Traditional propeller design theory

By T. P. O'Brien

The subject of screw propeller theory has received the attention of many research workers, both in the aerodynamic and hydrodynamic fields, and the results of early work on marine screws formed the basis for detailed work on airscrews, which has in turn been adapted to marine screws. Some aspects of the applied theory are of a complex nature and require the aid of a computer, but if certain assumptions are made it is possible to simplify the calculations and still retain the theoretical basis.

By using the computer in designing marine screws, the hydrodynamic characteristics can be specified and the corresponding geometrical features can be selected in a more detailed way than is possible by using standard series data. For instance, the computer designed screws can have a specified radial thrust distribution, the blade outline can be determined by choosing the blade section chords to correspond to specified lift co-efficients, determined by cavitation consideration. On the other hand, the standard type chart design screw has a thrust distribution which is unknown, the blade outline is fixed and the blade sections are of a standard type which might not be suitable for the required operating conditions. In the same way, screw performance estimates can be made in more detail using the computer results than the results of model experiments, since such experiments though providing overall performance values, do not give any information from which an evaluation of section performance can be made.

Developments in propeller theory have followed three distinct lines of approach based on momentum, blade element and circulation concepts. These are considered in detail by many of the early research workers, including Glauert, Schoenher, Burrill and Lerbs. They are briefly outlined in the following sections:

Momentum and blade element theories

The momentum theories, which have been developed from the early work by Rankine and R. E. Froude and others, are based on the concept that the hydrodynamic forces on the screw blades are due to momentum changes which occur in the region of fluid acted upon by a disc representing the screw and which forms the slipstream of the screw as shown in Fig 1. The slipstream has both an axial and an angular motion: in the simple momentum theory only the axial motion is considered, while the extended momentum theory and angular momentum is taken into account. In the simple momentum theory the motion of the fluid is considered relative to the screw and the speed of advance of the screw is represented by the axial velocity of the fluid far ahead of the screw. The disc representing the screw is assumed to be capable of imparting a sternward axial thrust to the slipstream by causing a reduction in pressure to the fluid approaching the screw disc and an increase in pressure to the fluid leaving the screw disc. This results in an increase in axial velocity and a corresponding reduction in the cross-sectional area of the column of fluid. It can be shown that the axial velocity at the screw disc is the mean of the axial velocities far ahead and far astern of the screw disc. A conventional way in which the axial velocities can be related is by the use of the axial inflow factor "a" as follows:

Velocity far astern of screw disc: VA (1 + 2a)
Velocity at screw disc: VA (1 + a)
Velocity far ahead of screw disc: VA

In the extended momentum theory, a similar relation between the corresponding angular velocities can be specified using the angular inflow factor "a" as follows:

Angular velocity far astern of screw disc: Wr (1 + 2a)
Angular velocity at screw disc: Wr (1 — 2a)
Angular velocity far ahead of screw disc: Wr

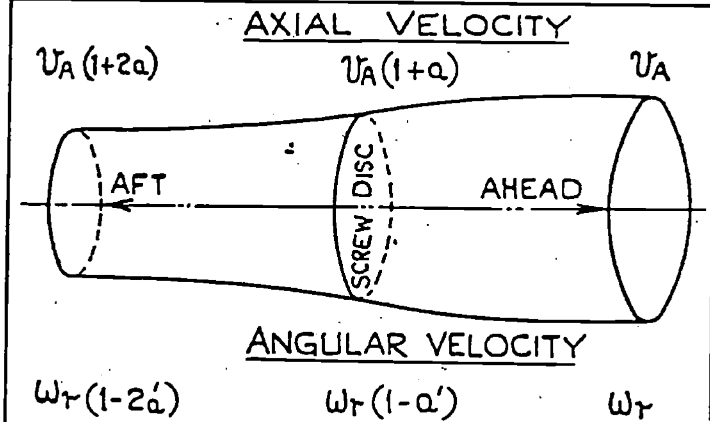
Equations for thrust, torque and efficiency can also be derived using momentum considerations and it is possible to extend the momentum theories to make allowance for the effects of viscosity. However, the practical application of these theories is limited because they do not yield data from which the geometrical details of the screw can be obtained.

Blade element theory

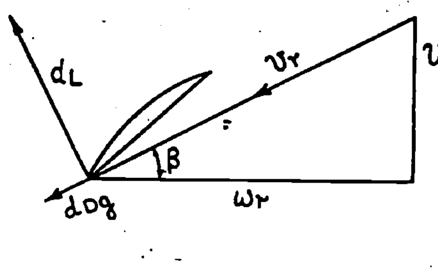
In the blade element theory, which is based on the early works of W. Froude and others, each blade of the screw is divided into a number of annular elements each of which is assumed to operate as if it were part of a hydrofoil. The velocity of the fluid relative to each blade element is the resultant of the axial and angular velocities as shown in Fig 2. The hydrodynamic forces on each blade element are a lift force dL acting perpendicular to the direction of the resultant velocity and drag force of dDg opposing the motion of the element and acting along the line of the resultant velocity. The blade section element forces at a radius r and reduced in axial and tangential directions giving a blade element thrust $\frac{dT}{B}$ and a blade element torque force $\frac{dQ}{rB}$ and hence a blade element torque $\frac{dQ}{B}$ where B is the number of blades. The blade element thrust and torque values are integrated for all the blade elements in order to determine the overall thrust T and torque Q of the screw.

Unlike the momentum theories, the blade element theory does not make allowance for the changes in axial and angular velocities but this defect can be overcome by combining the momentum and blade element theories as shown in Fig 3.

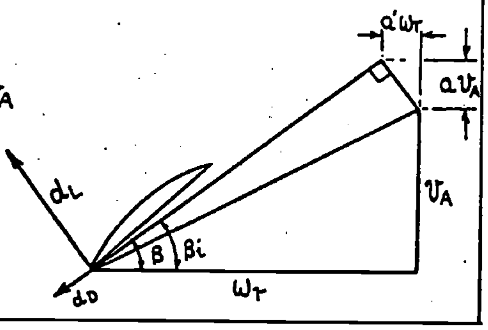
The combined momentum blade element theory provides a basic conception of screw propeller action, but it neglects certain factors that affect the fluid flow around the blades. However, the circulation theory makes allowance for these factors and provides a link between a blade section operating in two-dimensional flow and that operating at part of a screw. The circulation theory is based on the concept due to Lanchester that the lift developed by the screw blades is caused by a circulation flow that takes place around the blades. This will be discussed in a further article. ♣



Left. Fig. 1 Propeller momentum theory slip stream.



Below left. Fig. 2. Blade element theories.



Below: Fig. 3. Combined momentum blade element theory.

Strength analysis of unconventional types

With the application of propellers of unconventional design to achieve greater efficiency at quiet running, etc, problems such as heavier stresses are encountered. Strength analysis of the design is important, as outlined below from an article*, which records work being done by SSPA, the Swedish research establishment.

The classification rules and other design criteria available, which are to a large extent based on experience of operating with conventional designs, may not apply in cases where the new design deviates too much from the propeller design to which that experience relates. A detailed theoretical analysis is often the only way of establishing confidence in the new design.

Over the last six years a suite of computer programs for performing these calculations has been developed at SSPA. The method has been applied to numerous propeller designs, and has been regularly updated so that it now constitutes a versatile and reliable tool for use in the design of skew-back and other unconventional propellers.

