An Introduction to the Design of Marine Propulsors

ROBERT E. HENDERSON

The Pennsylvania State University

This paper is intended to serve as an introduction to the area of marine propulsor design by presenting a brief summary of current design methods. In addition, a list of reports dealing with the design of open propellers, ducted propellers or pumpjets, and waterjets is presented together with a discussion of some of the major problems facing today's marine propulsor designer.

The propulsion of a marine or waterborne vehicle represents one of the earlier applications of turbomachinery design. For the past 100 years, ships have been propelled by the open screw propeller while in more recent times the ducted propeller or pumpjet, the waterjet, and various novel forms of the open screw propeller have been employed. The similarities which exist between these marine propulsors and the axial-flow compressors of the modern aircraft engine or the liquid pumps employed in today's space rockets are obvious. One would think, therefore, that the methods employed in the design of these types of turbomachinery would be similar.

Indeed, the principles employed and the problems encountered in the designing of these turbomachines are similar. However, the design methods employed are many times quite different. It is hoped that, through this symposium on design methods, not only can data on methods for the design of improved marine propulsors be presented, but there can be an exchange of the design methods used for various types of turbomachinery, and this will provide solutions in common problem areas.

The design of a marine propulsor, like the design of any turbomachine, can be separated into four distinct steps. Each of these steps must be carried out in the indicated order to arrive at a final configuration which will provide the desired propulsive performance. These steps are

(1) A preliminary or one-dimensional design analysis to determine the design parameters at which the particular propulsor is to operate.

This step ensures compatibility between the propulsor and the power-transmitting machinery and performance characteristics of the marine vehicle on which it is to be operated. This step results in the selection of the type of propulsor to be employed (i.e., open propeller, pumpjet or waterjet).

(2) The determination of the flow field which results when the selected propulsor produces the desired performance characteristics. This includes the prediction of velocity distributions at the leading and trailing edges of the rotating element, usually based on an inviscid theory. Of primary importance in this step is a knowledge of the flow field on the vehicle in which the propulsor is to operate. This flow field, together with the desired performance characteristics, determines the spanwise and axial distribution of energy addition to the fluid.

(3) The determination of the shape and size of the blade, i.e., the camber, thickness, and angle distributions required to produce the desired performance characteristics. This step must consider the chordwise variations in flow over the individual blades and include effects of viscosity and cavitation. With regard to cavitation, the design must either avoid its occurrence, as in a subcavitating propulsor, or account for the influence of its presence, as in a supercavitating propulsor.

(4) The specification and description of the blades for manufacture and to comply with the stress requirements of the application. The involvement of the designer in the specification of the blades for manufacture is essential in ensuring that the final product faithfully reproduces the design surfaces.

The completion of all of these steps, in the order indicated, is necessary to complete a marine propulsor design. Each of the steps involves a considerable amount of detail and, in the following, each will be discussed briefly in relation to present-day design procedures.

THE PROCEDURE OF DESIGN

Preliminary Analysis

The preliminary or one-dimensional analysis of a propulsor is a very important step. It is from this step that the designer selects the type of propulsor which is to be employed and matches its performance parameters to those of the vehicle in question. In order to conduct this step, the designer must have a knowledge of the flow field of the subject vehicle; i.e., its drag and the velocity distribution on its surface, the characteristics of its power-transmitting machinery, and the desired operating characteristics of the propulsor-vehicle combination. Assuming that these data are accurately known (although this is sometimes not the case) the designer must select the optimum form of propulsor based on the thrust, efficiency, and cavitation performance together with its weight, size, and unsteady-force-producing characteristics.

This selection can still involve a great deal of "art" based on the designer's experience. Several attempts (refs. 1, 2, 3, 4, and 5) have been made to correlate this information in a manner similar to that employed in the selection of classical pumping machinery (ref. 6). This correlation is done in terms of a power factor, B_p, or the related thrust specific speed, n_{sf}. While some experimental data have been correlated on this basis (refs. 3 and 5), considerably more are required to provide the designer with a complete spectrum of propulsor performance.

Determination of Propulsor Flow Field

On completion of the preliminary analysis of the propulsor performance, the designer has determined the type, size, and operating characteristics of the propulsor to be employed. It is then necessary, as in the design of any turbomachine, to mathematically represent the action of this propulsor and determine the flow field through the propulsor in the process of producing the desired propulsive force. In particular, this is necessary at the inlet and exit of the blades in order that their shapes can be determined.

Historically, marine propulsor designers have employed vortex methods to represent the action of the propulsor and thus to determine the flow field. These representations of the blade action are based on finite wing theories and have progressed from lifting line to lifting surface representations. An excellent review of vortex design methods as applied to open propeller design is presented in reference 7. As discussed in this reference, vortex methods and, in particular, lifting surface methods have been developed to give a very accurate representation of the action of subcavitating propellers within the limits of the assumptions employed. These assumptions are an inviscid flow, no curvature of the streamlines or existence of radial pressure gradients, and axisymmetric inflow. With these methods, the effect of radial and chordwise variations in loading, radial variation of inflow velocity, finite blade effects, and skew of the blade surface can be considered accurately.

