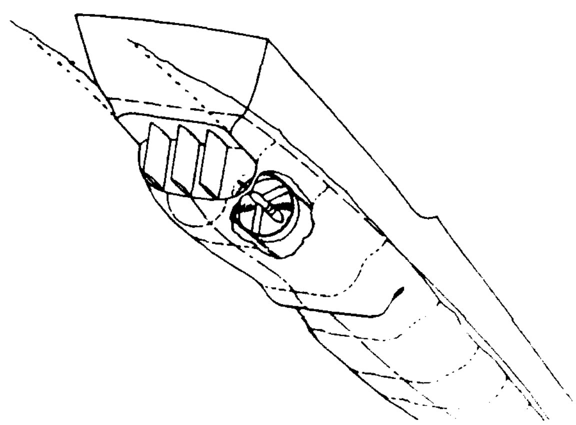

Figure 1. An integrated ducted propulsor (IDP) for a naval surface ship.

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DESIGN METHODOLOGY

To design a surface combatant is to design a complex system for which each subsystem has conflicting requirements which must be compromised to come up with a preferred (in some sense) ship system to meet the mission requirements. The subsystem of primary concern in this paper is, of course, the propulsor. This subsystem is part of the external hydrodynamic system which is made up of the hull, appendages and propulsor. For a surface combatant the hydrodynamic analysis must include the effects of wave making on performance in addition to the induced flows associated with the hull, appendage and propulsor pressure and skin friction forces. Hence, the design methodology proposed for an IDP includes the calculation of wave making effects on the propulsor. Other than the fact that the thrust deduction and wake fraction interaction coefficients, as estimated from stock propeller self-propulsion tests, take into account the effects of waves, the prediction of the velocity field induced by the waves as they are modified by the propulsor is a new issue in propulsor design analysis.

The design method proposed herein takes into account the limitations of existing computational tools. As part of the description of the design issues given in this section, reference will be made to some of the computational tools available to the designer. Fig. 2 illustrates a sequence of interrelated issues that must be considered at some point in the design of an IDP; the ordering of the steps outlined is not rigid. There are three main groups of steps that may be identified in this figure. The first group of steps is involved with the prediction of the effects associated with the hydrodynamic interaction between the propulsor, hull and free-surface. There are two phenomena of wave making that must be predicted to determine their effect on the performance of the propulsion system. One is the prediction of the wave making resistance including its contribution to the thrust deduction, *i.e.*, the prediction of wave resistance with the propulsor installed. The second is the prediction of the velocity field induced by the waves in and around the propulsor. The second group of steps is involved with shaping or designing the shroud. The third group of steps is associated with internal-flow passage and blade row design. The latter includes predicting the mass flow through and the power absorbed by the blades.

The design procedure described assumes that a baseline hull is specified. This is considered necessary to compare the performance of an integrated ducted propulsor with alternative propulsor designs. The selection of the hull form, from a conventional viewpoint, requires the design of a floating volume with low resistance that is stable, maneuverable and seaworthy. The primary assumption of the procedure described here is that the baseline hull has a shape that minimizes the ship's resistance.

The IDP is a concept that is intended to allow for relatively long, asymmetric shrouds that may have potential benefits in meeting design goals other than powering. If this type of propulsor design is desirable, then the procedure enumerated below may be followed to design an

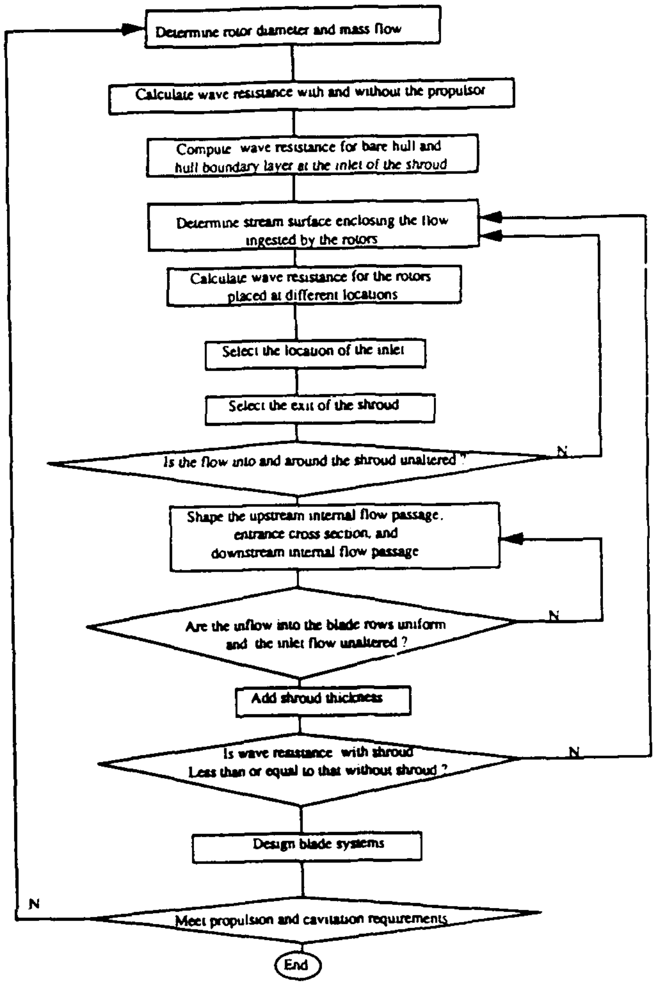

Figure 2. Design methodology for integrated ducted propulsor.