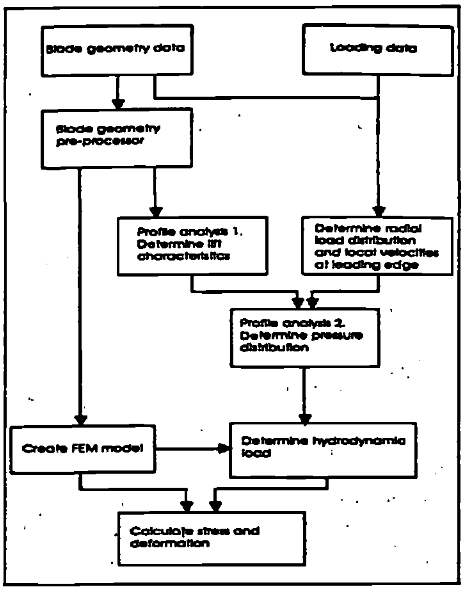
PROSA package

Correct determination of the stresses to which a propeller is subjected involves the study of local hydrodynamic load conditions and the way in which these vary during a single revolution of the blade; of the distribution of hydrodynamic pressure to which these load conditions give rise; and of the deformations and stresses that the calculated pressure distribution will cause.

Determination of the wake field is based on measurements obtained in cavitation tunnel or towing tank. Using this information and details of the propeller's open water characteristics, the velocity and angle of attack for which each blade section for different shaft and ship speeds can be determined.

The next step is to enter details of the blade geometry. This is normally done using a preprocessor. Starting from propeller data including rake, skew, thickness distribution, camber distribution and pitch distribution, the preprocessor determines Cartesian coordinates and profile thickness in about 200 node points on the blade.

The blade profile is not restricted to NACA profiles, but can be chosen freely. For the leading edge, which is of crucial importance to the blade's hydrodynamic properties, a much finer grid net is used.



The geometry data base is now used both as input for the pressure distribution calculation and to set up the Finite Element Model. Pressure distribution is calculated using a panel method for two-dimensional analysis of arbitrary profiles. Three-dimensional corrections are then applied.

Given the pressure distributions and the grid points of the Finite Element Model, the program integrates the pressures over the respective elements and thus determines the load to be applied. The resulting deformations and stresses are determined using the well-tried MSC/NASTRAN Finite Element code. The sequence of calculations is fully automated. Once the program package has been informed of blade geometry, load conditions and wake distribution, all subsequent calculations, including generation of the input deck for the NASTRAN program, can be carried out automatically. However, it is always possible to check intermediate steps in order to assure reliable end results.

Ideally, calculations of this type should be performed in advance of the model scale propeller tests, ensuring that the propeller to be tested is of realistic design. SSPA carries out calculations in connection with the hydrodynamic propeller design, but also sells the program package for implementation on the client's computer.

Fig. 1. Above. Steps in the calculation process.

Fig. 2. Below left. Blade stress levels in ahead.

Fig.3. Below right. Blade stress levels in astern.

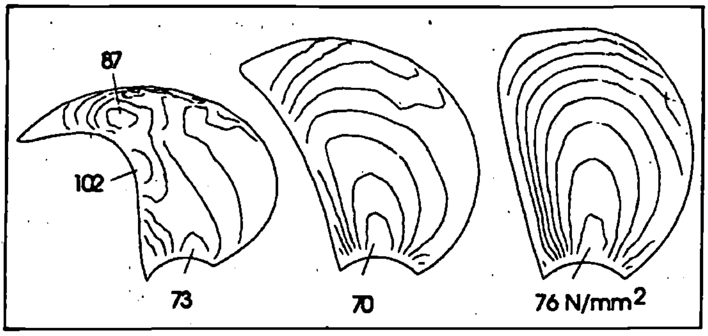
Typical examples

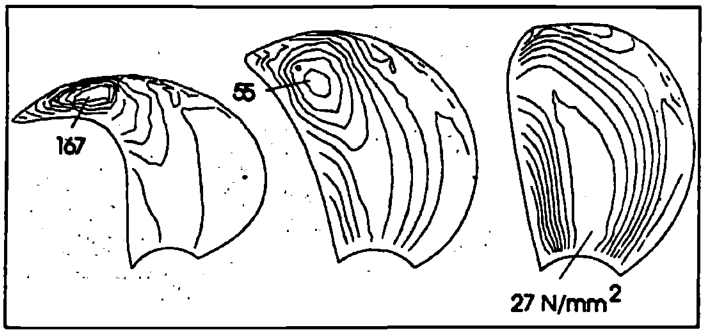
Fig 2 shows some examples of stress distribution for what is essentially the same propeller design, but with an increasing amount of skew-back. With the extreme skew propeller, the stresses at the root of the blade no longer determine the blade's strength. Instead, the maximum stress is at the trailing edge of the blade, around radius 0.5. This result is typical of skew-back propellers, and it is clear that stress calculations for this type of propeller cannot be performed employing the beam methods normally used for conventional propellers.

To determine the risk of fatigue, stress distribution is calculated at different blade angles in the wake, and the resulting average stress and stress amplitudes are plotted on a Goodman diagram, for comparison with given fatigue values for the specified material. With skew-back propellers, maximum stresses often arise during backing, so that it is also important to analyse this situation. In the case of the extreme skew propeller, maximum stresses during backing arise near the blade tip, and this stress level is about six times the level for a conventional blade subjected to the same load. A full-scale propeller of the extreme skew-back design referred to in these examples was manufactured and fitted to a ship before a proper strength analysis was available. The propeller failed after only a few weeks of operation, yielding along the tip of the blade, near the predicted point of maximum stress during backing. The propeller's failure emphasises just how important it is to analyse backing conditions with extreme skew-back propellers of this type.

Vane Wheel

The Grim Vane Wheel is another example of an unconventional propulsor that requires special attention. With a design of this type, the inner part of the vane wheel is subjected to negative thrust while the outer part is subjected to positive thrust. Although the net force from the vane wheel contributes only some 5-10 per cent of the total thrust, the loads to which the blade are subjected are quite sizeable, since the net force is the difference between the positive and negative thrust applied in different directions. The PROSA package is thus also very suitable for vane wheel analysis. ♣





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* "Unconventional Propeller Design: Focussing Attention on Strength," by Dr Staffan Sunnersjö, SSPA Maritime Consulting AB, Sweden. *SSPA Highlights, No 2 1987.*

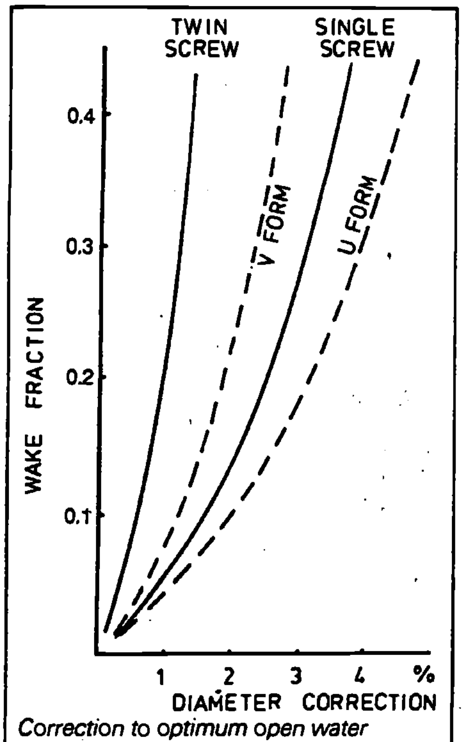
Evolution of the 'Meridian' propeller

The so called Meridian Propeller was first introduced in 1965, being the development of two former designs produced by different manufacturers who merged to form the single UK company, Stone Manganese Marine Ltd. Many thousands of Meridian propellers in powers from 90 to 58 000 shp per propeller have been produced and it has developed to include the variant large diameter slow turning "Economy" unit now used on large vessels such as VLCC's and bulk carriers. The development of the Meridian designs is discussed below, in extracts from a recent paper.[*]

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.


One of the larger Meridian propellers.

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 performance than a Meridian propeller fitted to a large bulk carrier, to the benefit of both.



