DESIGN OF PROPELLER TUNNELS FOR HIGH-SPEED CRAFT

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ABSTRACT

Propellers recessed into tunnels are worthy of consideration as an alternative to propellers on inclined shafts or waterjet propulsors. The enhancements achieved by using a partial tunnel include reducing the shaft angle, decreasing navigational draft and allowing the propulsion machinery to move aft for an appropriate longitudinal center of gravity location and/or improved arrangements. A partial tunnel allows large-diameter propellers to be fitted which may reduce cavitation or reduce shaft angle to minimize the variation in hydrodynamic blade angle.

There is an important relationship between the propellers and the geometry of the tunnel; they must be designed together as a propulsion system. This paper provides design guidelines for partial propeller tunnels and relative placement of propellers to achieve exceptional vessel performance.

1. INTRODUCTION

Many craft have propellers and appendages that project below the keel. A fundamental requirement for high-performance craft intended for shallow-water operation is minimum navigational draft. Draft can be minimized through the use of small-diameter propellers or waterjets; however, these techniques may not necessarily provide optimum propulsive efficiency throughout the operating speed range of the vessel. An alternative worthy of consideration is propellers recessed in tunnels. With tunnels, however, some of the expected reduction in navigational draft may not be realized because loss of hull-bottom surface results in reduction in both buoyancy and dynamic lift.

Introduction of tunnels into the hull offers many advantages to the designer in matching propulsive needs to mission requirements. Advantages include reduction in static draft by reducing the distance appendages extend below the hull and greater flexibility in placement of propulsion engines and shafting. Results of experiments indicate that the placement of propellers in tunnels has no adverse effect on propeller efficiency and, due to the shrouding effect of the tunnels, may increase efficiency. Shallow partial tunnels (propeller pockets) have also been utilized to reduce propeller-induced vibrations which, because of design constraints, can only be achieved by increasing propeller tip clearance.

Dimensionless speeds in this paper are represented by Volume Froude Number, $F_{n\nabla}$, for the vessel and cavitation number, σ_H, based on vessel speed and depth of the propeller. The relationship with other definitions of dimensionless speeds (Froude and cavitation numbers) has been discussed in detail by Blount (1993). Briefly, the relationships between several dimensionless speed coefficients and cavitation numbers are:

$$F_B = F_{n\nabla} (\nabla^{1/3}/B_P)^{1/2} \quad (1.1)$$
$$F_{nL} = F_{n\nabla} (\nabla^{1/3}/L)^{1/2} \quad (1.2)$$
$$\sigma_R = (\sigma_H J_T^2)/(1-W_T)^2(J_T^2 + \pi^2) \quad (1.3)$$

2. TUNNEL GEOMETRY

The propeller and tunnel design process must be integrated as they are hydrodynamically mutually interactive; the tunnel delivers water flow to the propeller and influences the exit velocity distribution. The propeller induces flow from the tunnel as it develops propulsive thrust and greatly influences both dynamic and steady pressures on the surface of the tunnel in the vicinity of the propeller.

The longitudinal shape of the tunnel has the primary influence on its performance when integrated with the hull because flow, generally, follows the buttocks of a high-speed craft. For this discussion, the tunnel geometry is described in Figure 1. Longitudinally, the tunnel design is made up of three regions; entrance, propeller and exit. Each region has different design limitations/criteria depending on the speed of the vessel. The longitudinal location of the propeller in the tunnel, Borda (1982), also can have a significant influence on performance.

It is convenient to normalize the geometry relative to tunnel diameter at the plane of the propeller. For example, a 40-percent tunnel would be recessed, vertically, 40 percent of the tunnel diameter into the hull at the buttock plane of the propeller shaft.

2.1 Tunnel Entrance Region

The design of the entrance impacts the transition of the water flow from the hull bottom up into the tunnel. This transition length must not be excessive so as to result in too large a loss of buoyancy and/or dynamic lift near the stern of the vessel. In most cases, the design of a tunnel entrance is analogous to that of waterjet inlet design, Mossman and Randall (1948).

The slope of the tunnel roof must be designed to avoid flow separation. It is recommended that the slope of the tunnel roof not exceed a 15-degree change relative to the hull buttocks for speeds of $F_{n\nabla} \leq 2.5$ and that the slope be less for higher speeds. The entrance should be no wider than the width of the tunnel at the propeller plane, Dawson (1996).

The cross-sectional shape of the tunnel entrance can be varied to the same degree. In general, a flat roof with a radius at corners or circular sections are suitable, Hankley (1976). Tunnel entrances with flat roof sections are preferred for high speeds while circular sections are commonly used on boats up to 35 knots. Examples of these two tunnel entrances are depicted in Figure 2.

