The Evolution and Development of the MERIDIAN Propeller

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SYNOPSIS

The design philosophy and methodology evolved by a leading designer and manufacturer of marine screw propellers is presented, with particular reference to improvements in efficiency and economy of operation. The subjects discussed include the main features of the propeller geometry including diameter, blade area, profiles and thickness. The nature of the wake adaption concept is discussed along with its effects on propulsive efficiency and cavitation performance. The control of cavitation and propeller excitation forces are investigated by means of varying the radial distribution of hydrodynamic loading together with the introduction of highly skewed blade geometry. Throughout the paper emphasis is laid on the continuous evolution of a practical propeller design method in the search for improved ship performance.

INTRODUCTION

The Meridian propeller was introduced in 1965 following the merger two years earlier of the two major UK propeller manufacturers into a single identity. At that time each manufacturer was marketing individual designs know as the 'Scimitar' and the 'Heliston' propellers, each of which represented more than 50 years experience in propeller design, although employing markedly different methodology. The Meridian propeller was an obvious and logical rationalisation of these two design techniques, and was formulated to incorporate the best features of both methods.

Since its introduction, many thousands of Meridian designs have been prepared for ships and marine vehicles of all types and sizes, with installed powers ranging from 90 to 58 000 shp per shaft. Over the years numerous technical difficulties have been encountered and successfully overcome. In this context the design of propellers to suit very high powered container ships, inherently prone to problems of cavitation erosion and propeller associated vibration, is particularly noteworthy. In addition, the pioneering work carried out in the design and manufacture of large diameter, low blade area Economy propellers has enabled many shipowners to reap the benefits of reduced fuel consumption brought about by improved hydrodynamic efficiency.

The 1970s and 80s have witnessed tremendous changes in the field of marine propulsion engineering. Increased energy costs have led to the almost universal choice of diesel machinery for new and converted tonnage, and have brought about a reduction in the optimum voyage speed on most trades. Whilst there would currently appear to be a re-awakening of interest in high powered machinery for certain classes of ships, the specification of lower installed powers with the highest possible propulsive efficiency is now commonplace. Associated changes in worldwide trading patterns have brought about drastic reductions in the numbers of certain ship types such as VLCCs and 'tween deckers, while other sectors of the market such as bulk carriers and cruise liners have, in relative terms at least, expanded.

Furthermore, increased attention has been directed towards shipboard habitability and the provision of a more kindly environment for the installation of sophisticated electronic equipment, so that the avoidance of propeller related noise and vibration has become of greater significance. Generally speaking, there is now an increased awareness amongst Naval Architects of the importance of ensuring a good flow into the propeller. In parallel with these changes in the design environment, advances have been made in the understanding of the hydrodynamics of propeller action, whilst the power of computing facilities has increased enormously.

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Mr L. Bodger served at sea with Shell Tankers and Ellerman City Lines, following which he returned to full-time study at Plymouth. After graduating in Nautical Studies he obtained consultancy experience as a surveyor before joining Stone Manganese Marine in 1979. He is presently employed as a Project Engineer within the Technical Services Division.

DESIGN PHILOSOPHY

At its inception the Meridian propeller was intended to provide a satisfactory blend between theory and practice. In effect this comprised the utilisation of wake adaption techniques (optimising the section cambers and pitch distribution to suit the individual flow field) as applied to a standard basic propeller geometry. By this means the application of a consistent and reliable design approach led to a high level of confidence in the finished product.

Over the years, however, as the design developed to meet the changing demands placed upon it, the name Meridian has become associated more with a design philosophy than a particular design method. Put quite simply, this philosophy is to ensure that the chosen geometry is the best suitable for the actual working environment. To this end, whilst of necessity some level of standardisation is employed, the emphasis is upon maximum design flexibility. As a result a Meridian propeller fitted to, say, a warship will be quite different in appearance and perfomance than a Meridian propeller fitted to a large bulk carrier, to the benefit of both. The naval application will have different profiles, different widths, loading characteristics and skew, to suit the different design requirement with its emphasis upon noise reduction, whereas the bulk carrier propeller will aim primarily for maximum efficiency.

The above is of course an extreme case but it illustrates the range of flexibility available to the designer, whilst retaining the necessary confidence and reliability for the end product.

A fundamental feature of the Meridian philosophy is that the propeller geometry is optimised for service conditions, at which the ship will operate throughout its life, being adjusted as necessary to perform satisfactorily at the contracted trial conditions. The difference in terms of efficiency, when compared with a propeller designed specifically for trial conditions, seems relatively small (in the order of 0.5 to 1%) but when considered over the lifetime of the ship will amount to a notable saving in the fuel bill.