Correction to optimum open water diameter to obtain behind diameter.

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, seems relatively small (in order of 0.5 to 1 per cent) 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.

Diameter

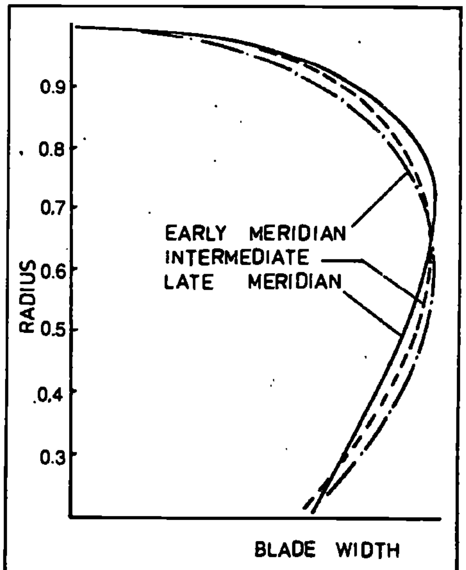
The choice of the propeller diameter is the single most important decision made by the designer. This is not only from efficiency considerations but also because of the dominating influence that the diameter has upon the resulting performance characteristics of the propeller in action. This includes 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 development of the Meridian a reduction in diameter of 5 per cent for single screw ships and 3 per cent for twin screw ships was globally applied in common with prevailing design practice. More recently, the results of research have enabled a more rational assessment of the appropriate correction to the open water diameter to be obtained.

Blade area

The widths of a propeller's blade sections are a function 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



Blade width distributions.

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[*] "The Evolution and Development of the Meridian Propeller", by G. Patience and L. Bodger, Stone Mangenese Marine Ltd., England. *SMM Technical Paper No. 21*, October 1987.

thrust. 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.

Further developments in vortex theory have enabled the action of a propeller in any specified flow regime to be investigated such that the local volocities 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.

As a result of the knowledge and experience gained in this field it is now possible in most instances to confidently 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.

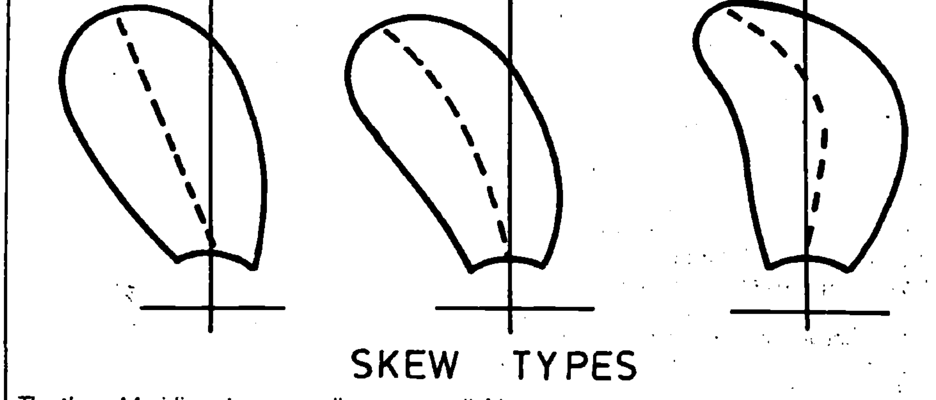
Section profiles

Whereas many designers commonly employ NACA profiles derived from aerofoil development 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.

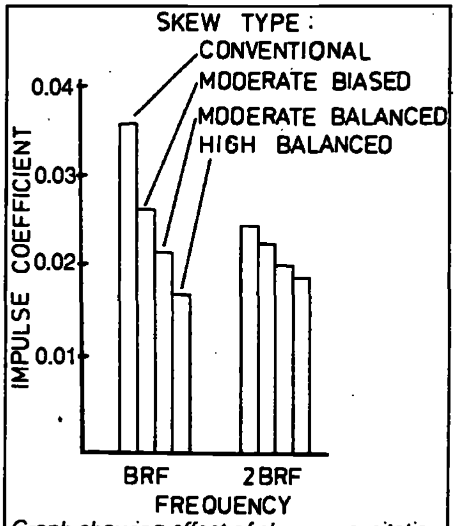
The majority of Meridian propellers are subject to a wake adaption progress as an integral feature of their design. The blade section is considered as a mean line, or camber line, extending from the section nose to the tail, about which the intermediate section thicknesses are evenly distributed. The 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 dependant 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.

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 methematical 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 analysis of full-scale trials and service results. In the case of the Meridian this has been accumulated over many years of successful applications.



The three Meridian skew propeller types available.



Graph showing effect of skew on excitation forces generated by the propeller in a non-uniform wake.

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 thickness 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. The level of the imposed stress derived from such a calculation is best considered in qualitive 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 permissable design stress which has been assigned in the light of previous experience with a large number of similar propellers.

More recently, the use of beam theory techniques for propeller blade stressing has to a large extent been supersceded 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. In this way it is possible to obtain a detailed insight into the distribution of stress throughout the blade.

Skewback

The term skewback as applied to propellers refers to the displacement of successive blade sections along the helical surface forming the blade datum. 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 the 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. Consequently, the safe design of highly skewed blades cells 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.

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.

Noise and vibration

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 lead 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 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.

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.

From the outset the fundamental geometry of Meridian propellers incorporates certain features 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. 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.

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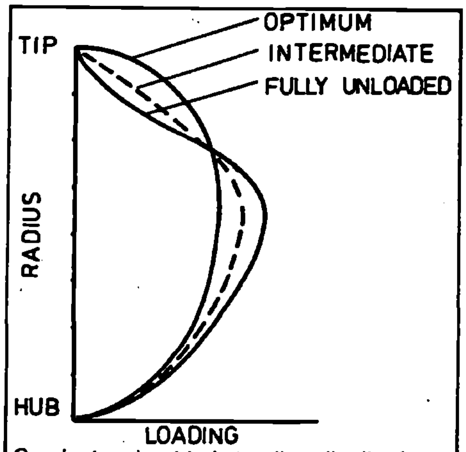


Graph showing blade loading distributions.

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 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 structure to achieve adequate clearances. As such it has no influence upon the design other than its implications upon the blade thickness in those cases where it is found necessary to employ high rake for this purpose.

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 philosophy and helps to explain why the design has for over 20 years been at the forefront of marine propeller technology. ♣

French fixed outdrive propeller

Following the lead established by Italian and British companies, a French company, Helice France, has developed a propulsion system for high speed boats using a fixed surface propeller. These systems differ from the variable propulsion systems developed in the USA such as the Arneson and Kaama Drives by using a fixed shaft which cannot be varied to give steering and trim control. Exponents of the fixed systems claim that they offer better reliability whereas the steering and trim features are claimed to give better control.

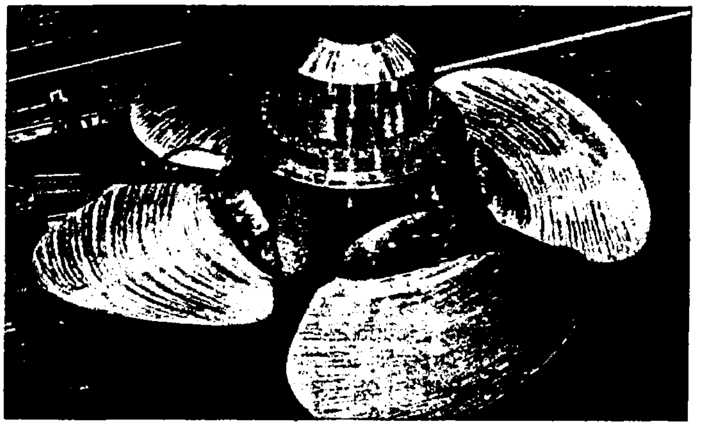
The system developed by Helice France uses a fixed outrigger bracket in cast aluminium to provide the shaft support. This bolts on to the transom to simplify installation and incorporates the engine exhaust outlet and the cooling water pick up and the rudder.