2.2 Propeller Region

The propeller region of the tunnel has a circular transverse section and its center concentric to that of the propeller. The co-location of the circular section and propeller axes permits a near constant clearance between the tunnel and the propeller blade tip. The longitudinal axis of this circular section is generally parallel to the floating waterline of the vessel. Geometric features of this propeller region are defined in Figure 1.

The propeller region of the tunnel has significant impact on the achievable propulsive efficiency. Of particular note is the longitudinal distance between the propeller and the tunnel entrance, Koelbel (1979) and Denny (1980a). Should the propeller be placed too near the downward-sloping tunnel roof, its low pressure field (suction force) can act to increase tunnel resistance. Figure 3 provides design guidance based on thrust loading and longitudinal location of the propeller relative to the tunnel entrance. This guideline is intended to show a balanced trade-off between added drag and loss of buoyancy.

Propellers with small tip clearances in a tunnel tend to exhibit higher than open-water efficiency by reducing tip losses and operating in a more favorable wake. Blade-rate pressures in the tunnel are also manageable when tip clearances are small. However, to minimize vertical forces, the number of blades of a propeller must be considered relative to the included angle of the tunnel (2ϕ) so as to avoid having blades entering and exiting the tunnel at the same instant of shaft rotation.

Tip clearance can be minimized subject to the limitation of the relative stiffness of shafting support as the propeller blades rotate in close proximity to the tunnel. Mechanical contact between propeller blade tips and the interior surface of the tunnel is to be avoided. Tip clearances, d/D, as small as 0.5 percent of propeller diameter have been successfully utilized.

2.3 Tunnel Exit Region

The tunnel exit extends aft from the propeller region to the hydrodynamic transom of the vessel. Some variation may be made in the transverse section shape so long as the desired longitudinal cross-sectional area results in smooth flow transition. The rudder is generally located in the tunnel exit.

The longitudinal distribution of the cross-sectional area of the tunnel exit has an important impact on the running trim angle of the vessel, Hankley (1980) and (1986). For high-speed vessels, caution must be taken with regard to reducing the tunnel exit area in the aftward direction since accelerated propeller wash results in a bow-down moment, Hough and Ordway (1964). Large dynamic lift developed at the tunnel exit can result in excessive hull drag due to bow-down trim and may induce yaw and roll instabilities. However, in the semi-planing speed range, $1.0 \leq F_{n\nabla} \leq 2.5$, reducing the tunnel exit area in the aftward direction is a very effective design feature for controlling running trim and enhancing speed potential. Full-scale trial data demonstrates the effectiveness of decreasing trim by reducing tunnel exit area as seen in Figure 4.

Figure 5 shows the increase in transport efficiency, E_T (reduction in power at constant speed and displacement) for reducing tunnel exit area, Blount (1993). Substantial power reduction is possible in the speed range for $1.2 \leq F_{n\nabla} \leq 2.3$ by reducing the exit area. However, power increase is likely for $F_{n\nabla} \geq 2.8$ when the exit area is reduced.

Some brief mention of tunnel design relative to vessel stopping/backing is important to note. When stopping, or especially when backing at low speed, it is possible for air to be drawn into the tunnel from the water surface at the transom. This is not a common problem when the hydrostatic head at the top-most point of the tunnel exit is greater than the pressure drop generated by the propeller during backing. Should ventilation occur when backing, a transversely-hinged flap can be mounted on the transom covering the tunnel exit. The hinged flap will trail in a horizontal position when the vessel is moving ahead. Another consideration for backing maneuvers is the maximum angle and placement of the rudder should be selected to avoid blocking forward-moving water flow in the tunnel to the propeller.

3. PROPELLER FACTORS

As the propeller is optimized for the operating environment of a tunnel, a number of factors should be considered: Propulsive factors including wake, thrust deduction and relative rotative efficiency. Geometric factors of propeller tip clearance, draft and shaft angle. Dynamic factors consisting of the number of propeller blades and blade rate pressures.

3.1 Propulsive Factors

A series of model propulsion tests have been conducted with propulsive factors reported for 40, 65 and 100 percent tunnels. These tests were conducted with a twin-screw hard-chine monohull with tunnels constructed by two intersecting cylinders (see Figure 2). These tests reported by Harbaugh and Blount (1973), Ellis and Alder (1977), Koelbel (1979) and Borda (1982), address the affects of boat speed and propeller tip clearance. The changes in trim and center of gravity rise for the parent hull are also reported in those references, but are not quantified in this paper. Detailed information regarding wake, thrust deduction factor and relative rotative efficiency is available in these references. The bandwidth of data for each propulsive factor includes the influence of tunnel depth and propeller tip clearance. These variables are provided in Figure 6 as a function of $F_{n\nabla}$.