IDP. The proposed procedure follows the general ideas outlined in Fig. 2. The interrelated steps are as follows:

1. Estimate the diameter of, the mass flow through, and the power absorbed by the blade system at the design speed. The selection should be based on cavitation inception and propulsive efficiency requirements. Multiple sets of tandem rotors and stators, *i.e.*, multi-stage, should be evaluated in this step. One method that could be used is the method of singularities (the literature that describes the details of this method is cited in step 6, below).

2. Compute the wave making resistance with and without the influence of the propulsor taken into account. These calculations are required to assess whether the effect of the propulsor on wave resistance is a critical issue in a particular design scenario. The XYZFS program developed by Dawson [1] is one of several potential flow computer codes that may be employed to predict the wave resistance. This program uses a Rankine source panel

method to compute three-dimensional, steady, potential flow about ship hulls; it has three principal features. First, XYZFS satisfies the Neumann boundary condition on the ship's hull rather than on the ship's centerline as is done in classical thin-ship theory. Second, XYZFS accounts for the non-uniform flow generated by the ship hull using a double hull linearization. Finally, XYZFS contains the option of including a propulsor in the calculation; in this code the propulsor is modeled by its equivalent sink disk representation.

3. Determine the external geometry of the shroud with the purpose of reducing the wave resistance underway as compared with the wave resistance predicted with the conventional propellers in place. There are two items to consider in this step. They are:
   - Calculate the pressure distribution around the bare hull and the velocity distribution including the effect of the hull boundary layer at the proposed inlet location of the shroud. The VSAERO code developed by Maskew [2] may be employed for these calculations. This code was developed to calculate the nonlinear aerodynamic characteristics of arbitrary configurations in subsonic flow. A surface singularity panel method using quadrilateral panels is the basis of the program. Doublet and source singularities are distributed on the panels in a piecewise constant manner. A boundary layer calculation method is coded in VSAERO to investigate the inviscid/viscous flow interaction problem in a 2-D stripwise manner. It can be executed to predict the streamwise growth of the boundary layer assuming that there is no cross-flow within the boundary layer.
   - Determine the stream surface that encloses the flow ingested by the propulsor modeled by an equivalent actuator disk that is located where the center of the blade system is expected to be located. Calculations with XYZFS and the equivalent actuator disk model placed at several locations in proximity to the hull can be done to determine its optimum location in terms of wave resistance (*i.e.*, in terms of favorable propulsor/hull/free-surface interaction). Once the preferred location is determined, the next step is to compute the geometry of the streamtube boundary that surrounds the flow through the equivalent actuator disk. *It is this stream surface that provides the initial geometry of the outer surface of the shroud.* Determine the inlet and exit locations.[2]

4. Determine the geometry of the inner surface of the shroud and the need for asymmetric stator vanes such that secondary flows are minimized, flow separation is prevented, and the flow field seen by the blades is uniform. Two items must be considered in the design of the internal flow passages. They are:
   - Design the entrance section from the inlet to the blades and design asymmetric stators such that the inflow into the rotor blade rows is as uniform as possible. This may require modifying the stern shape of the baseline hull. The VSAERO program could be applied to predict the potential flow through the internal flow system. Then, VSAERO could be used to estimate the growth of the boundary layers along the walls of the internal flow passages. Finally, a Reynolds-Averaged Navier-Stokes code, *e.g.*, DTNS3D, could be used to estimate the velocity field including the secondary flows generated and potential problems of flow separation which are known to contribute to the losses through the internal flow passage of the IDP; see Gorski [3] for a description of this RANS code.
   - Design the downstream passage so that the effects of the exit jet on the wave resistance and on the interaction between the waves and the wake are reduced. The exterior flow problem may be analyzed with VSAERO by modeling the inlet of the IDP with flow through sink panels and modeling the exit with a jet slipstream the boundary of which may be modeled by a doublet sheet in VSAERO. The effect of the IDP and its slipstream on the pressure distribution along the mean water surface as modeled by an inviscid wall may be compared with the same result for the propellers in their conventional location. This provides the designer with a comparison of the disturbances applied by the hull and propulsors on the free surface. (There is a need for a method to predict the effect of the slipstream location on the wave patterns.)