The engine exhaust is linked to a connection in the casting which directs the exhaust downwards to exit through the propeller shaft bracket where the exhaust gases serve to ventilate the top half of the propeller which in turn allows the propeller to rotate at higher speeds to help the boat through the critical power phase when the boat is coming on to the plane.

The rudder is mounted at the extremity of the outrigger, immediately behind the propeller and extending below the bottom of the propeller line. A tube attached to the rear of the rudder and extending just below the bottom of the rudder provides the pick up for the engine cooling water which is transferred to the engine.

Helice France offers five models of its surface drive capable of transmitting power outputs between 50 and 2000 hp. They are equally suitable for petrol or diesel engines and are primarily aimed at high performance craft with speeds over 40 knots where the surface propeller starts to show increased efficiency. ♣

Stainless steel or bronze for ice?



One of the larger KaMeWa built propellers for icebreakers.

Controllable pitch propellers for ships built to operate in ice are made of stainless steel or NiA1-Bronze and despite the 10 per cent increase in cost for the stainless steel propeller. the Swedish manufacturer. KaMeWa AB. claims this type to be the most suitable for ice conditions. The case for stainless steel as presented by the company is put forward here.

When comparing different materials suitable for propellers. one must be aware of the totally different working conditions and requirements for normal or low ice-strengthened propellers and propellers intended for heavy ice service. Blades for operation in open water or light ice conditions are solely dimensioned with regard to dynamic loads. and the corrosion fatigue strength of the material is the main factor influencing the thickness calculation. For icebreakers and other ships operating in ice covered waters. to a major extent the dominating loads are due to interaction with ice and they are 5 to 10 times higher than the hydrodynamic load on the blades. In the latter case. the yield strength of the material becomes an important factor for the thickness calculation.

Traditionally. NiA1-bronze is the material mainly used for propellers with or without low to medium ice-strengthening due to its low price. Its corrosive fatigue properties are good. In view of the low price it is. of course. tempting to use NiA1-bronze also for heavy ice-strengthened propellers but this should only be done after a careful investigation of the actual ice loads on the blades. The blade thickness must then be chosen large enough to avoid stresses exceeding the maximum allowable shock stress limit for the material.

Due to the usually higher oxygen content in cold water. stainless steel tends to passivate and the corrosion fatigue properties improve while NiA1-bronze instead gets more sensitive to corrosion. The ice impact leads to mechanical wear of the blade surface and experience shows that stainless steel is highly superior to NiA1-bronze in keeping the surface finish within recommended ISO limits. NiA1 blades must be frequently reconditioned in order to keep surface friction and fuel consumption down to acceptable levels.

In order to choose the correct material for a propeller for an ice going ship. blade performance on existing propellers is important to consider. Blade damage on propellers for ice going ships usually is bent edges and tips. broken blades are rare. However. slightly damaged blade edges or tips can be detrimental to the propeller's performance and lead to. for example. vibrations and reduced efficiency. Therefore. even slightly damaged propellers have to be repaired.

A higher yield point means a higher resistance to bending and less risk of bending damage. Experience from ferries in service between Finland and Sweden shows that bronze blades in general have considerably more ice damage than blades of stainless steel. The stainless steel c.p. propellers for the single screw icebreaking cargo ships of the SA-15 series and for the twin-screw icebreakers of the MUDYUG class. have had no blade failures in an accumulated lifetime of more than 100 years. The blade surfaces are practically in the same condition as when delivered from the factory 5 years ago.

Not only the tensile strength but also the yield point has to be taken into consideration. when deeming the suitability of propeller blade materials for ice-going ships.

TABLE 1: MECHANICAL AND CHEMICAL PROPERTIES OF METALS

	Cr-Steel	CrNi steel	Cunial
Ultimate tensile strength	65	73.5	66
Yield strength	45	49	26
Elongation	15	15	20
Corrosion fatigue strength	9	9	11
Impact strength Charpy	25	40	22
Brinell hardness	230	240-300	165
Chemical composition A1			9
C	0.08	0.035	—
Cr	13	16	—
Cu	—	—	80
Fe	82	Balance	5
Mn	1	0.8	1
Mo	1	1.0	—
Mb	—	—	—
Ni	1	5.0	5
Si	1	—	—
Zn	—	—	—
Magnetic	Martensite	Austenite-Martensite	Light

Stainless steel material can be exposed to at least 40 per cent higher load than bronze material before deformation arises. In order to obtain blades with equivalent resistance against bending and edge damages. the dimensions of bronze blades have to be increased compared to stainless steel.

The reinforcement of bronze blades can of course be attained in different ways depending on how much deterioration of the hydrodynamic performance of the propeller is acceptable. In order to obtain a bronze blade with completely equivalent load to a stainless one with regard to the stress level in relation to the effective yield point of the material. the blade thicknesses have to be increased by at least 20 per cent over the entire blade area. A blade of bronze reinforced like this will sustain exactly the same outer load as a stainless steel one before permanent deformation arises. In order to maintain the required cavitation margin with the blade with increased thickness. the section lengths of the profiles have to be increased. An increased section length means a larger blade area. a higher hydrodynamic friction of the blade and a reduced propeller efficiency.

It appears that a ship with stainless steel propeller blades designed to the same strength as a NiA1-bronze blade will have lower fuel consumption than a ship with NiA1-bronze blades. The difference in fuel consumption with the two materials is estimated at 0.5-1 per cent.

The ice load on nozzle propellers is lower than on open propellers. In view of the higher corrosion fatigue strength bronze is acceptable for nozzle propellers, provided the fatigue load. not the ice load is the dominating factor for the design. However. chromium steel propellers also in a nozzle are superior in view of their higher surface hardness and erosion resistance. When operated in shallow water nozzles have a tendency to draw gravel into the water entering the propeller. Hence a nozzle propeller is exposed to erosion to a greater extent than an open propeller.

Casting of c.p. propeller details can be accurately controlled. Of course a bronze foundry will have difficulties with stainless steel. Material checking methods for chromium steel are far more reliable than for bronze. With bronze usually only surface cracks are discovered. The checking of chromium steel can be done right through the material.

With regard to repairability of minor damages stainless steel and NiA1-bronze are equivalent technically and cost-wise. Major damage is much more easily repaired with stainless steel than with bronze, because stainless is easier to weld. After heat treatment stainless steel and bronze both have the same fatigue strength.

Looking at the complete c.p. propeller system (including the shaftline, hydraulics and remote controls) equipment with propeller hub and blades in stainless steel is only about 10 per cent more expensive than with NiA1-bronze hub and blades.

KaMeWa has over 40 years of experience from c.p. propellers operating in ice. It has delivered 334 stainless steel and 268 NiA1-bronze propellers for ships with high ice class, i.e. equal to or above the Baltic 1A, USSR UL, CASPPR 2, GL E3 or comparable classification requirements. Based on service experience from these propellers, KaMeWa has hard facts regarding the most suitable propeller material for heavy ice strengthened propellers. More than 95 per cent of the world's icebreakers and icebreaking cargo ships have stainless steel propellers. Hence it is obvious that NiA1-bronze is a highly unusual material for heavy ice strengthened propellers.

TABLE 2: DnV PROPELLER BLADE REQUIREMENTS

	Yield point (N/mm)	UTS (N/mm)
Chromium steel 13.1	390	590
Chromium steel 13.4-6	590	735
Chromium steel 16.5	590	785
NiA1 bronze	(245-275)	590

The corrosion resistance of both materials is equal. Both materials are exposed to crevice corrosion in blade sealing areas to the same extent. However, sealings cause wear to bronze to a higher extent than to stainless steel. With stainless steel propellers the risk for crevice corrosion can be eliminated by welding on stainless steel of higher corrosion resistance in the sealing areas as it is done with the SA-15 propellers. Such possibility does not exist with NiA1-bronze.