A further basic feature is the choice of the layout of the propeller in relation to the machinery installation. This is an aspect for which no general rules can be specified or applied, each application must be considered on its own individual merits. The factors involved are numerous: the type of machinery; the type of ship service; effects of draught and trim and of weather; tolerances on design, manufacture and measurement; even the manufacturer of the main engine. All will have a contribution to make to the final decision. The weighting given to each will depend upon experience, since in many applications a compromise will be found to be necessary.

DIAMETER

The choice of the propeller diameter is the single most important decision made by the designer. This is not only from efficiency considerations but also because of the dominating influence that the diameter has upon the resulting performance characteristics of the propeller in action. This includes cavitation, strength and power absorption as well as the control that the diameter exerts upon the vessel's stern arrangement and of course the propeller's capital cost.

It is well known that for any given combination of power, revolutions and speed of advance there is one propeller diameter which is the optimum in terms of hydrodynamic efficiency. This optimum diameter, in the case of the Meridian, has been formulated from appropriate design charts. Alternatively it may be derived from the results of vortex theory calculations carried out for a range of diameters bracketing the expected value, although for production design purposes this is uncommon and unnecessary.

The above derived optimum diameter, however, applies to uniform flow conditions and it has long been appreciated that a propeller designed for the same power and revolutions operating at the same mean advance velocity but in the non-uniform flow field behind a ship's hull should have a slightly smaller diameter. In the early develoment of the Meridian a reduction in diameter of 5% for single screw ships and 3% for twin screw ships was globally applied in common with prevailing design practice. More recently,[1] the results of research have enabled a more rational assessment of the appropriate correction to the open water diameter to be obtained. A diagram showing the applicable corrections is shown in Fig. 1.

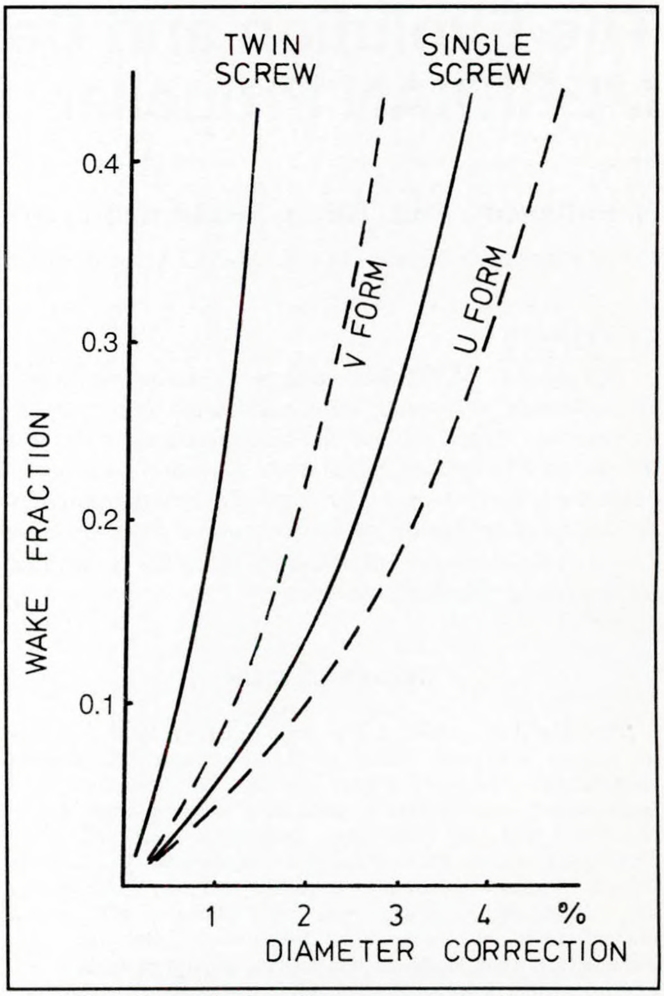

FIG. 1: Correction to optimum open water diameter to obtain behind diameter

BLADE AREA

The widths of a propeller's blade sections are a funtion of both the blade surface area of the propeller and also the distribution of that area as dictated by the blade outline or shape. The minimum section widths are usually determined by the need to avoid the harmful effects of cavitation, which usually appears as blade erosion, excessive noise and vibration or, in extreme cases, loss of thrust.

Propeller cavitation can appear in various forms, not all of which are necessarily harmful or detrimental to the operation of the propeller, and not all of which are significantly influenced by the blade section width. The criteria used[2] for the assessment of blade surface area in the design of Meridian propellers are first the provision of an adequate margin against bubble cavitation emanating from the mid-chord region, and secondly the limitation of the chord-wise extent of the leading edge back sheet cavity to an acceptable level.