A detailed velocity survey and wake analysis in the propeller plane of a shallow tunnel (propeller pocket) were reported by West and Crook (1967).

3.2 Geometric Factors

Propellers in tunnels permit reduction in shaft angle and navigational draft. Operational requirements and/or the designer's decision controls the tunnel depth and shaft line such that they are correctly integrated with the propulsion machinery and hull dimensions. For most high-performance craft, tunnel depth seldom exceeds 40 percent when draft reduction is a primary goal. This seems to be a practical limit for minimum operational draft as dynamic squat/sinkage of deeper tunnels tends to offset hydrostatic draft advantage associated with deeper tunnels. In general, 100 percent tunnels are only employed on craft with an extreme draft requirement and waterjets are not feasible. Tunnel depth and shaft angle are design variables available to optimize and integrate the propulsion system with the vessel to satisfy operational requirements.

While propeller tip clearance, d/D, has both geometric and hydrostatic advantages (reduced tip clearance permits small tunnel radius to minimize lost buoyancy) it has a significant influence on propulsive efficiency. Dramatic increases in speed have been demonstrated on vessels by reducing tunnel diameter to achieve very small propeller tip clearance. The small clearance tends to permit the propeller to operate with increased efficiency due to reduced tip losses and operation in a more favorable wake.

Figure 7 shows the improvement in speed obtained during sea trials when propeller tip clearance was reduced from 6% to 2% of the propeller diameter. For these sea trials, tip-clearance reduction was achieved by increasing propeller diameter. Thus, for this example propeller thrust loading, K_T/J_T^2, was reduced along with d/D. Both of these factors tend to improve propulsive efficiency.

3.3 Dynamic Factors

Selecting the number of blades for a propeller in a tunnel has greater significance than for a conventional inclined shaft installation. In the latter case the number of propeller blades is selected to minimize torsional resonance in the normal operating rpm range of the propulsion machinery. With a propeller in a tunnel, torsional resonance of propulsion machinery as well as vertical blade rate forces must be minimized. In general, minimizing vertical blade rate forces is achieved by not having one blade enter and another exit the tunnel simultaneously. A method for estimating vertical blade rate forces was developed by Denny (1980b).

Blade rate pressure amplitudes have been measured in a 65 percent tunnel at three longitudinal locations along the tunnel centerline, Peck (1974). These data, for three-bladed propellers, are reduced to non-dimensional blade frequency pressure coefficients, K_{P3}, for the lowest cavitation number ($\sigma_H = 0.6$) reported; the highest pressures measured and presented in Figure 8. These pressure data at the propeller center plane reduce with increasing cavitation numbers. Blade rate pressure data measured upstream 20 percent and downstream 25 percent of the tunnel diameter were always lower than the data at the propeller center plane shown in Figure 8.

The designer has the choice of varying tip clearance, d/D, blade number, Z and/or thrust loading, K_T/J_T^2, to achieve acceptable propeller-induced blade rate pressures at the surface of the tunnel structure.

4. SUMMARY AND CONCLUDING REMARKS

The advantages offered by incorporating propellers into tunnels can be a good alternative to propellers on inclined shafts and/or waterjets. A summary of the advantages and disadvantages of propeller tunnels is provided in Table 1.

Attention to design detail is especially important with regard to longitudinal placement of the propeller within the tunnel, propeller tip clearance and longitudinal distribution of cross-sectional area in the tunnel exit. For craft with high design operating speeds, the tunnel depth should be kept to the minimum consistent with operational requirements. Tunnel depth and shaft angle are design variables for optimization and integration of the propulsion system with the vessel to satisfy operational requirements. The designer has the choice of varying tip clearance, d/D, blade number, Z, and/or thrust loading, K_T/J_T^2, to achieve acceptable propeller-induced blade rate pressures at the surface of the tunnel structure.

5. ACKNOWLEDGMENTS

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7. NOMENCLATURE

B_P	-	Projected chine beam
d	-	Propeller tip clearance
D	-	Propeller diameter
E_T	-	$\eta/(R_{BH}/W)$ - Transport efficiency
F_B	-	$v/(g\ B_P)^{1/2}$ - Beam Froude number
F_{nL}	-	$v/(gL)^{1/2}$ - Length Froude number
$F_{n\nabla}$	-	$v/(g\ \nabla^{1/3})^{1/2}$ - Volume Froude number
H	-	Depth of propulsor below water surface
J_T	-	Propeller advance coefficient based on thrust
g	-	Acceleration due to gravity
K_{Pz}	-	$P_z/(\rho n^2 D^2)$ - Blade rate pressure coefficient
K_T	-	$T/(\rho n^2 D^4)$ - Propeller thrust coefficient
L	-	Waterline length
n	-	Propeller rotational speed
P_D	-	Total shaft power for propulsion
P_z	-	Propeller blade rate pressure amplitude
R_{BH}	-	Bare hull resistance
t	-	Thrust deduction fraction
T	-	Propeller thrust
v	-	Velocity of craft