Stainless steel has obvious advantages also when used for propellers operated in open water. However, due to the fact that it is difficult to cast large solid fixed pitch propellers in stainless steel in one piece (It has been considered to build up large solid propellers from pieces of stainless steel) and that stainless steel requires much heavier milling and grinding equipment for machining, the vast majority of non or light ice-strengthened fixed-pitch propellers are made of NiA1-bronze. Large bronze foundries are available to meet the demand from the shipbuilding industry. Today the market is depressed and the bronze foundries cannot fill their capacity. Bronze is available on the market at very low prices, by which the bronze suppliers try to increase their market share.

Ice going propellers are extremely good business, especially bronze propellers, because of the demand for spare blades and repair, which is considerably higher than with stainless steel. Therefore, and because of lack of orders for large fixed pitch propellers, the bronze propeller manufacturers put special efforts on ice breaker projects today, which they did not during the days of the tanker boom.

KaMeWa has experience from operation in ice with both materials with 334 highly ice strengthened KaMeWa propellers in stainless steel and in NiA1-bronze. From this experience, KaMeWa draws the conclusion that stainless steel is to be recommended as the superior material in ice.

Propulsion control by computer

In a functional "ship" system, several subsystems can be distinguished, the propulsion sub-system being relatively important. Its performance can be optimised with respect to efficiency, maintenance, safety and operational cost. These duties can be successfully accomplished by a suitable computer system, and for complex propulsion plants and joystick controlled sub-systems, the advantages are most striking. A recent paper*, extracted from here, describes the development of a microcomputer based propulsion control system. Propulsion remote control systems.

Traditionally, Lips has supplied control systems as a part of the propulsion package further consisting of propellers, shafting, shaft seals, thrusters, nozzles and servo-systems.

Early control systems were of electric or pneumatic type and merely acted as pitch positioners. With the development of more reliable electronic components it became possible to accommodate more functions into the control system, such as overload protection and schedulers. Electronic propulsion control systems contain advanced functions as load control and load sharing. Such systems can be used to control the manoeuvring of the vessel, eg joysticks integrate control of all propulsion and steering devices.

Variation of the parameters of the propulsion control process can be made in such a way that they lead to minimisation of fuel consumption. This is of special interest for ships doing long distance voyages and for combatant ships requiring a long range.

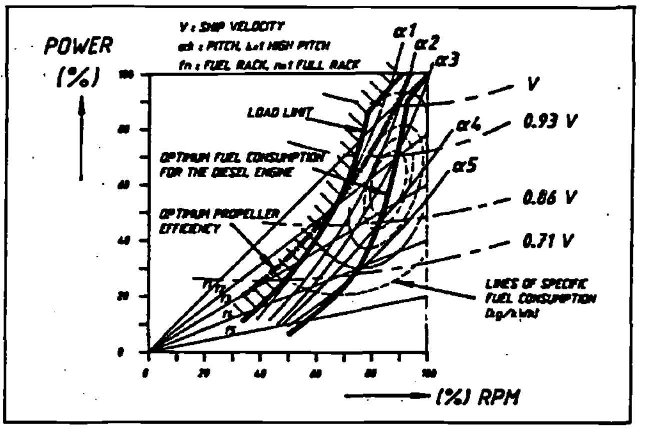


Fig. 1. Graph showing propulsion power absorption and optimum propeller efficiency.

An example of the operational area of a diesel engine together with the characteristics of a controllable pitch propeller are shown in Figure 1.

The curve of maximum engine efficiency is found where the specific fuel consumption is minimum for a given power.

The curve of maximum propeller efficiency is found where the required power is minimum for a given ship speed. The curves hardly ever match. Depending on the ratio maximum/service power they only intersect at the design point of the propeller. Operational aspects of the vessel may very well complicate the design of the propeller; the requirement to complete a variety of missions such as station keeping and special manoeuvring, and operation over a wide speed range. Limitation of pressure pulses on the hull also may result in the propeller curve to deviate from designs with fewer constraints. The maximum efficiency curve for the propeller is based on calculations and model tests, for the diesel engine on testbed results. The best combination of propeller pitch and revolutions is somewhere between the curve for maximum propeller efficiency and the one for maximum engine efficiency, taking into account the engine load limit. It is calculated by evaluating the gradient by which propeller and engine efficiency decrease when drifting away from the maximum efficiency setting. In practice large deviations can occur due to fouling of propeller, hull and engine, but also because of bottom clearance and trim. A microcomputer can take into account all these effects when the actual fuel consumption, thrust, revolutions and speed are measured. Computerised propulsion control can improve fuel efficiency up to about 3 per cent.

Changing the propeller pitch and speed of rotation, influences the noise spectrum

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* "Computerised Propulsion Control", by J. de Cock, Lips B.V. Presented at the 6th Lips Propeller Symposium, Drunen, The Netherlands.

emitted by the propeller and the level and frequency of pressure pulses to the hull.

For ferries, cruise ships and research vessels noise and vibration can be minimised. For ships engaged in anti-submarine warfare, the potential to improve or modify the ship's noise signature is of vital importance. Lips has successfully tested a minimisation algorithm on board the standard frigate HMS PIETER FLORISZ of the Royal Netherlands Navy.

Beside the noise minimisation routine use is also made of electronic propeller pitch feed-back of high accuracy. During the trials the radiated noise of the propulsion system was reduced by 3 to 12 dB depending on the selected ship speed. The fuel consumption by the gas turbines plant appeared to alter in a range up to 12 per cent during this exercise. This spearheading performance made the optimisation environmental equipment for the Multi-purpose Frigates under construction.

Manoeuvring simplification

An example of controlled ship motion is constant speed of advance being of interest for dredgers and cable layers. Limited tension in towing or mooring lines is desirable for tugs, drill ships and semi-submersibles with anchor assist dynamic positioning systems. Ferries, diving support vessels, supply vessels and dredgers require precise position control. Icebreakers require propulsion control systems assuring maximum available power to or thrust delivered by the propellers.

Propulsion and manoeuvring devices are co-ordinated by analogue or digital joystick systems. Lips has delivered a dozen digital Lips-stick systems, which have the advantage of containing far less printed circuit boards as compared to the analogue electronic versions.

Both types of integrated control greatly improve the effectiveness of propellers, rudders and thrusters in the most varying conditions, meanwhile relieving the crew from operational fatigue. Moreover, digital dynamic positioning systems stimulate the application of adaptive control, which means correction of control parameters based on actual conditions. Such adaptive controls are used in auto-pilot systems now. Their advantage is an increased accuracy in rudder control and consequently a better fuel efficiency. Future station — and track-keeping control systems, though of higher order, will take advantage of adaption techniques.

Lips propulsion control

The first generation of the Lips digital propulsion control systems are based on the Intel 8085A microprocessor. Nowadays, analogue control systems are composed of dedicated single eurocard printed circuit boards. With the demand for versatile systems analogue boards no longer can be applied in extensive configurations on a cost-effective basis. Although it is feasible to apply micro-technology in existing analogue systems, Lips has decided to select a commercially available microcomputer system.