The choice of blade surface area is inevitably a compromise between the conflicting requirements of a low surface area for maximum efficiency and the minimum area necessary to ensure satisfactory cavitation properties. Historically, the selection of the blade surface area was made on a rather arbitrary basis, relying heavily on the experience of the individual designer. This situation was much improved by the introduction of cavitation charts, such as the widely used Burrill diagram, which was incorporated in the Meridian design method for many years.

However, such charts only provide general guidance and should be used with discretion since they are unable to make any allowance for the quality of the wake pattern as determined by the relative magnitudes of fluctuating wake peaks. Further developments in vortex theory have enabled the action of a propeller in any specified flow regime to be investigated such that the local velocities and pressures around the section profiles can be realistically assessed, thus permitting calculation of the associated distribution of pressure around the blade.

It is therefore possible, in the preliminary design stages, to make a reliable estimate of the appropriate surface area making use of an assumed wake distribution typical of the type associated with the proposed hull form. As the project progresses, with a model wake survey of the final hull form usually becoming available, it is possible to formulate a definitive propeller design and, on completion, to calculate the pressure distributions around the blade sections for various positions around the propeller disc.

Pressure distribution studies are nowadays carried out for all Meridian propellers intended for installations where the design conditions are likely to impose an unfavourable cavitation environment. Most importantly, the results of many such theoretical studies have been correlated against observations made at model scale in the cavitation tunnel and with records of cavitation erosion at full scale.

As a result of the knowledge and experience gained in this field it is now possible in most instances confidently to evaluate the risk of erosion damage at full scale and to modify the design accordingly without recourse to model testing. In this way the incidence of cavitation related problems with Meridian propellers operating under their specified design conditions has been eliminated.

The development of reliable methods of estimating the nature of the pressure field around propeller blade sections has enabled designers to investigate the effects of varying the radial distribution of width, that is the shape of the blade outline. The majority of the propeller's thrust is generated at the outer sections of the blade, the inner sections being comparatively lightly loaded.

It follows from this that the blade outline should reflect the thrust distribution and, providing that the wake distribution does not impose any unduly arduous operating conditions on the inner blade sections, it is common practice for Meridian propellers to employ a wide-tipped outline. As well as imposing less drag and hence returning a higher efficiency, whilst maintaining the same margins against cavitation, there is a further benefit from a reduced metal content leading to a lower weight and inertia with reduced first cost.

A sample of typical blade width distributions illustrating the development towards wider tips is shown in Fig. 2.

