The Voith Schneider Propeller
Current Applications and New Developments

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Voith Schneider Propellers (VSP) are used primarily for ships that have to satisfy particularly demanding safety and manoeuvrability requirements. Unique to the Voith Schneider Propeller is its vertical axis of rotation. The thrust is generated by separately oscillating, balanced propeller blades. Due to its physical operating principle and its design, thrust adjustments can be done very quickly. The VSP, a controllable-pitch propeller, permits continuously variable thrust adjustment through 360°. Combining steering and propulsion. Rapid, step-less thrust variation according to X/Y coordinates improves ship handling.

Voith Schneider Propellers operate at a comparatively low rotational speed and are therefore notable for their long service life and very low maintenance requirements. Currently, VSPs are used primarily on Voith Water Tractors (VWT), double-ended ferries (DEF), mine countermeasure vessels (MCMV), passenger ships, buoy layers and floating cranes. The development of the Voith Water Tractor (VWT) is significant and has dramatically increased the safety of tug operations. When escorting ships carrying hazardous cargo, the Voith Water Tractor achieves the highest assistance forces for a wide speed range due to its optimum design. Specifically designed VWT´s enable escort duties to be carried out safely, even at high speeds. The Voith Water Tractor marked the introduction of indirect steering to ship assistance.

Recently, the systematic use of Computational Fluid Dynamics (CFD) has provided a more detailed understanding of the flow physics of the Voith Schneider Propeller. Combined with the use of modern development tools (3D-CAD, FEM), CFD is opening up new prospects for accelerated development work. Continuous improvements in the VSP’s hydromechanical properties
will bring in new applications for this type of propeller. The Voith Schneider Propeller is based on an invention by Ernst Schneider dating from 1925. The Voith company took up the idea and, working with the inventor, brought it to maturity. By 1927, the propeller was sufficiently advanced for a test boat to be produced. The idea behind the Voith Water Tractor and its practical implementation are associated with Voith engineer Wolfgang Baer. Development of the VWT started in 1952.

The following sections describe the construction of the Voith Schneider Propeller, the physical principle behind its operation and examples of its application. They also describe recent developments such as the Voith Cycloidal Rudder and the Voith Turbo Fin.

The Voith Schneider Propeller generates thrust by means of profiled blades that project from the bottom of the ship and rotate about a vertical axis. The blades are mounted in a rotor casing that is flush with the bottom of the ship (Figure 1).

Superimposed on the rotary motion of the blades about the common vertical axis is a local oscillating motion about the respective axis of each blade’s shaft. To generate the oscillating motion, a kinematic mechanism is used to control the blades relative to the blade circle tangent as they revolve as a result, directional thrust is obtained.

Since the VSP simultaneously generates propulsion and steering forces, there is no need for additional appendages such as propeller brackets, rudders, pods, shafts etc.

A significant difference between the Voith Schneider Propeller and the screw propeller is the direction of the axis of rotation relative to the direction of thrust. In the case of screw propellers, the axis of rotation and the direction of thrust are identical with the VSP they are perpendicular to one another (Figure 2).

Thus the Voith Schneider Propeller, has no preferential direction of thrust and allows infinite variation in the magnitude and direction of thrust.

Figure 3 shows a 3D-CAD illustration of a type R5 Voith Schneider Propeller. The sectioned view (Figure 4) illustrates its construction. The energy required to generate the thrust is supplied to the rotor casing (1) via the flanged-on reduction gear (7) and the bevel gear (6). Gland bearings or special roller bearings are used to support the blade shaft. The rotor casing is axially supported by the thrust plate (10) and centered radially by the roller bearing (11). Due to the kinematic system (3), the blades (2) perform an oscillating
motion. The amplitude and phase of the blades’ motion is determined by the position of the steering center and hence the magnitude and direction of thrust are varied by means of the control rod (4).

The control rod is actuated by two orthogonally arranged servo motors (5). The propulsion servo motor is used to adjust the pitch for longitudinal thrust (forward and reverse motion of the ship). The rudder servo motor is used for transverse thrust (motion to port and starboard). The two servo motors permit steering according to Cartesian X/Y coordinates (identical with the principal axes of the ship), controlled changes in thrust are possible via the thrust-free condition (“from zero”). For example, its direction can be changed from full ahead to full astern at a constant speed of rotation without creating disturbing transverse forces.