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[2]One example of the approach to designing the initial shape of the outer surface of the shroud is as follows. Select the shape of the equivalent actuator disk such that it fits flush to the hull surface and has a cross section shape such that its perimeter is the same shape as the shroud that is desired at its horizontal location. This disk is *not* the model of the rotors; a circular disk would be the correct model of the rotors. The equivalent actuator disk is the model of the thruster (or integrated ducted propulsor) for the exterior flow problem, *i.e.*, the problem solved to predict the exterior surface of the shroud. The assumption made here is that the exterior and interior flow problems are separable and that they can be matched at the inlet and exit boundaries of the IDP. Thus, a criterion for selecting the locations of the inlet and exit ports, within the framework of the proposed design procedure, is that they should be far enough from the equivalent actuator disk such that the internal flow passage can be designed to successfully match the inlet and exit flow conditions as prescribed by the solution of the exterior flow problem. The inlet and exit port geometries are the cross-sectional areas of the streamtube used to model the exterior of the shroud at the respective locations of the inlet and exit ports.

At the inlet and exit ports the velocity field is prescribed by the external flow analysis; it is assumed that these velocity distributions are boundary conditions that must be matched by the internal flow passage design. The inlet and exit conditions are thus prescribed and the internal flow passages must be designed such that its geometry changes smoothly from the prescribed inlet shape to a circular shape at the rotor locations and subsequently change smoothly to the prescribed exit geometry.

The principal requirement of the exterior flow problem actuator disk is that it produces the required thrust at design speed; hence, it is an equivalent actuator disk for the shrouded propulsor. The required mass flow to produce the design thrust must be imposed on the equivalent disk. The propulsor/hull/free-surface interaction force for this configuration must be computed to ensure that the location of this disk is optimal. *The streamtube that surrounds the flow through this disk provides a first approximation for the shape of the shroud.*

Determine the location of the inlet of this shroud by selecting a location far enough upstream of the actuator disk such that there is no direct influence of the actuator disk on the inlet flow field; hence, the geometry of the actual blade system will not be important in terms of the outer flow problem. This location should be at least one characteristic length upstream of the equivalent actuator disk. Determine the exit location of the shroud such that the flow leaving the IDP is in the desired direction, *e.g.*, it is parallel to the forward motion of the ship underway. This shroud is an initial shape which will not alter the wave resistance predicted for the equivalent actuator disk with XYZFS.

5. Add thickness to the *inner surface* of the shroud for structural integrity. Design the shroud to support internal struts and shafts, stator and rotor blades, et cetera. Adding thickness as prescribed modifies the internal geometry only; hence, its effect on the hydrodynamic performance of the blading system design parameters must be assessed. For this case, the effects of adding thickness on the wave resistance is assumed negligible by design. However, if thickness must be added to the outer surface of the shroud, then its effect on all of the hydrodynamic performance parameters including its effect on wave resistance must be assessed. If there is an increase in wave drag associated with adding thickness to the shroud, then increasing the fullness of the stern near the inlet could be considered to offset this increase. There is some evidence, based on the linearized ship theory of Yim [4], that the waves induced by increasing the fullness of the ship near the inlet of the integrated propulsor can be cancelled by a "stern bulb" which may be modeled by a distribution of doublets. Note that the thickness distribution of the shroud may be modeled by a distribution of doublets in the same way as the stern bulb.

6. Design the blade system to minimize power and maximize cavitation performance (this is the principal part of the internal flow passages design). One model that may be used for the blades of the rotors and stators is the lifting line model. To model the wall effect of the shroud an axisymmetric neutral duct model may be used; one model for the duct of an axisymmetric ducted propeller consists of using ring vortices and ring sources to model the duct boundaries. Kerwin *et al* [5] and Kinnas and Coney [6] programmed such a model. In addition, they developed a numerical method to determine the optimum blade loading for a rotor in a shroud. It is this set of numerical tools that were applied in the present study to predict the power required by the rotors. If the rotors are tip driven, then the first form of cavitation expected is tip leakage vortex cavitation. The leakage vortex is caused by the flow in the gap between the tips of the rotors and the inner surface of the shroud. The prediction of leakage vortex cavitation inception was based on the formula[3] of Farrell [7] modified by ARL/PSU. This modified formula assumes that the rotor operates at the optimum gap and all designs have similar thickness to chord ratios and tip loading gradients.

One of the principal problem in the design of a shape which is completely arbitrary is selecting a starting point. The design procedure described above provides one such starting point. In summary, with the help of the equivalent actuator disk model for the IDP and with a prediction of the mass flow through the blade system, the geometry of the stream tube that surrounds the flow through the disk is predicted. It is this geometry that provides a convenient starting point for the shroud design. It is from this geometry that an investigation of perturbations in the geometry could commence.

Even in this approach there is an infinity of shapes that can be generated because of the infinity of shapes that could be selected for the actuator disk. Of course the actual disk of the blade system, particularly for the rotors, is circular. It is assumed that the outside geometry of the shroud can be selected such that the inlet and exit orifices are sufficiently far from the rotor blades so that the shape of the equivalent actuator disk is not important in terms of designing the internal flow passage except in determining the shape and the boundary conditions at the inlet and exit. It is expected that the internal flow passages will take in the inlet flow and pass it through an entrance passage designed such that its cross section varies smoothly towards the circular rotor disks. This is a two zone modeling approach for which the flow field at the inlet boundary and the exit boundary are matched in the internal and external flow analyses. This concludes the outline of a design procedure.