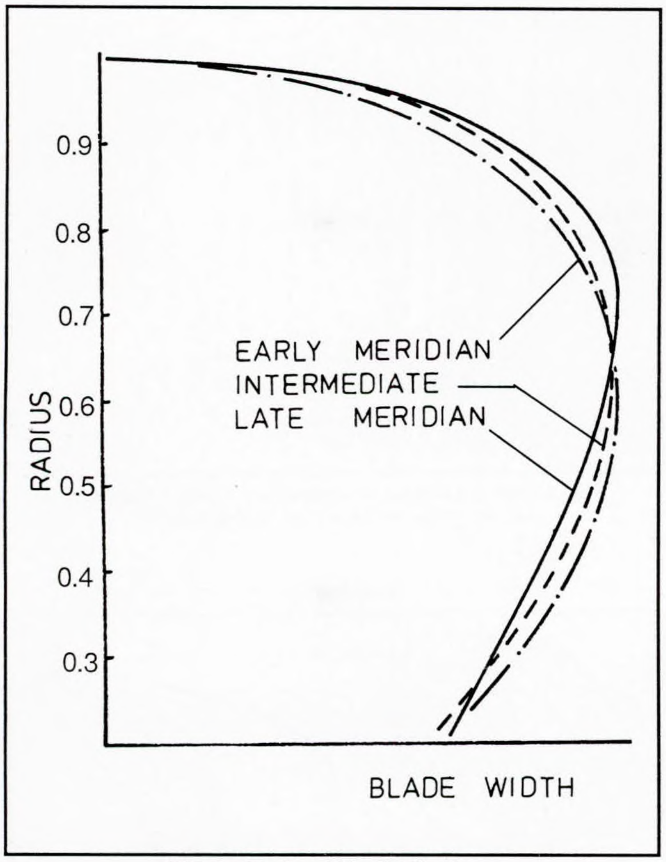

FIG. 2: Blade width distributions

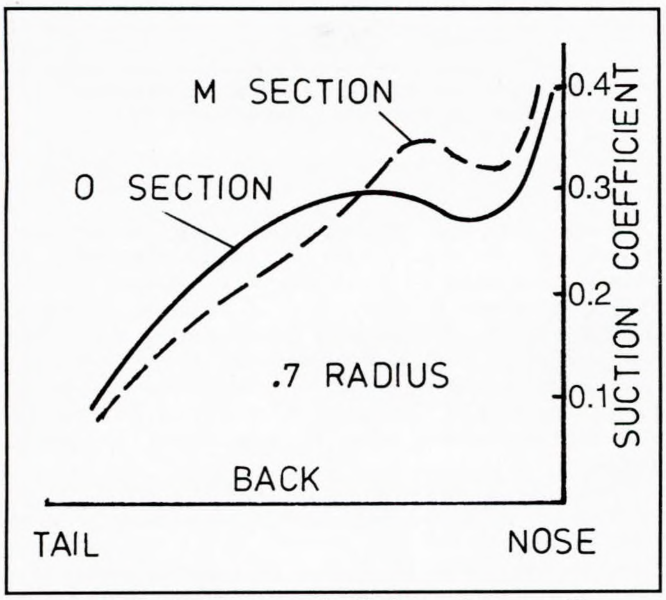

FIG. 3: Typical pressure distributions of outer profiles operating at high incidence

BLADE SECTION PROFILES AND PITCH

Whereas many designers commonly employ NACA profiles derived from aerofoil development,[3] the section profiles of Meridian propellers have been formulated specifically for use in the very specialised application of marine screw propellers.

A Meridian propeller may incorporate one of a number of basic section forms necessitated by the wide range of design situations encountered. Currently this menu of sections comprises separate profiles for such applications as high speed patrol craft, tug and trawler screws, and single and twin screw merchant ship types.

As with all other aspects of the Meridian design, the basic section profiles are subject to continuous review. Initially a form of profile, designated type 'M', was favoured for most merchant ship propellers, with the exception of certain very high powered applications which employed an alternative profile form, designated type 'O'. However, within the last decade the use of type 'O' sections has become more commonplace. This change has been brought about largely as a result of considerations of the characteristics of the pressure fields about the the types of section. As can be seen from Fig. 3, the type 'O' section, which has its maximum thickness and maximum camber located nearer to mid-chord than does the type 'M' section, generates a more even distribution of suction over its back, with consequent benefits in terms of cavitation performance without any measurable effect upon its efficiency.

The majority of Meridian propellers are subject to a 'wake adaption process' as an integral feature of their design. The blade section is considered as a 'mean line', or camber line, extending from the section nose to the tail, about which the intermediate section thicknesses are evenly distributed. The exact shape of this camber line has a significant effect on the performance of the section both in terms of its hydrodynamic efficiency and its characteristic pressure distribution.

The hydrodynamic lift associated with an aerofoil section set at an angle of attack to an incoming flow is mainly generated by the acceleration of fluid over the section back causing a localised reduction in pressure. This increase in local stream velocity is composed of two fundamental components: the first is dependent upon the magnitude of the angle of incidence, while the second is dependent upon the amount of section camber.

The total lift generated by any propeller blade section is therefore a function of the angle of incidence, which may be controlled by adjusting the section pitch angle, and the section camber, which may be controlled by modifying the form of the basic section.

It can be shown that there is an optimum radial distribution of hydrodynamic lift, or load, such that total energy losses are minimised and the highest overall efficiency achieved. Furthermore, having determined the optimum lift at each individual section, it is possible to arrange the section pitch and section camber in such a way that the generation of the required lift is apportioned between camber and incidence in a manner serving to minimise viscous losses with generally acceptable cavitation properties.

Whilst it is normally possible to use the optimum distributions of camber and pitch for conventional merchant ship propellers, it is sometimes necessary to effect minor adjustments in order to modify the cavitation performance as predicted from the vortex analysis and pressure distribution calculations.

The final choice of mean pitch, which will determine the power absorption of the propeller, is governed by the need to ensure that the design power is absorbed at the specified rate of revolutions. At present, none of the numerous mathematical models available can be relied upon to produce designs consistently with the required power absorption characteristics to a sufficient level of accuracy. Consequently, it is essential for the designer to have access to an extensive data bank correlating a consistent design technique with the analyses of full-scale trials and service results. In the case of the Meridian this has been accumulated over many years of successful applications.

BLADE STRENGTH

Unless accidentally damaged beyond repair, the bronze screw propeller can be expected to last the lifetime of the ship. This is despite the fact that the blades operate within an extremely hostile environment involving high fatigue loading in a corrosive medium.

Blade thicknesses should ideally be kept to a minimum consistent with adequate blade strength, thereby reducing the propeller weight, moment of inertia and first cost, while also offering marginal improvements in hydrodynamic efficiency and cavitation performance.