While vortex representations have also been employed in the design of ducted propellers and pumpjets (ref. 8), these propulsors have also employed streamline curvature or through-flow analysis in their design (refs. 9, 10, 11, and 12). These latter methods allow for the inclusion of streamline curvature effects and, empirically, the effects of viscosity. The extension of present-day propeller design methods to include these effects may be possible by combining the vortex methods and those of reference 10 or 11. Since the methods for including streamline curvature are iterative in their solutions, the vortex theory can be used as an initial or starting solution. In addition to the effects of radial pressure gradients, the effects of viscosity and, in particular, wall boundary layers and secondary flows can be included (ref. 13).

Determination of Blade Shape

With the determination of the flow field at the inlet and exit to the rotating blades, the designer must determine the shape of the blades which will produce this flow field. This includes the determination of the camber, thickness, and pitch distribution. In addition to the desired propulsive action, the cavitation performance and required strength characteristics must be considered.

As in the design of any turbomachine, this step is conducted using two-dimensional data with appropriate corrections to include the effects of the three-dimensionality, viscosity, and finite-blade effects. The effects of viscosity obtained from experimental data are included as inviscid corrections in the lifting surface or through-flow analysis. Reference 14 presents a tabulation of these inviscid corrections derived from lifting surface theory for a NACA ($a=0.8$) mean camber line.

The use of an existing camber line and thickness distribution implies the specification of a particular chordwise pressure distribution. The design of a blade to minimize the occurrence of cavitation can be hindered by such an approach. Thus, the design of a blade shape to give a specific pressure is desirable and can be accomplished by the mean streamline method (ref. 6). This method is based on two-dimensional experimental data with the necessary corrections for three-dimensionality, viscosity, and thickness.

Cavitation in a marine propulsor is avoided by the selection of the proper chordwise and radial loading distribution. In addition, the designer must consider blade end effects which result in tip vortex or leakage cavitation (refs. 15, 16, and 17). A survey of the effects of cavitation in propulsors and pertinent design data is presented in reference 18.

Specification of the Blade for Manufacture

Once the designer has completed the determination of a propulsor configuration which will provide the desired propulsion action, the propulsor must be converted to actual hardware. While this does not appear to be a design step, it is important that the designer concern himself with the process if the final hardware is to perform satisfactorily. The manufacture of hardware can result in variations in blade shape and contour which result in major deviations from the design performance and greatly affect the cavitation performance of the propulsor (refs. 19 and 20).

To ensure that the hardware produced is a replica of what the designer has specified, computer graphic techniques (refs. 21 and 22) and numerical machining of master hardware are being used. In this way, the blade can be accurately represented to the manufacturer and a detailed interpretation of the design configuration for use in different manufacturing processes can be provided.

SOME PROBLEMS IN MARINE PROPULSOR DESIGN

The marine propulsor designer is faced with many problems requiring additional research. These include (1) minimization of unsteady forces, (2) the effects of viscosity in design, (3) the design of propulsors with cavitation, (4) the design of heavily loaded propellers, and (5) the prediction of off-design performance.

In the area of unsteady forces, considerable effort has been devoted to the prediction of the unsteady forces which exist on a given propulsor operated in a known time-varying environment (refs. 23 and 24). As in the design of axial flow compressors and liquid pumps, these predictions must be supplemented by methods which will allow the designer to choose that configuration of blade geometry which will minimize the generation of unsteady forces. Such data would be similar to those currently available for the selection of blade geometries to minimize the occurrence of cavitation.

Present-day methods of calculating the flow field through a propulsor must be extended to include heavily loaded propellers and the effects of streamline curvature and radial pressure gradients. Possibly, this could be done by employing a combination of the existing vortex lifting-surface methods and the streamline curvature of through-flow analysis used in axial-flow compressor design. The combination of these two methods will also allow viscous and secondary flow effects to be included. In addition, the area of the prediction of off-design performance must be considered.

The design of supercavitating propulsor blades (i.e., the design for the presence of cavitation) is far from being complete (ref. 25). At present, only one-dimensional and empirical methods of design are available. The methods for the design of supercavitating propellers are undergoing the same development as the subcavitating design methods experienced in the early 1950's. This development must be continued in light of high-speed vehicle development.

Current two-dimensional experimental data relating blade-section performance lags the design requirements of blade solidities, stagger angle, and chordwise loading. Therefore, additional data must be obtained. These should include higher solidities, higher blade stagger angles, the effects of turbulence, and changes in axial velocity through the blades.

SUMMARY

This review is very brief and certainly does not, by itself, present a complete description of marine propulsor design. It is hoped, however, that together with the included references and, in particular, those review papers indicated, it will provide an introduction to the area and, together with the other papers in this session, will serve as a basis for the discussion of marine propulsor design. (Refs. 26–33 are sources of information utilized in addition to those specifically referred to in the preceding text.)

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