OVERVIEW OF IDP

To provide an overview of the application of the design methodology described in the previous section, we considered the application of an IDP on a transom stern hull typically used for naval surface combatants. Some of the evidence provided in this section suggests that the IDP concept is viable. Some of the potential performance benefits of the IDP are discussed next.

The examination of performance presented here includes calculations of the shaft horsepower (and, hence, the propulsive efficiency) and the cavitation inception speed. In the following discussion the performance of the IDP configurations is compared with the conventional open propeller, or single rotation (SR) propeller. The calculations for the IDP concept were based on the following conditions:

1. The powering and cavitation predictions were for a Froude number of 0.276.
2. The propulsor/hull/free-surface interaction force was chosen to be the same as for the SR propeller with the conventional shaft and strut configuration.
3. The inflow was assumed to be uniform.
4. The skin friction of the duct and the losses through multiple blade rows were taken into account. However, the blade tip-gap loss was not considered.
5. The drag due to the shaft and the struts was removed because a shaftless motor is considered.

The propulsor types considered are a postswirl integrated ducted propulsor and a contrarotating integrated ducted propulsor. As described in the design methodology, a lifting line model was used to represent the blades and a linearized lifting surface model was used to represent the neutral duct that was used to model the wall effect in the primary problem of predicting the power requirements of the rotors as part of the internal pas-

[3]Karafiath, G. and K.-H. Kim, David Taylor Research Center, as reported in a classified document.

sages flow problem; these models are described in detail in Kerwin *et al* [5] and Kinnas and Coney [6]. One-set and two-sets propulsor arrangements were studied. Table 1 describes the range of geometric characteristics and rotation speeds considered for the IDP.

Table 1. Geometric characteristics of the IDP.

	Postswirl IDP		Contrarotating IDP	
	Diameter(ft)	RPM	Diameter(ft)	RPM
One set	16 and 17	40 - 70	15 and 16	40 - 70
Two set	15 and 16	40 - 70	14 and 15	40 - 70

The total resistance used in this analysis of the IDP is for the fully appended hull minus the drag due to the shafts and struts plus the duct drag. In addition, the drag of a center strut to support the rotor hub was included for the contrarotating IDP configuration. Table 2 shows the resistance breakdown used in the IDP performance calculations. Note that the propulsor/hull/free-surface interaction coefficients were assumed to be equal to those for the SR propellers with conventional shaft and strut configuration (this has been stated previously in the design condition item 2 above). There is some justification for this assumption; this is discussed next.

Table 2. Resistance information of the IDP.

Prop diameter (ft)	Duct length (ft)	Total resistance		Fully appended resistance	Shaft & strut resistance	Duct skin friction	Center strut drag
		PS IDP	CR IDP				
17	42.5	1.278	---	1.252	0.138	0.164	--
16	40.0	1.259	1.275	1.252	0.138	0.145	0.016
15	37.5	1.242	1.258	1.252	0.138	0.128	0.016
14	35.0	--	1.241	1.252	0.138	0.111	0.016

Note: Calculated resistances are nondimensionalized by resistance of bare hull with dome.

The propulsor on a surface combatant interacts with the hull and free-surface. The combined effect of waves and propulsor is a drag force on the hull. This part of the drag is caused by the propulsor/hull/free-surface hydrodynamic interaction. It is assumed that this force is primarily associated with potential flow effects. Hence, XYZFS was used to evaluate this problem. Wave resistance and flow field calculations for the bare hull and for the hull with the equivalent actuator disk models of the conventional propulsor and the IDP were computed by Cheng [8]. The predictions of Cheng neglect the effects of sinkage and trim. (In an actual design scenario this assumption should be relaxed.) The results of these calculations were used here to determine the initial design of the outer surface of the shroud.

The results of tow tank resistance experiments for a typical surface combatant are summarized in Table 3.[4] The results are normalized by the bare hull resistance which includes the resistance of a bow dome in this case; hence, the table illustrates the increase in resistance associated with the appendages. At a Froude number of 0.276, the appendages contribute 25% of the resistance. At a Froude number of 0.44 only 8.6% of the resistance is caused by the appendages.

Table 3. Measured resistance of a naval surface combatant.

	Towing	Tank	Experiment	
Froude number	Fully appended	Shaft & strut removed	Shaft,strut & rudders removed	Bare hull with dome
0.276	1.252	1.114	1.078	1.0
0.440	1.086	1.028	0.992	1.0

Note : Measured resistances are nondimensionalized by resistance of bare hull with dome.