The traditional beam theory approach to blade strength, providing that it is adequately correlated, will provide a satisfactory yardstick for conventional propeller stressing. This method, involving the assessment of the contributions of the torque, thrust and centrifugal forces imposed upon the blades, is normally evaluated for the condition corresponding to the transmission of the maximum installed power.

The level of the imposed stress derived from such a calculation is best considered in qualitative rather than quantitative terms, ie as a relative figure for guidance purposes rather than as an absolute measure of stress. Consequently, when assessing the required blade root thickness using this technique it is necessary to relate the calculated stress levels to a permissible design stress which has been assigned in the light of previous experience with a large number of similar propellers.

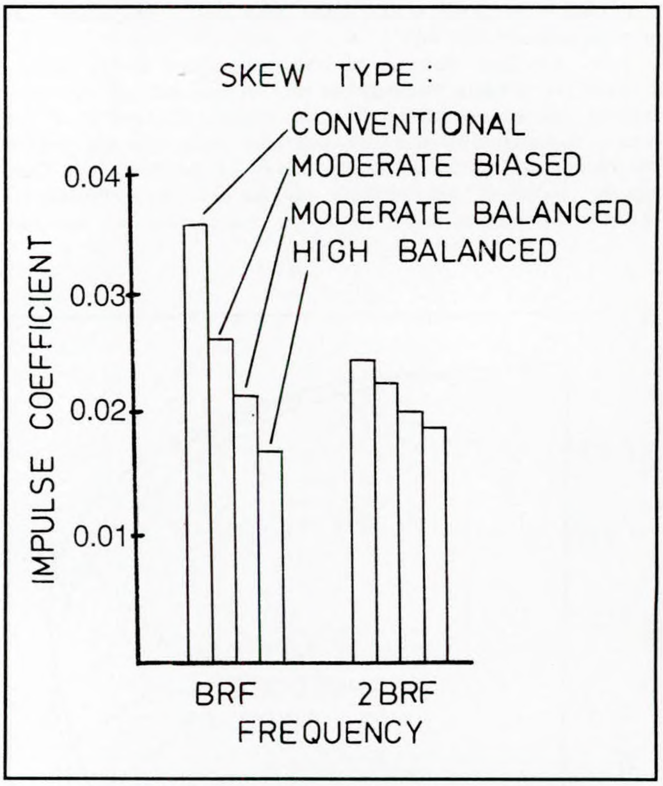

FIG. 4: Effect of skew on excitation forces generated by the propeller in a non-uniform wake

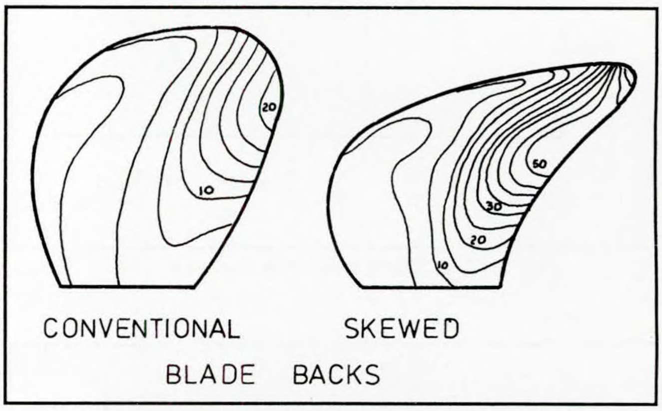

FIG. 5: Finite element stress analysis of conventional and skewed blades under astern bollard condition

Having determined the appropriate value of maximum thickness in the root section, the radial distribution of thickness is arranged so as to provide a consistent level of strength throughout the blade. It is of particular importance to ensure an adequate continuity of strength in way of the rapid changes in form at the intersection of the blades and boss contour. In this region the blade root fillets perform the dual role of ensuring this continuity as well as providing for a smooth non-turbulent flow of metal during the casting process.

During the development of the Meridian design, in an endeavour to refine the above method of assessing propeller blade stresses, an extensive research project was conducted during the early 1970s to establish the fatigue properties in a corrosive environment of the various alloys used in the manufacture of Meridian propellers.[4] Concurrently, further research effort was directed at the problem of establishing some form of criterion which could be used to take account of the fatigue loading likely to be imposed on any given propeller. This was formulated based on a joint consideration of the characteristics of propeller performance and of the non-uniform wake field behind the ship's hull. The variation in thrust between the extremes of maximum and minimum inflow velocities was related to revised design stresses taking due account of the propeller weight and the fatigue properties of the material employed.[5]

More recently the use of beam theory techniques for propeller blade stressing has to a large extent been superseded by the development and implementation of suitable numerical analysis methods using as input data the basic propeller geometry together with the results of pressure distribution calculations, combining these with an appropriate finite element mesh structure.[6] In this way it is possible to obtain a detailed insight into the distribution of stress throughout the blade. This provides the designer with a much greater knowledge than was previously possible of the stress distribution within the blade and it is this increased understanding of blade stresses which has permitted the confident introduction of designs incorporating increased levels of skewback.