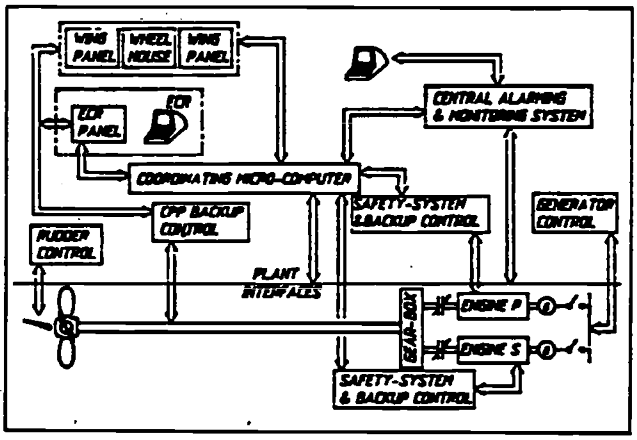


Fig. 2. Layout of a propulsion control system.

This decision is based on the conviction that future systems must be multi-functional. The lasting efforts to reduce cost and increase capacity of microcomputers will only stimulate the application.

The Lips microprocessor propulsion control now under development will be equipped for speed control and manoeuvring control.

Speed control in this context means coordination per propeller unit of propeller pitch, prime movers, clutches and power take-off by one dedicated microprocessor.

The control can take care of load limits, safety of operation, backup, optimisation as well as health monitoring.

Manoeuvring control implicates the levels of microprocessor control. *The central level* microprocessor is equipped to integrate control of all manoeuvring devices: rudders, propellers and thrusters. *The individual level* concerns the microcomputer as described for the speed control system. All manoeuvring devices should have their own dedicated microprocessor control system. The lowest level control simply means the back-up control by push-buttons for every individual propeller, engine, rudder and thruster.

Lips has selected a system based on Intel 8086 microprocessor supported by an Intel 8087 numeric data processor for arithmetic processing. The central processing unit is provided with a local bus and a communication bus. The local bus is intended for extension of Random Access Memory (RAM) and Red Only Memory (ROM), the communication bus for data exchanges with other central processing units and input/output boards. The operator is provided with system data on monitor. Request for data can be given *via* a keyboard. The keyboard/monitor combination together with the application of Electrically Erasable Programmable Read Only Memories (EEPROM) enable the operator to scale input and output signals after main repairs to the machinery. It is also used as diagnostic support in case of malfunctioning. Interfaces for data exchange with other computer systems are available. Malfunctioning of the microcomputer system is detected by a watch-dog board. The internal power supplies are checked and health signals are received by this board. In case of a fatal error — one of these signals is lost — a back up system automatically will take over control ensuring a stay-as-it-is mode. Non-fatal errors are detected and consequently a signal is given to the central alarm system. By means of the diagnostic support program, the fault can be isolated by the operator.

Fig 2. depicts a lay-out for a propulsion system consisting of a controllable pitch propeller driven by twin diesel engines. Essential functions such as hydraulic pump control, pitch indication and shaft speed indication are not executed by the microcomputer system. These functions are performed by separate electronic lamps such as the clutch state are connected by hard wire to the respective switches. In case of a malfunctioning it must be ensured by the back-up system that the respective station remains in service. Both pitch and shaft revolutions must be controllable from this station without risk for overload situations. System integrity and safety will be ensured by a hardware configuration as described above. Installing a triplex system as a back-up facility is much more expensive. At set-up time, the propeller is not under control of the computer, but under control of the back-up system. During set-up, the operator has the possibility, with aid of a keyboard and a display unit to change parameters and save them in EEPROM to prevent loss in case of a power failure. Several system checks and diagnostic routines are available to the operator to facilitate maintenance and to locate eventual malfunctioning of the system. In the set-up phase, control of the propeller can be passed on to the microcomputer with the aid of a simple keystroke. At run-time, a logging task is active, which logs and stores data as defined during set-up. These and some statistical data, can be used for display and for sending to a printer or another computer system. Such data, logged by the logging task, are useful to monitor engine and propeller performance and can be used to indicate deterioration of propeller efficiency due to fouling.

During run-time, an operator task is active. This task has low priority in order not to disturb propeller control. With this task, the operator can stop the control of the propeller (eg to run diagnostics or other modules), change parameters, show the status of several process parameters or can display various (statistical) results of the logging tasks. ♣

Advantages of the Speed Z units

In recent years it has become apparent that the existing propulsion and steering concept for high speed craft (catamrans, surface effect ships) has become out of date in relation to the requirements for weight, efficiency, and simplicity for modern craft of this type. The only breakthrough in this field is the waterjet which has a limited area of application. Two Norwegian companies, Liaaen Helix A/S and A.M. Liaaen A/S have developed a new propulsion system, considered to be suited for high speed craft of today and generations to come. This is known as the Speed Z propulsion system.

Construction

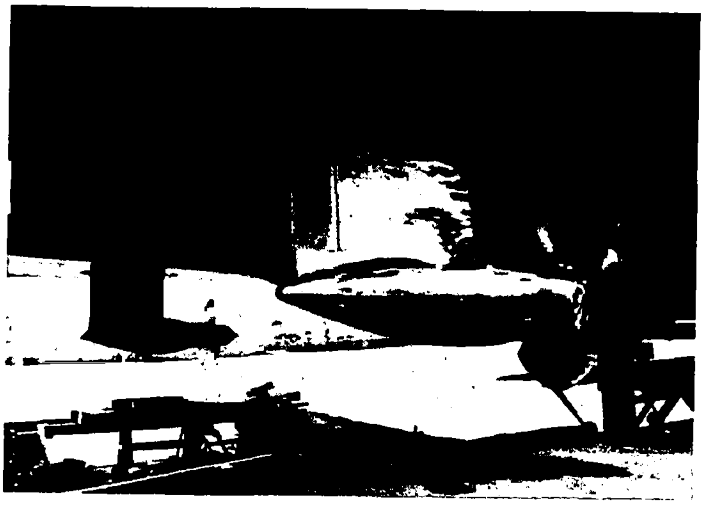
The Speed Z unit consists of a top gear with clutch and an underwater gear with rudder and propeller. The propeller is of controllable pitch type and the complete unit integrates all necessary functions for propulsion and steering of a twin-screw vessel. The power from the main engine is transmitted by means of shaft, clutch and bevel gear. Since the main engine is usually mounted on flexible supports to reduce vibrations, the intermediate shaft from the main engine to the upper bevel gear is equipped with curved-tooth couplings. The clutch is of multiple type and is actuated hydraulically. It also has a supply of lubricating oil which allows it to run disengaged for an unlimited period of time. The spiral bevel gears are manufactured to a high degree of precision according to Klingelnberg's HPG method which guarantees a low level of noise and smooth running. The shafts on which the gears are bolted are substantially supported in roller bearings.

The top gear housing is cast in high strength aluminium and the lower gear housing cast in stainless steel. The four-bladed propeller hub is cast in NiA-bronze.

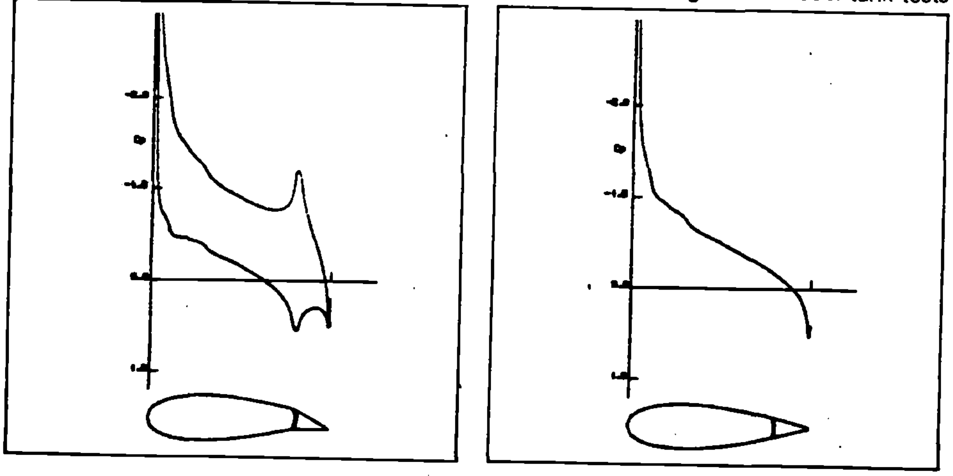
The total weight of the propulsion unit has been kept to a minimum. Necessary rigidity in the housings has been obtained by optimal geometrical design and by the use of ribs.