The stern waves generated by a hull under the towed condition of a resistance test are typically attenuated by using a transom. The effect of a transom may be modeled by an appropriately placed distribution of sinks. In the case of the IDP, the shrouded thruster may be modeled by an equivalent sink (or actuator) disk. The disk selected is *not* circular because it is selected to model the exterior flow field induced by the IDP. The shape of this disk depends on the cross-sectional shape of the exterior part of the shroud of the IDP desired by the designer near the center of this device.

The geometry of exterior surface of the shroud is taken to be the dividing stream surface that separates the flow through the equivalent actuator disk (which will be the required flow rate through the internal flow passage of the IDP) and the flow exterior to the surface of the shroud of the IDP.

The equivalent actuator disks for the conventional propeller and the IDP are shown in Figs 3 and 4, respectively. (Note that the location of the equivalent actuator disks for the IDP, as shown in Fig. 4, is further aft and closer to the free-surface as compared to the conventional propellers illustrated in Fig. 3.) The exterior geometry of the shroud depicted in Fig. 5 in this paper was constructed from the stream surface surrounding the streamtube of the flow through the equivalent disk shown Fig. 4. The propulsor/hull/free-surface interaction calcula-

[4] Borda, G., David Taylor Research Center, as reported in a classified document.

Figure 3. Equivalent circular sink disks for the conventional propulsors.

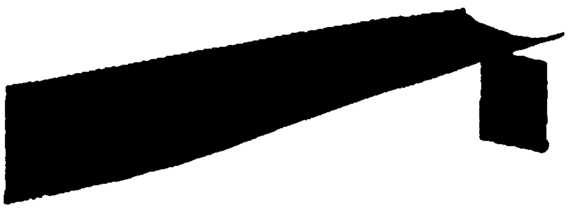

Figure 4. Equivalent actuator (sink) disks for the integrated ducted propulsor.

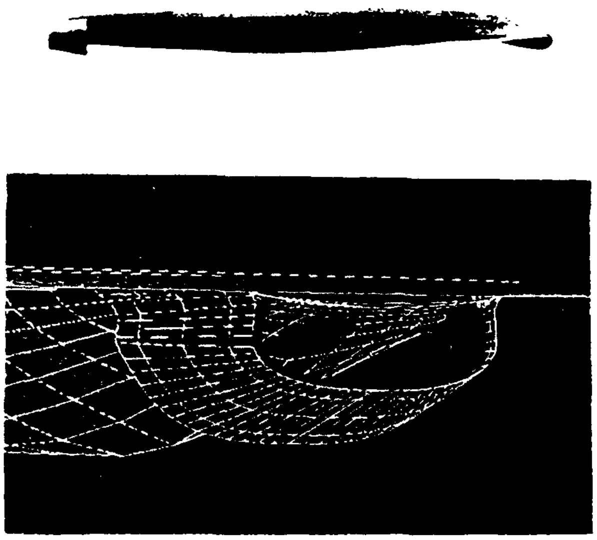

Figure 5. An example of a shroud for an integrated ducted propulsor.

tions with the equivalent actuator disk described in the next paragraph indicate that locating the equivalent actuator disk towards and in proximity of the stern does not alter the wave resistance detrimentally. This, of course, means that the design of the transom would be altered for the propulsor in its new configuration. It is this result that led us to the development of the proposed method to design the exterior of the shroud; the primary assumption, of course is that any stream surface in a potential flow field may be used as a body boundary and the resultant flow field exterior to this surface is identical to the flow produced by the original disturbances (or equivalent actuator disk singularities) that created this stream surface.

The added resistance associated with the propulsor/hull/free-surface interaction force for the two sets of equivalent actuator disks at different locations in proximity of the hull was computed by Cheng [8] using XYZFS. The conventional propellers were represented by circular disks and the exterior flow of the IDP was modeled by adjacent rectangular disks, the reasons for which were already described. (Recall that the primary assumption in the proposed method is that the inlet is far enough upstream that the geometry of the blade rows is not important in terms of designing the exterior surface of the shroud, *i.e.*, the internal flow passages can be designed separately from the external shape of the IDP with the requirement that the internal and external flows be matched at the inlet and exit of the shroud.) Table 4 summarizes the predictions of the increase in resistance associated with the interaction between the hull, conventional propellers and free surface. Again, Fig. 3 illustrates the location of the circular disks that were used to represent the two, conventional, open propellers. With the conventional propellers in place, the wavemaking/hull interaction flow resistance increases from 18% to 24% at a Froude number of 0.276. This increase in resistance is the estimated thrust deduction factor, t, and it includes the effects of waves; thus, the predicted thrust deduction is $1-t = 0.94$. From stock propeller model tests of the hull examined in this study, the thrust deduction is $1-t = 0.91$ at the Froude number of 0.276 with conventional open propellers installed; this is consistent with the XYZFS predictions (recall that the sinkage and trim were neglected in the predictions). The wavemaking/hull interaction resistance with propellers at a Froude number of 0.44 increases from 45% to 47% of the bare hull resistance so that the estimated $(1-t) = 0.98$. The measured thrust deduction is 0.93 at this Froude number, *i.e.*, the thrust deduction factor t is lower at the higher speed. Again, although the magnitude is not predicted well, the trend is correct, *i.e.*, $1-t$ increases with speed according to the model tests and according to the predictions of Cheng [8].