The reliability of the finite element techniques employed has been investigated by comparison with stresses measured in Meridian propellers at both model scale and full scale using arrays of bonded strain gauges.[7]

SKEWBACK

The term skewback as applied to propellers refers to the displacement of successive blade sections along the helical surface forming the blade datum.

Since the earliest days of screw propulsion it has been intuitively appreciated that propeller blades incorporating an increased amount of skew would have a softer interaction with wake peaks in the flow behind the hull, and that cyclic variations in propeller blade loading around the disc would accordingly be reduced. Whilst the earliest proponents of more highly skewed blades were primarily concerned with reducing the levels of shaft-borne forces, subsequent research and application revealed that, in addition, significant reductions in the amplitudes of water-borne pressure fluctuations on the adjacent hull surfaces could also be achieved.[8] This is illustrated in Fig. 4 and it is this second beneficial effect of blade skew which has now assumed the greater degree of importance.

Making use of lifting surface theory and finite element stressing techniques, research has shown that the magnitude and distribution of stress within highly skewed blades is significantly different from those found within blades of more conventional form. In conventionally shaped blades the maximum stress levels are normally found at the inner radii and the design stresses are assessed in relation to that region of the blade, traditionally using techniques based on cantilever beam theory.

However, in the case of highly skewed blades, localised concentrations of stress well in excess of the normal design stress levels have been identified.[7] Consequently, the safe design of highly skewed blades calls for more sophisticated methods of load and stress assessment, together with correlation of calculated results with those determined in respect of more conventional blade forms so that a satisfactory level of confidence may be achieved.

In addition to the modified stress patterns found in the normal operating mode, highly skewed blades are subject to increased stress levels during manoeuvring operations. The bollard astern mode represents the most extreme loading case likely to be met in practice and the effect of skewback on stress in such conditions is shown in Fig. 5. Furthermore, the trailing edge region towards the tip may be particularly vulnerable to mechanical damage when running astern, and the unusual blade form and often unorthodox pitch distribution necessary to achieve a satisfactory hydrodynamic loading may render identification and rectification of blade distortions difficult.

The stress levels within a skewed blade are of course greatly influenced by the distribution of skew along the blade. Increased displacement of the centroids of lift, drag and centrifugal forces introduces couples on the blade which can give rise to very high torsional stresses about a radial axis. These twisting moments can however be reduced by selecting a distribution of skew which aligns the various centroids in a radial sense.

Figure 6 contrasts the form of skew incorporated into the earliest Meridian propellers with an unbalanced form and the balanced form commonly used for today's Meridian designs. Although the distribution of skew will generally conform to a standard type, the amount of skewback incorporated into any particular design is carefully assessed on its merits, taking account of the characteristics of the wake pattern applicable.

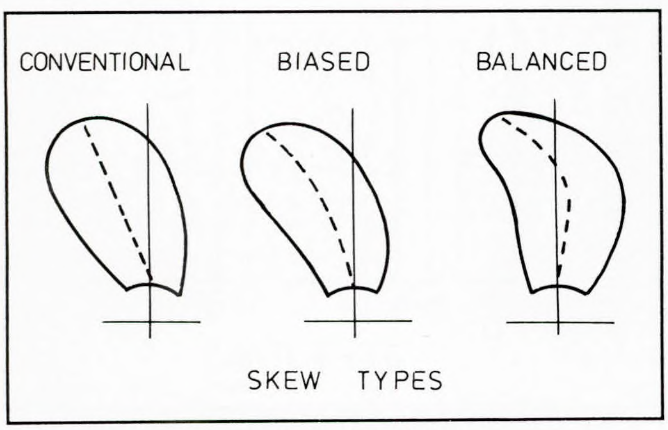

FIG. 6: Definitions of skew

SPECIAL TECHNIQUES

Noise and vibration

On occasion, the propeller design specification incorporates requirements which render it necessary to incorporate special adjustments to the Meridian design approach. For example, the specifications of propellers intended for warships or for hydrographic/oceanographic research vessels usually include a restriction on the propeller-generated noise level under certain operating conditions. Similarly, the installation of high powered machinery in high-speed merchant ships can render them inherently prone to propeller-associated vibration problems.

As the major part of the noise and vibration impulses emanating from a ship's propeller is associated with the growth and decay of cavities within the fluid, these types of design problems lend themselves to solution by means of carefully designing the blades to minimise the extent of, and to delay the onset of, cavitation.