v_R	-	Resultant velocity of flow at tip of propeller
W	-	Weight of displaced water at rest
W_T	-	Thrust wake fraction
X	-	Distance of propeller blade tip from tunnel entrance
Z	-	Number of propeller blades
η	-	Total (overall) propulsive efficiency
η_o	-	Efficiency of propulsor in absence of hull influence
η_R	-	Relative rotative efficiency
Δ	-	Displacement of craft at rest
∇	-	Volume of displaced water at rest
α	-	Angle of tunnel roof relative to buttocks
ϕ	-	Half of included angle of tunnel arc at the plane of the propeller
ρ	-	Mass density of water
σ_H	-	Cavitation number based on vessel speed
σ_R	-	Cavitation number based on resultant velocity at propeller tip.

Table 1 Propeller Tunnel Application

DESIGN FEATURE	ADVANTAGES	DISADVANTAGES
Reduced draft	•Enhanced navigation •Improved propulsion system protection	•Reduced hull dynamic lift •Increased hull construction costs •Loss of aft hull buoyancy •More complicated rudder design & placement
Reduced shaft angle	•Machinery location flexibility •Reduced circumferential blade load vibration •Reduced shaft torsional loads	•Increased potential for air drawing
Increased propeller diameter	•Reduced cavitation •Reduced blade-rate hull pressures •Reduced propeller cavitation erosion	•Heavier propeller •Heavier shaft •Heavier reduction gear
Increased propeller/hull tip clearance	•Reduced blade-rate hull forces •Reduced hull erosion	•Reduced propulsive efficiency
Decreased propeller/hull tip clearance	•Increased propulsive efficiency •Increased transport efficiency •Increased range	•More critical relationship between blade number and tunnel shape •Additional shaft alignment requirements •Potential for reduced backing capability •Increased tunnel resistance component in short tunnel
Tunnel/propeller induced hull trim control	•Increase in speed for semi-planing speeds •Improved pilot visibility	•Excessive bow-down moment at high speed

CURRICULUM VITAE

Donald Blount is the principal of Donald L. Blount and Associates, Inc., a private practice located in Norfolk, Virginia. He serves as the design manager of DESTRIERO, the 68-meter gas turbine vessel holding the non-refueled Atlantic ocean crossing record at 53.1 knots. In addition, the firm is well known for its expertise in the design of sportfishing vessels. Formerly, Mr. Blount spent 15 years at the David Taylor Model Basin followed by his employment with and ultimately becoming civilian head of the Combatant Craft Engineering Department, United States Navy; he retired from navy civil service in 1990 after 35 years of employment.

Mr. Blount's extensive experience as a naval architect and marine engineer focuses on technologies for high-speed boats and craft. During his career he has co-authored and presented thirty-one papers to various technical societies in the United States, Asia and Europe. Mr. Blount is a fellow of both the Society of Naval Architects and Marine Engineers and The Royal Institution of Naval Architects. Mr. Blount received a B.S. degree in Mechanical Engineering from George Washington University in 1963 and is a registered professional engineer.