Table 4 also summarizes the predictions of the increase in resistance associated with the interaction between the hull, IDP disks and free-surface. Fig. 4 illustrates the location of adjacent, rectangular equivalent actuator disks that were used to represent the external flow effects of the IDP. These disks are not in the same location as the circular disks that were used to model the conventional propellers. With the IDP disks in place, the resistance increases from 18% to 22% of the bare hull resistance at the Froude number of 0.276. Therefore, the thrust deduction predicted is $1 - t = 0.96$. The resistance with IDP disks at the Froude number of 0.44 is 46% of the bare hull resistance. *Thus, the propulsor/hull/free-surface interaction force for the IDP disks is essentially the same as the propulsor/hull/free-surface interaction force for the conventional propellers.* No more can be said in light of the inherent uncertainties in the predictions.

Table 4. Propulsor/hull/free-surface interaction resistance.

Froude number	Bare hull with dome*	With circular sink disk*	With rectangular sink disk*
0.276	0.18	0.24	0.22
0.440	0.45	0.47	0.46

Note: Calculated resistances are nondimensionalized by resistance of bare hull with dome.
* Calculations are based on integrating the hull surface pressure.

Since the thrust deduction caused by the IDP (equivalent rectangular disks) is essentially the same as the thrust deduction for the conventional design (circular disk), in order to maintain this interaction force the geometry of the outside surface of the shroud of the IDP is designed by determining the stream surface that divides the flow through the disks and the flow outside the disks. It is assumed that if the outer boundary of the shroud is placed on this surface the waves produced will be the same; this is, at least, true if the flow was actually potential.

The thickness required to give the shroud strength is added to the *inner surface of the shroud boundary;* it should be added such that the outer flow problem is unchanged. Hence, the actual diameter of the IDP rotor blades is significantly smaller than the dimensions of the equivalent actuator disk. Fig 5 illustrates the outer surface of the shroud that was designed by the method described. The inner surface of the shroud, *i.e.*, the internal flow passages, must be small enough (in terms of its cross-sectional areas such that there is sufficient thickness between the inner surface and the exterior surface of the shroud for structural integrity). The length of the shroud shown is about 10% of the overall length of the ship.

A tip driven rotor was considered in this overview. In general, tip-gap or tip leakage vortex cavitation for ducted propulsors and tip vortex cavitation for SR propellers occur prior to other types of cavitation. Hence,the tip-gap or leakage vortex cavitation inception speeds for the IDP are examined and compared with the tip vortex cavitation for the SR propeller. The modified formula of Farrell [7], described in the design methodology section, was used to estimate tip-gap cavitation inception.

Postswirl Integrated Ducted Propulsor

The ratios of the computed shaft horsepowers of one- and two-set postswirl IDPs to that of an SR propeller are shown in Fig. 6. For a fixed rotor diameter, the shaft horsepower changes substantially with the rotation speed. The minimum shaft horsepower occurs at a specific rotation speed. In contrast to the conventional SR propeller, the shaft horsepower of the IDP increases slightly due to either an increase or decrease of rotation speed from this minimum shaft horsepower. This is because ducted propulsors, in general, have the characteristic of maintaining the same mass flow while absorbing the design power over a broad range of design rotation speeds. Similarly, for a specified rotation speed, the shaft horsepower is not significantly dependent on the rotor diameter.

As Fig. 6 shows, the shaft horsepower of the one-set postswirl IDP is almost the same as that of the SR propeller. Although, the drag due to the shaft and strut were removed, the long shroud creates a significant amount of skin drag which makes the total drag increase. However, the recovery of rotation energy that is normally lost in the slipstream overcomes the above increased drag. The two-set postswirl IDP (i.e., a tandem arrangement of two postswirl IDP sets) shows 4 to 7 percent less shaft horsepower than the SR propeller. In addition to the above reasons for the one-set postswirl IDP, this results from lower loading per blade because two rotors share the total thrust so that the efficiency for a given disk is higher.

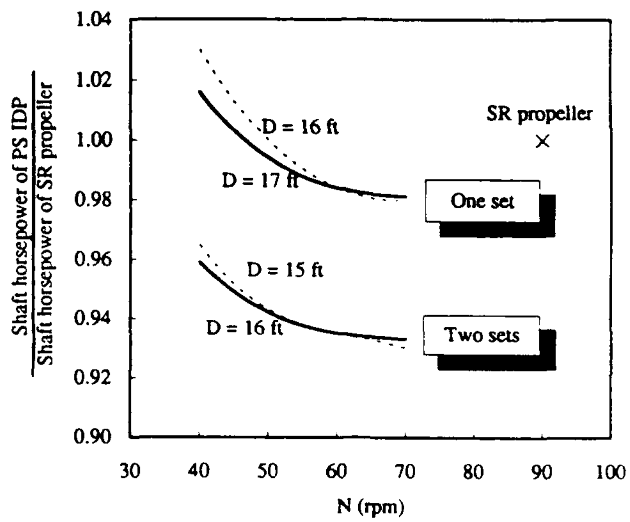

Figure 6. Powering performance of the postswirl IDP.