A significant contribution to noise and vibration phenomena is made by a cavitating tip vortex, and the suppression of this feature is a notable aspect in the design of such propellers, with further attention being directed towards the avoidance of transient, unstable cavitation at other radii. Consequently, when circumstances call for such measures to be taken, an arbitrary non-optimum distribution of loading (see Fig. 7) is imposed on the blade with the object of reducing the rate of change of hydrodynamic loading towards the propeller tip, thereby reducing the strength of, or even completely eliminating, the tip vortex.[9]

The distribution of loading along the blade is controlled by the amounts of camber and pitch assigned to each blade section, while the blade widths and thicknesses are assessed with reference to the cavitation performance of the sections as well as the structural integrity of the blade. Having determined the appropriate loading at each section, the apportioning of lift between camber and incidence is carefully examined with a view to minimising the extent of all cavitation phenomena.

For this purpose recourse is made to the use of pressure distribution calculations for each of the design sections and which are employed to identify the available margins against the various forms of cavitation under the relevant operating conditions. In addition to modifying the distribution of loading for propellers of this type it is also the practice to incorporate an enhanced degree of skew in order to reduce further fluctuating propeller impulses on the adjacent hull surfaces.

Using these techniques, very significant reductions in propeller excitation forces can be achieved (see Fig. 8), although there is a small penalty on propulsive efficiency associated with this approach.

From the outset the fundamental geometry of Meridian propellers incorporates certain features intended to offset any tendency towards the phenomenon of blade singing. These features were derived over forty years ago, mainly relating to the section profiles and their radial disposition, and the success of these measures has been such that to date no Meridian propeller design, other than a very few cases that have been found to be associated with distortion to the blade geometry, has encountered this particular problem.

Economy propellers

A further variant of the Meridian propeller is the Economy propeller, specifically designed to provide optimum efficiency at reduced operating powers.[10] Following the dramatic rises in fuel oil prices during the 1970s, it then became common practice on most trades for owners to implement a slow steaming policy. Typically, perhaps only 50-60% of the ship's installed power would be employed to maintain the reduced service speed.

The ship's propeller would, in the normal run of events, have been designed to absorb safely the maximum installed power and been optimised on the basis that a large proportion of the available power would be in continuous use. Consequently, various features of the design, in particular the blade surface area, would be far removed from the optimum for the revised operating condition. Recognising the opportunity to improve their vessels' hydrodynamic efficiency, and thus cut fuel costs, numerous owners opted to retro-fit Meridian Economy propellers, thereby realising significant savings and recovering the cost of the new propellers over a period of 12 months, or even less in many cases.

The greatest savings associated with Economy propellers have been achieved in those cases where it has proved possible to reduce the shaft speed/power relationship and fit a large diameter slow turning screw. The Meridian Economy propeller illustrated in Fig. 9 is one of a number retro-fitted to a class of steam-powered VLCCs during the late 1970s, and at 11 m diameter represents the largest monobloc propeller manufactured in the world.

BLADE NUMBER AND RAKE

Although the number of blades is a fundamental feature of propeller design, its choice is nevertheless usually outside the control of the screw designer. This is because the main criterion for the selection of blade number is the avoidance of coincidence between the blade rake frequency and the natural or resonant frequency of the ship structure or shaft train. It is the shipbuilder, together with his consultants or classification society, who is best placed to undertake the necessary vibration analyses at the design stage, so that the responsibility for specifying the propeller blade number usually rests in their hands.

Blade rake, on the other hand, is simply a device for positioning the propeller within the sternframe aperture to achieve adequate clearances. As such it has no influence upon the design other than its implications upon the blade thicknesses in those cases where it is found necessary to employ high rake for this purpose.