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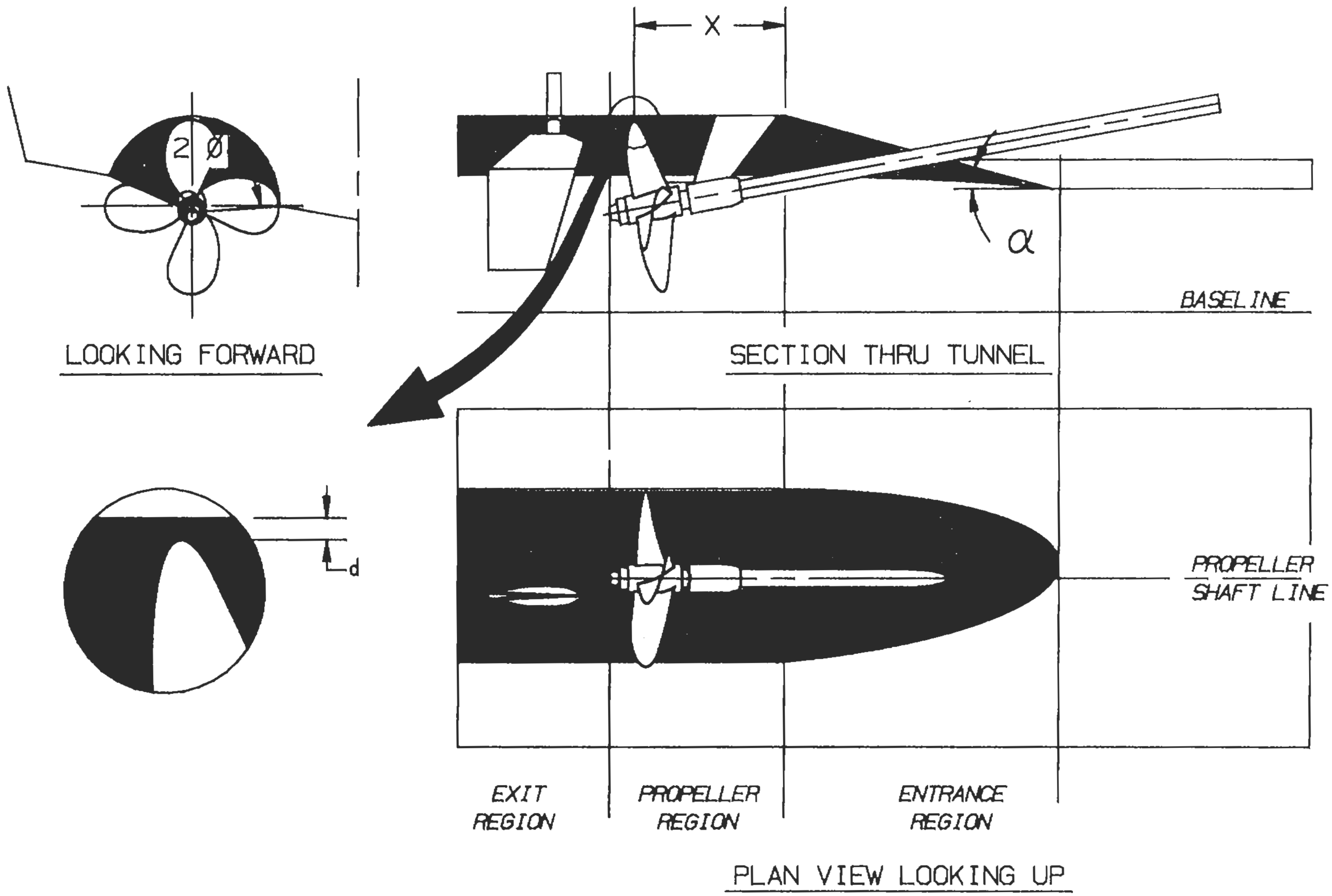