The ratio of the computed cavitation inception speeds of one- and two-set postswirl IDPs to those of SR propeller are shown in Fig. 7. As was described previously, the first type of cavitation to occur for the IDP is tip leakage vortex cavitation and that for the SR propeller is tip vortex cavitation. For a fixed rotor diameter, the cavitation performance shows a dramatic change with change in rotation speed. The lower rotation speed has the higher tip leakage vortex cavitation inception speed. For a specific rotation speed, the cavitation inception speed shows little sensitivity to a small change in the rotor diameter.

As Fig. 7 shows, the tip leakage vortex cavitation inception speed of the one-set postswirl IDP for rotors with special tip treatments is 16 to 50 percent better than the tip vortex cavitation inception speed of the SR propeller. This is because the rotation speed of the postswirl IDP is lower than that of the SR propeller. As described previously, the propulsive efficiency of an IDP is not as sensitive to a broad range of rotation speeds as that of the SR propeller. An IDP can be designed to perform better from a cavitation inception standpoint without unduly sacrificing the powering performance. The two-set postswirl IDP shows a 35 to 74 percent higher cavitation inception speed than the SR propeller. This improvement over the one-set IDP is because the blade loading was reduced. Table 5 shows the summary of the normalized shaft horsepower and the normalized cavitation inception speeds for the postswirl IDP.

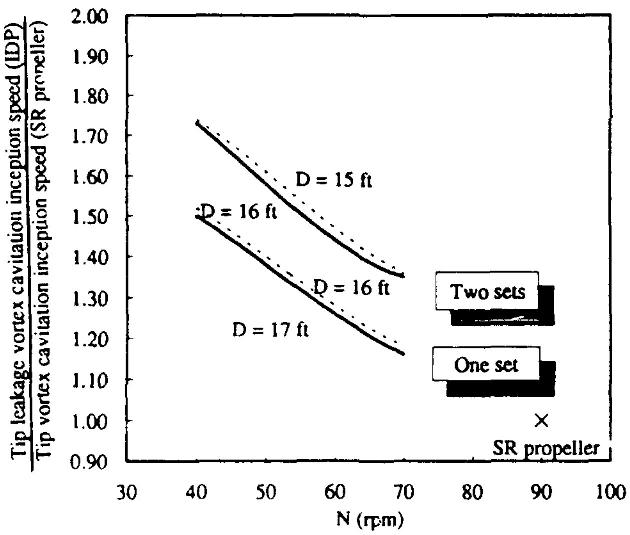

Figure 7. Cavitation performance of the postswirl IDP.

Table 5. Powering and cavitation predictions of the postswirl IDP.

	Postswirl IDP			
	Diameter (ft)	RPM	SHP_{IDP}/SHP_{SR}	V_{IDP}/V_{SR}
One set	16	40 - 70	1.03 - 0.98	1.52 - 1.18
	17	40 - 70	1.02 - 0.98	1.50 - 1.16
Two set	15	40 - 70	0.96 - 0.93	1.74 - 1.36
	16	40 - 70	0.96 - 0.93	1.73 - 1.35

Note: V_{IDP} - Tip leakage vortex cavitation inception speed for IDP.
V_{SR} - Tip vortex cavitation inception speed for SR propeller
SHP_{IDP} - Shaft horsepower for IDP.
SHP_{SR} - Shaft horsepower for SR propeller.

Contrarotating Integrated Ducted Propulsor.

The normalized shaft horsepower of the contrarotating IDPs are shown in Fig. 8. In addition to the drag components for the postswirl IDP, the total drag due to a center strut, designed to support the hub, was incorporated. For a fixed propeller diameter, the shaft horsepower is even less sensitive to rotation speed than for the postswirl IDP. This is because the contrarotating IDP has a lower loading per blade than the postswirl IDP. The shaft horsepower of the one-set contrarotating IDP (i.e. two propellers) is slightly less than that of the SR propeller. However, it is larger than that of the two-set postswirl IDP. This is because the additional skin friction drag due to the mid strut needs to be overcome by the contrarotating IDP. The two-set contrarotating IDP (i.e., a tandem arrangement of two contrarotating IDP sets or four propellers) shows less shaft horsepower than the SR propeller by 7 to 9 percent. Although the two-set contrarotating IDP may encounter mechanical complexity, the purpose for this study is to show the benefit from the hydrodynamic point of view.