To minimise the frictional loss in the oil, the oil, which fills the unit completely when not running, is pumped up to a tank located at a higher level. This means that only a small quantity of oil is left in the bottom of the lower gearcase. In operation the pump takes its oil from the bottom of this gearcase.

Right. The two Speed Z thruster units fitted to the ANNE LISE.



Below left. Pressure difference across the stern when the rudder is actuated and, below, not actuated.



An equivalent amount of cooled and filtered oil is led continually back to the gearhouse *via* the lubrication points. When the main engine is stopped the unit is automatically filled up with oil from the overhead tank. Since the lower gearhouse operates at atmospheric pressure, it has been necessary to supply oil at a suitable pressure to the propeller hub and to the shaft seal box. This has been achieved by a simple nozzle and valve system which takes oil from the pitch control system.

To ensure that the propeller runs with as little vibration as possible, the propeller blades are dynamically balanced, while the propeller hub and pitch changing mechanism are statically balanced. The control of the pitch of the propeller blades and the control of the rudder is electronic/hydraulic, with the hydraulic valves situated on the hydraulic module.

The remote control is a computer based control of the Liaaen Helitron CPZ type which integrates the control of engine speed, propeller pitch, rudder and engine load in a common system.

Steering

For steering the vessel, the stem of the underwater casing is shaped as a vertical hydrofoil, into which the rudder surface is integrated. The stem is not steerable, but the small rudder surface at the rear of the foil creates a lift pressure over the whole surface of the foil, in a similar way to a flap on an aircraft wing. From model tank tests with the complete unit, it was shown that this principle gives large rudder forces. Adjusted to the full scale engine output of 2040 kW, a propeller speed of 769 rev/min, and a ship speed of 25 knots, the test tank measurements gave a rudder force of 98 kN at 35 degrees rudder angle.

Propeller

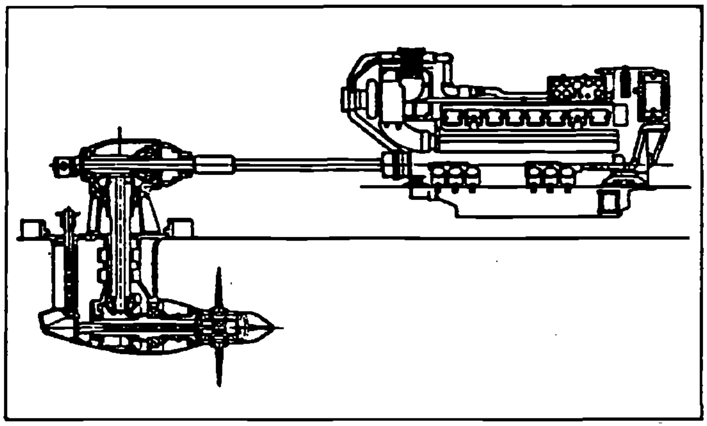
Since the Speed-Z unit uses a traction (pulling) propeller there are no apendages in front of it and therefore the propeller acts in a homogenous velocity field. These are ideal conditions for efficiency and avoidance of damaging cavitation. This has been substained by cavitation tests and prototypes in operation which produce no noticeable noise or vibration in the hull.

Another major advantage is the right angle drive which allows the propeller to be installed in line with the water flow. A conventional propeller installation is always a compromise between keeping the shaft angle low to avoid harmful root cavitation and ensuring sufficient clearance between the propeller and the hull to avoid noise and vibration from the high pressure pulses created by the propeller. The Speed-Z unit has, as mentioned, the best possible conditions of flow to the propeller giving stable cavitation conditions and minimal fluctuating forces.

A comparison has been made, based on model test tank results with the Speed-Z unit, with a conventional installation with sloping shaft, brackets, and rudder. The propeller on the conventional installation had a diameter of 1.6 metres with a maximum speed of 525 rev/min, while the Speed-Z unit has a diameter of 1.25 metres at 769 rev/min. Even though the Speed-Z unit is more highly loaded, that is the power per unit area is greater, the propeller efficiency is 76 per cent at an engine output of 2040 kW and ship's speed of 28 knots. The corresponding efficiency of a conventional installation is 72 per cent.

When the resistance of the appendages was taken into account the improvement in efficiency was even more significant. The result of the model tests showed that the overall propulsive efficiency of the model fitted with the Speed-Z was 66 per cent at

28 knots which compared with 58 per cent for the conventional system as described above. In this case the new Speed-Z gave an improvement in efficiency of eight per cent, that is to say a saving in installed power of 13.8 per cent to achieve the same speed.



The Liaaen propulsion and steering system for high speed craft.

Pitch/load control

The Speed-Z unit has a controllable pitch propeller. This is considered to be necessary for this type of high speed craft which will meet a substantial increase in resistance in heavy seas and in the loaded condition. With a C.P. propeller combined with load control it is always possible to make use of the maximum engine power at reduced speeds. If a fixed propeller is used it will become too "heavy" to drive at lower speeds due to the increase in resistance. The speed must therefore be reduced to avoid overloading the engine. This in turn will reduce the engine power, causing a further reduction of speed.

The first two Speed-Z units are installed on a cargo-catamaran, ANNE LISE, which was built by Westmarin A/S for the shipowner Gods-Trans A/S. The boat is built for a speed-range up to 28 knots and has demonstrated good manoeuvrability using the integrated rudder down to as low as four knots. Since the vessel has two propellers it can easily be manoeuvred at lower speeds by varying the propeller pitches. ♣

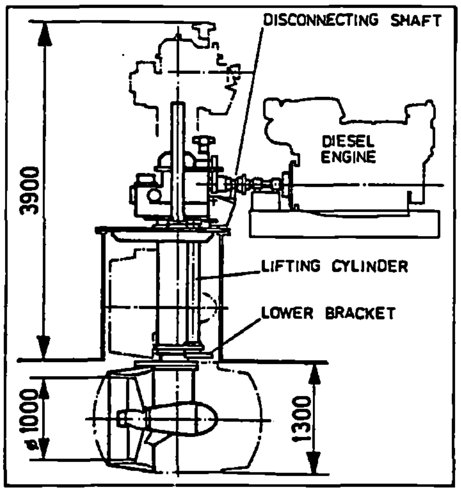
Tug upgrading service from Wijsmuller

A service to tug and other specialised craft owners to improve performance and a maintenance planning system, are now available from the Dutch consultants, Wijsmuller Engineering B.V., IJmuiden. The tug upgrading service applies to older conventional vessels and involves the fitting of a retractable thruster unit in the bow of tugs that are structurally sound but lack manoeuvrability and pulling power compared with modern tractor tugs. According to Wijsmuller, the advantages of such a conversion are:

- ● Increased operational performance of single/twin screw tugs to that of a modern stern drive or tractor type tug.
- ● Increased total bollard pull.
- ● Extended life of the tug by some 10 to 20 years depending upon the condition of the tug.
- ● Increased safety in operation for the tug and its crew.
- ● Greater flexibility in operation.
- ● Crew reduction can be achieved within statutory requirements.
- ● Higher utilisation can be achieved.