CONSTRUCTED WITH TWO INTERSECTING CYLINDERS AND
A HULL BOTTOM AT 10 DEGREE DEADRISE

FIGURE 1. TUNNEL GEOMETRY

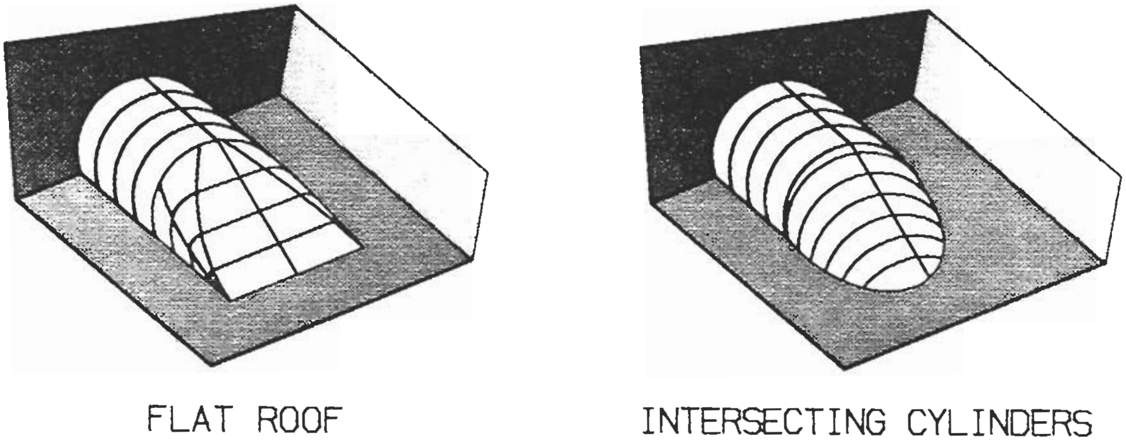

FIGURE 2. TUNNEL CONSTRUCTION TYPES

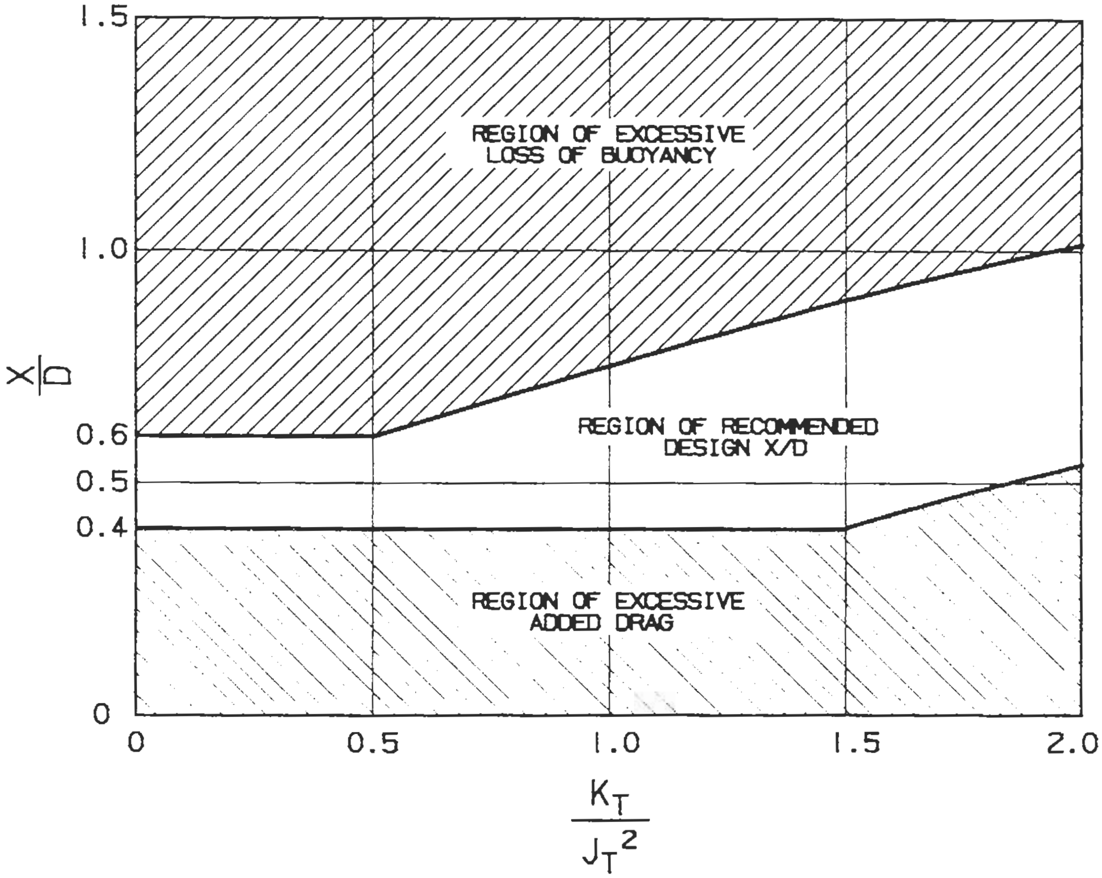

FIGURE 3. PROPELLER LOCATION IN TUNNEL