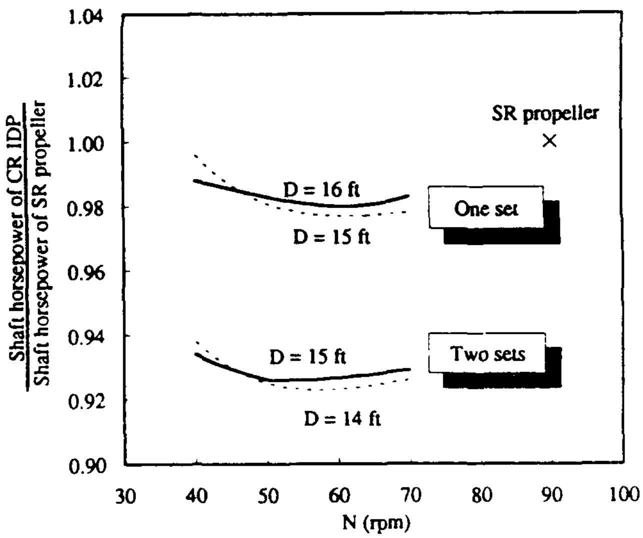

Figure 8. Powering performance of the contrarotating IDP.

The predicted cavitation inception speeds of the contrarotating IDPs are shown in Fig. 9. The cavitation inception speed of the one-set contrarotating IDP for propellers with special tip treatments is 33 to 71 percent better than that of the SR propeller. The improvement of the cavitation inception speed for a one-set contrarotating IDP is about the same as that for a two-set postswirl IDP because two propellers or two rotors reduce the blade loading. Table 6 gives a summary of the normalized shaft horsepower and normalized cavitation inception speeds for the contrarotating IDP.

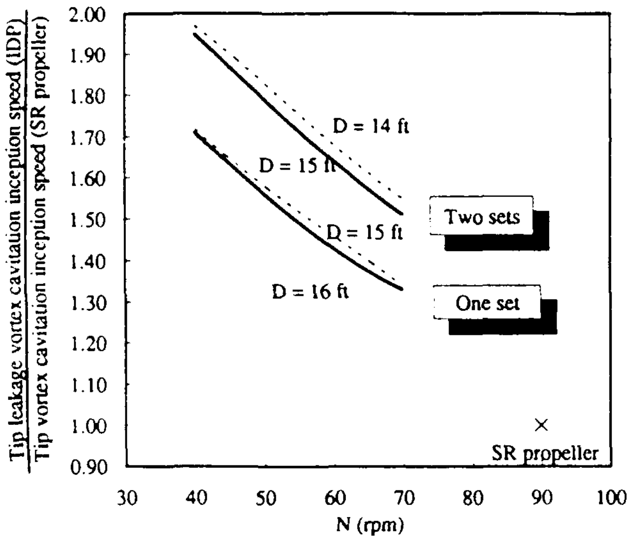

Figure 9. Cavitation performance of the contrarotating IDP.

Table 6. Powering and cavitation predictions of the contrarotating IDP.

	Contrarotating IDP			
	Diameter (ft)	RPM	SHP_{IDP}/SHP_{SR}	V_{IDP}/V_{SR}
One set	15	40 - 70	1.00 - 0.98	1.72 - 1.34
	16	40 - 70	0.99 - 0.98	1.71 - 1.33
Two set	14	40 - 70	0.94 - 0.93	1.97 - 1.55
	15	40 - 70	0.93 - 0.93	1.95 - 1.51

CLOSURE

The concept of an integrated ducted propulsor (IDP) was presented. A method to initiate the design of an IDP was described. A discussion of the concept was presented to provide some evidence of the feasibility of the concept as it applies to naval surface combatants. The main conclusions that can be drawn from the present study are summarized as follows:

1. The estimated shaft power of a one-set postswirl IDP is almost the same as that of the conventional open propellers. A two-set postswirl IDP has 4 to 7 percent less shaft horsepower. The shaft horsepower of a one-set contrarotating IDP is estimated to be slightly less than that of the conventional open propellers and that of a two-set contrarotating IDP is 7 to 9 percent less. Although the two- set contrarotating IDP may not be practical, this study is mainly to show the concept. All in all, the above results indicate that the shaft horsepower of an IDP can be made comparable to or less than that of conventional open propellers.
2. The estimated tip leakage vortex cavitation inception speeds of a one-set and a two-set postswirl IDP for the rotors with special tip treatment are 16 to 50 percent and 35 to 74 percent higher than the tip vortex cavitation inception speeds of the conventional open propellers. The estimated cavitation inception speeds of the one-set and the two-set contrarotating IDP for rotors with special tip treatment are higher than the tip vortex cavitation inception speeds of the conventional open propellers by 33 to 71 percent and 51 to 97 percent. However, the unsteady interactions resulting from multi-blade rows which may degrade the cavitation performance were not considered in the cavitation inception calculations.
3. The effects of the propulsor/hull/free-surface interaction for the propulsor configurations studied were assumed to be the same. Although the calculations presented in this study provide some support for this conjecture, further research is required to assess the important issues of the effects of waves on propulsor design. Methods that include predicting the velocity and pressure fields of a self-propelled ship on the propeller/hull/free-surface problem are required, as are supporting experimental evaluations.

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