The azimuthing thruster unit is purchased from specialist manufacturers such as Holl-ming, Finland, but considerable preparatory work and supervision is done by Wijsmuller. The nature of tasks that can be undertaken are as follows:

- ● Conduct a technical, operational and financial feasibility study to the possibility of installation of a retractable thruster unit.
- ● Prepare a General Arrangement plan and specification for the modifications with location of the thruster with regard to operational and space requirements. Determination of the required output of the thruster and allowing for re-arrangement of the wheelhouse and deck equipment. Investigation of the steering gear and rudders for sternwise operation and re-arrangement of the accommodation.



Above. The retractable Aquamaster UL316 azimuthing unit.

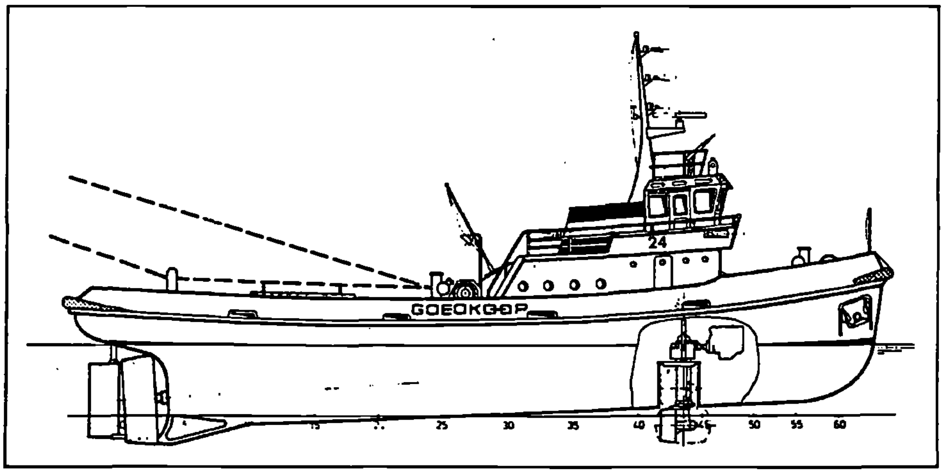
Below. PETRONELLA J. GOEDKOOP, one of the tugs converted to a Combi tug.

- ● Preparation of the tender documents for equipment required, steelwork and outfitting.
- ● Training of tug crews on similar vessels and on the job training by Wijsmuller's experienced captains.
- ● Preparation of technical and operating manuals.
- ● Introduction of the vessels on delivery to pilots, harbour authorities etc. at the owner's port of choice.

Today many single screw tugs, fitted with 360 degree steerable bow thrusters are in operation in the USA, Finland, UK, France and The Netherlands, to the satisfaction of owners. These vessels range in power from 900 to 3000 bhp while the installed thrusters range from 300 to 650 bhp.

A further Wijsmuller Engineering service introduced this year is the Maintenance Planning and Control System (MPCS). The computerised system provides the vessel owner with a comprehensive overview of the day to day checks on maintenance, running hours, repairs and surveys, giving information on past, present and future running hours/maintenance requirements per vessel and per item. The software is user friendly and can be installed in an IBM compatible computer and it requires a Lotus 123 spread sheet.

The above are two examples of consultantcy services offered by the Dutch company to small vessel owners worldwide. ♣

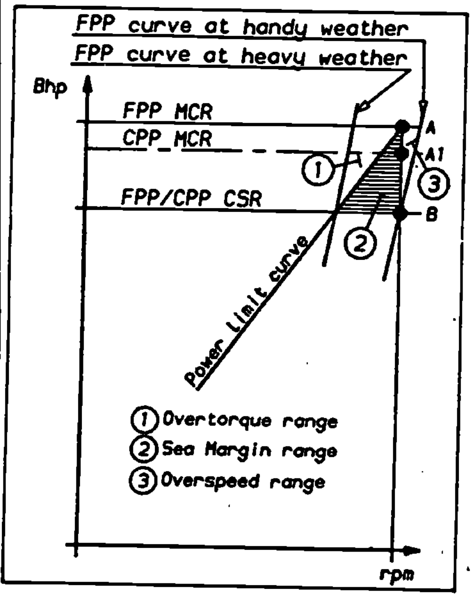


Save fuel with a c.p. propeller

There have long been arguments about which is most efficient, a fixed pitch or controllable pitch propeller. The fixed pitch propeller is designed for "average" service conditions and therefore cannot always be used optimally during a voyage. A c.p. propeller can use larger diameter highly skewed blades and it is said can be more efficient. A study made by the Swedish manufacturer, Kamewa and reported in this article, aims to show that with a c.p. propeller the installed power will in any condition be made available to create propulsive thrust.

Kamewa's study for a cargo vessel was based on the following data:

	f.p.p.	**c.p.p.**
Propeller dia. m	6.3	6.8
Engine power, bhp mcr	18 880	17 850
Engine power, bhp csr	15 680	15 680
Shaft speed, rev/min	117	102
Prop eff at 14 kts	0.48	0.51
Voyage distance, n.m.	2000	2000
Average speed, kts	13.89	14
Sailing time, hours	144	143
Fuel cons. tons	279	274



Any ship's propeller must be able to meet large variations in weather etc. Referring to Fig 1., a c.p. propeller is capable of operating at any power up to the level of point A, independent of weather, whereas a f.p. propeller is designed for point B at handy weather in order not to overload the engine at heavy weather. As a consequence, the f.p. propeller is not able to reach point A at handy weather, without overspeeding the engine. The sea margin (range between A and B) is required to minimise losses in speed at heavy weather.

With a c.p. propeller the possibility to keep a given time schedule improves considerably because in heavy weather ship speed losses due to shaft speed drop in the overtorque range are avoided by decreasing pitch. Also, in handy weather, ship speed can be increased by increasing pitch. Neither of these two measures is, of course, possible with a fixed pitch propeller. With a c.p. propeller, a small sea margin is required and the engine must be designed for an mcr power corresponding to A, while for a c.p. propeller, a lower mcr power corresponding to A1 is sufficient. The investment cost for the engine is therefore reduced with a c.p. propeller.

Improved propulsive efficiency

Highly skewed blades with their protruding blade tips are not feasible with a f.p. propeller because they will not withstand the excessive stresses in astern operation. The advantage of the skewed blade design means about 50 per cent lower propeller induced pressure pulses.

Left. Fig. 1. Propeller performance in varying weather conditions.

Below. Fig. 2. Propeller operational profile diagram.

Below right. Overall savings in fuel costs offered.

The propeller diameter can be increased and consequently propeller efficiency improved, provided the optimum shaft speed is chosen. In spite of smaller clearance, the specified pressure pulse level limit is then maintained. With a 10 per cent increase in propeller diameter the fuel saving is a 3-5 per cent.

Study results

In the operational profile diagram (Fig 2) the trip with a f.p. propeller vessel as well as a c.p. vessel can be followed. The ship will reach its destination within 143 hours. The distance is 2000 nautical miles. The required average speed corresponds to the speed at csr of 14 knots.

There are three phases of weather periods during the trip.

1. Handy weather during the first 72 h.
2. Heavy weather corresponding to an increase of ship resistance by 30 per cent during 24 h.
3. Handy weather during the end of the trip.

The comparison f.p. propeller/c.p. propeller in the three weather phases is as follows:

Phase 1: 14 knots both for c.p. and f.p.

Phase 2: 13.3 knots for f.p. due to shaft speed drop. 13.4 knots with c.p. (MCR condition).

Phase 3: 14 knots with the f.p. 14.25 knots with the c.p.

In Phase 3 the captain tries to increase the speed in order to compensate for the delay caused by the heavy weather during Phase 2. This is impossible with the f.p. propeller without overspeeding the engine. With the c.p. propeller the pitch can be increased and consequently the speed as well.

The conclusion is that with the c.p. propeller the time schedule is kept in spite of the smaller engine and with the f.p. propeller it is not possible to fully utilise the power installed. Due to 3 per cent better propulsive efficiency with the c.p. propeller, the fuel consumption is less.