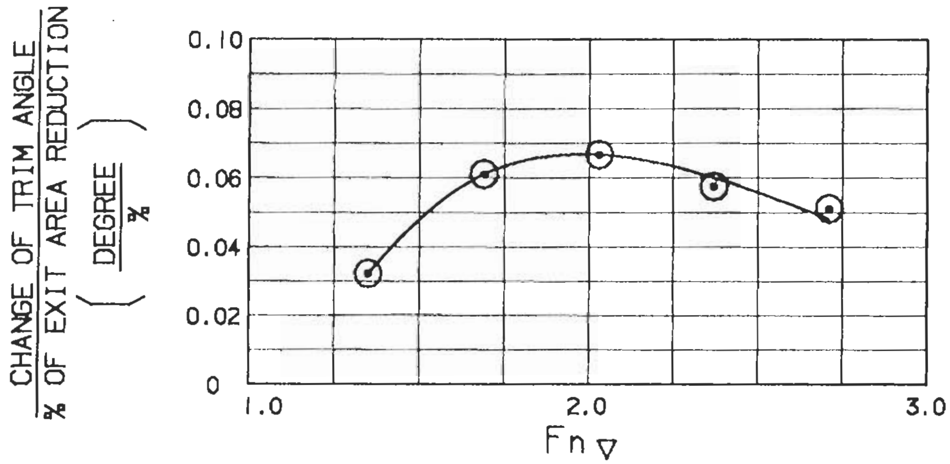

FIGURE 4. EFFECT OF EXIT AREA REDUCTION ON DYNAMIC TRIM ANGLE

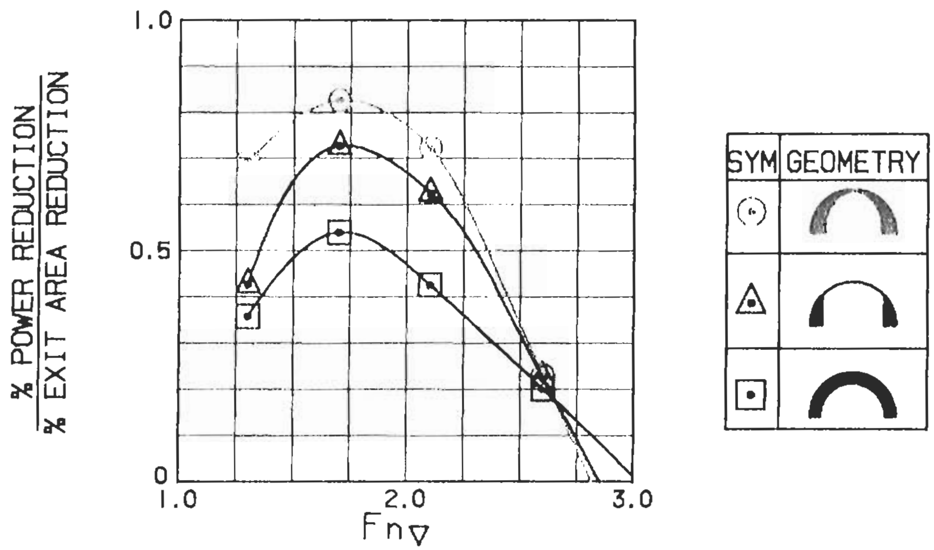

FIGURE 5. POWER REDUCTION EFFECTS

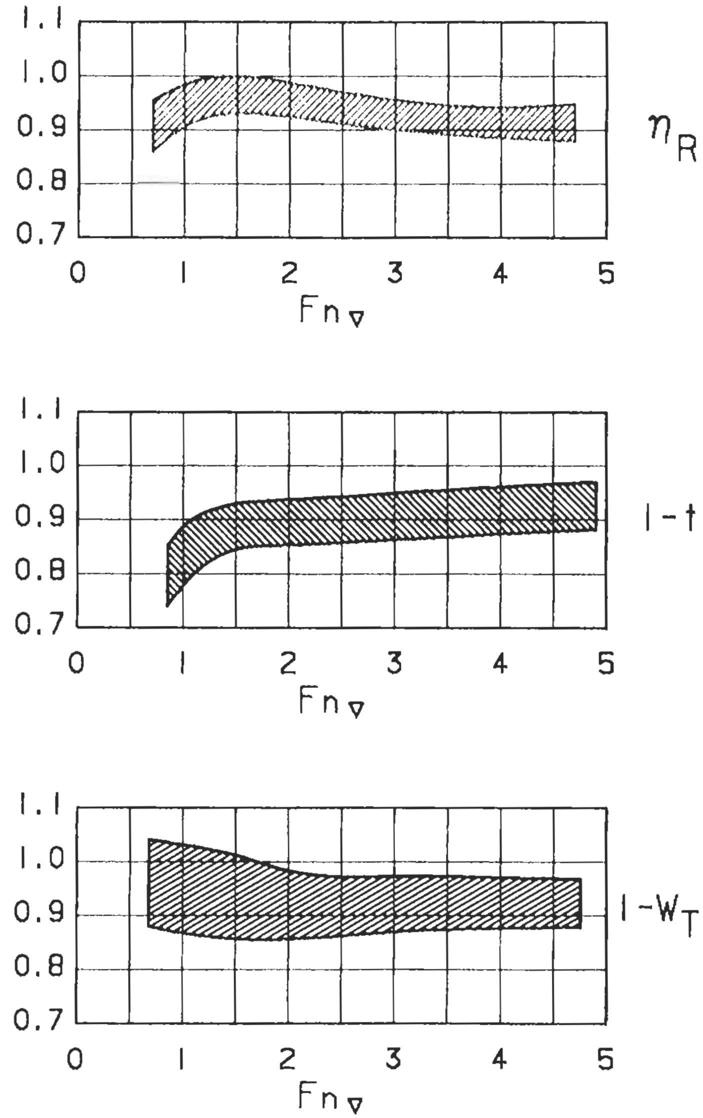