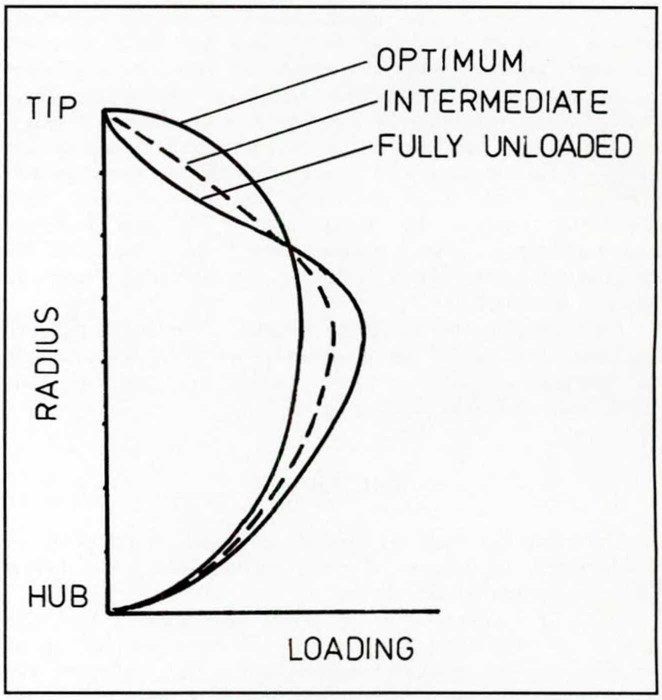

FIG. 7: Blade loading distributions

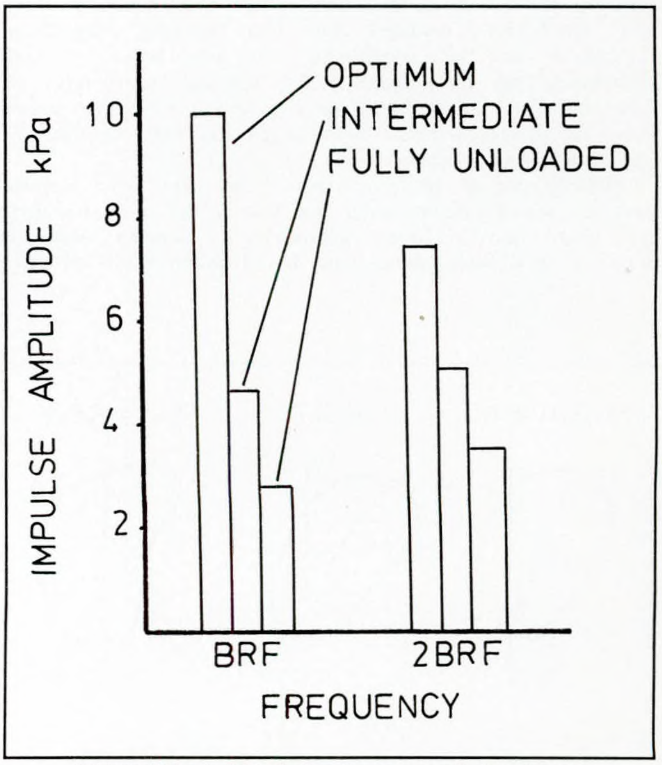

FIG. 8: Effect of blade loading on excitation forces generated by the propeller in a non-uniform wake

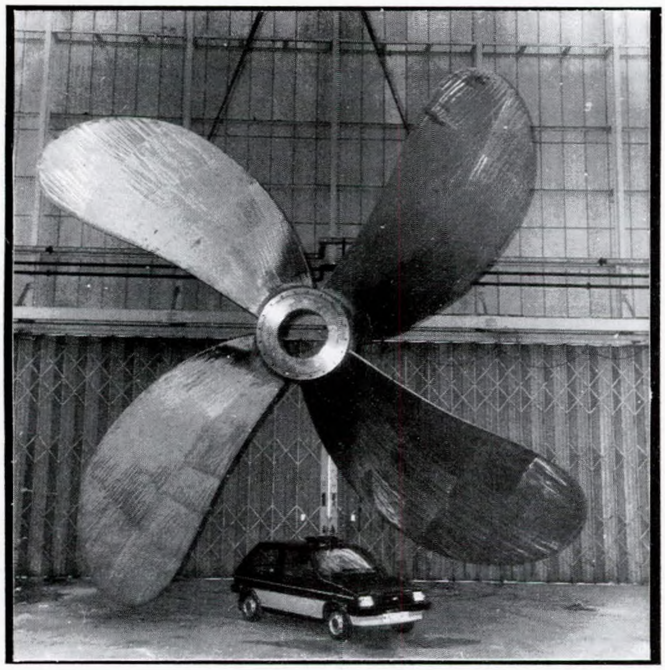

FIG. 9: A Meridian Economy propeller of 11 m diameter weighing 69 tonnes in Nikalium

CONCLUDING REMARKS

From the foregoing it should be apparent that Meridian propellers are not members of a standard series or family as is the case with, for example, the MAU or better known Troost B propellers. This is not to say that standard series work does not have an important role to play in design, and indeed a series incorporating Meridian design features has been tested over the last two decades[11] and serves as an essential base for the Meridian methodology. However, the widely varying and individual nature of ships' wake fields means that it is essential to adapt the basic series geometry in order to obtain maximum efficiency for any specific application.

This basic reasoning encapsulates the thinking behind the Meridian design philsosophy and helps to explain why the design has for over 20 years been at the forefront of marine propeller technology. With a policy of continuous development and design flexibility supported by a proven pedigree, the Meridian propeller design is able to look forward with confidence to the future challenges set by the marine propulsion industry.

ACKNOWLEDGEMENT

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