FIGURE 6. SUMMARY OF PROPULSIVE CHARACTERISTICS

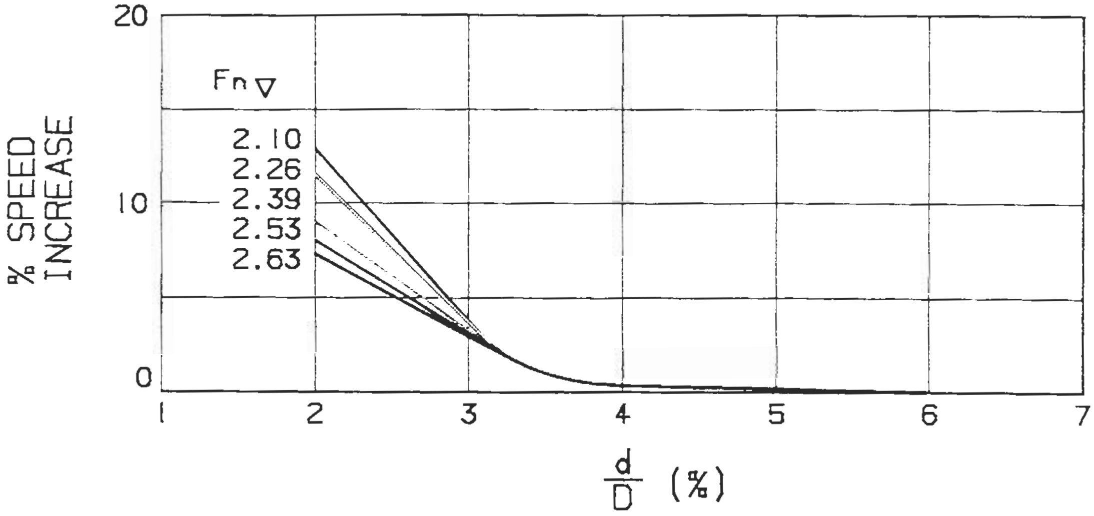

FIGURE 7. PROPELLER TIP CLEARANCE
(SPEED INCREASE AT CONSTANT HORSEPOWER)

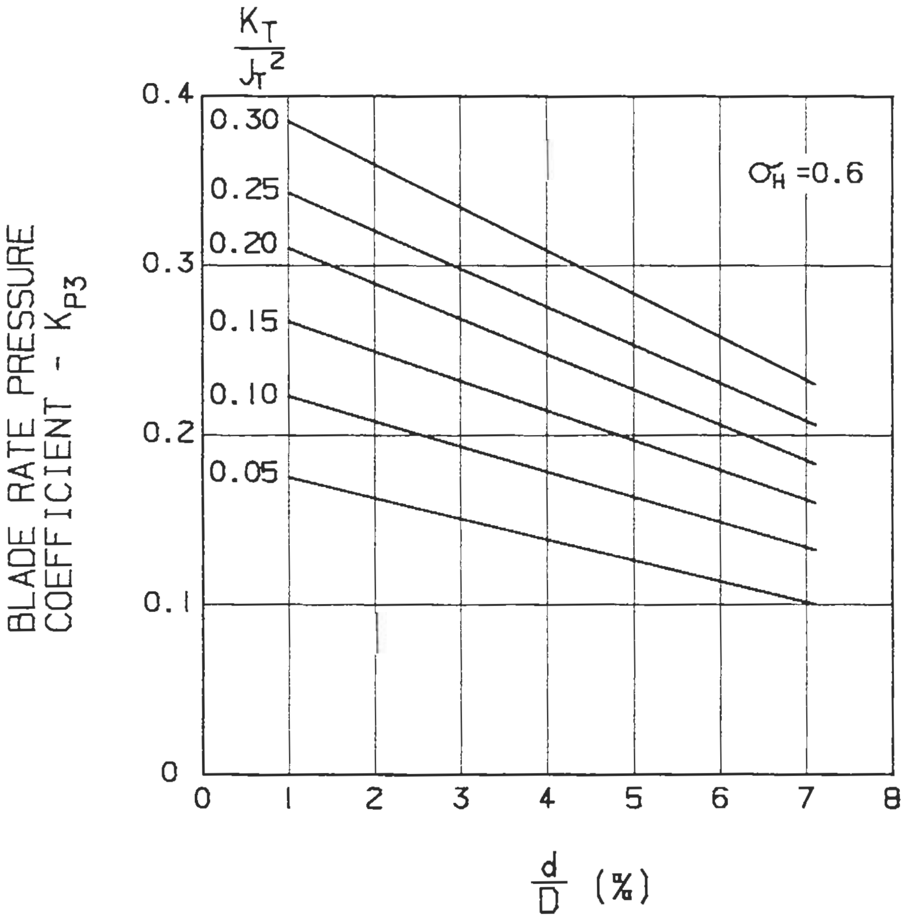

FIGURE 8. BLADE RATE PRESSURE COEFFICIENT
FOR A PROPELLER WITH THREE BLADES