The division into propulsion thrust and steering forces, i.e. steering according to Cartesian coordinates, makes handling the ship an easily understood and user-friendly process for the helmsman. Fitting the Voith Schneider Propeller with mechanical controls for the servo motors and an oil pump (12) flanged to the input gear results in a self-contained propulsion and manoeuvring system which, apart from the torque input, requires no other source of power.

The step-less nature of the controllable pitch Voith Schneider Propeller, which is not direction-dependent, is made possible by a technically sophisticated kinematic system. Various mechanical kinematic systems and hydraulic blade actuating systems were developed and used in the course of development [1]. The current generation of VSPs is fitted exclusively with the robust crank-type kinematic system. Figure 5 illustrates the kinematic principle of the VSP.

If the centre of the lower spherical bearing (steering centre) is at the centre of the rotor casing, the blades are not angled relative to the tangent to the blade circle (Figure 6a). If the lower spherical bearing is moved away from the centre of the rotor casing by the actuation of one or both servo motors and the lever action of the control rod, the blades are set at an adjustable angle to the tangent of the path as they revolve.

The maximum angle of attack of the blades increases with the eccentricity. Since the blades are very largely balanced, that is to say the resultant force due to the hydrodynamic effect and inertia acts in the region of the extended shaft axis, the eccentricity can be varied very quickly and with little power from the servo motors, thanks to the considerable leverage effect of the control rod (Figure 5).
This technical solution is the basis for the rapid and sensitive variation in thrust of Voith Schneider Propellers. For reasons of design, the mechanical excentricity, i.e. the position of the lower spherical bearing (Figure 5) is very much less than that of the position of the hydrodynamic steering centre N or N', which will be explained below (Figure 7).

Due to the controllable pitch of the Voith Schneider Propeller, it can be operated at a constant speed. However, it is customary to vary the speed and pitch to optimize energy utilization. Voith Schneider Propellers are currently available for input power up to 4 100 kW. The blade orbit diameter varies within a range from 1.2 m to 3.8 m. VSPs are manufactured with four, five or six blades.

The blades of the Voith Schneider Propeller move along a circular path while simultaneously performing a superimposed pivoting motion.

The perpendiculars of the chords of the profiles intersect at a single point, the steering centre N, as the blades revolve. Figure 8 shows the movements of the blades a) for an observer standing on the propeller and moving with it and b) for a stationary observer.

The excentricity e – also referred to as pitch – of the Voith Schneider Propeller is defined as:

\[ e = \frac{ON}{D/2} \]

The pitch of the Voith Schneider Propeller can be varied within a range \( e \leq 0.8 \). Propellers with a pitch \( e > 1 \) are known as trochoidal propellers. The Kirsten-Boeing propeller is a special case, with a pitch of \( e = 1 \).
The advance coefficient \( (\lambda) \) of the VSP is the ratio of the inflow velocity of the propeller \( (V_A) \) to the circumferential velocity \( (u) \) of the blades:

\[
\lambda = \frac{V_A}{u}
\]

The circumferential velocity \( (u) \) at the blade circle, with rotor speed \( (n) \) and blade orbit diameter \( (D) \), is given by:

\[
u = \pi \cdot D \cdot n
\]

The motion of the blade relative to a stationary observer, as illustrated in Figure 8 right, arises from the superimposition of the rotary movement and a straight line representing the forward motion of the vessel. The blade follows a curve of a cycloid. The rolling radius of the cycloid is \( \lambda \cdot D/2 \). In one revolution, the propeller travels a distance \( \lambda \cdot D \cdot \pi \) in the direction of motion of the ship. Because the blades travel along a cycloidal path, the Voith Schneider Propeller is also referred to as a cycloidal propeller.

Figures 7 and 8 illustrate the inflow conditions in the zero thrust condition. In each angular position, the water flows in at a zero lift angle, i.e. there is no hydrodynamic lift. The drag for the profiles are negligible in these analyses.

To generate thrust, the blades are set at an angle \( \lambda \) relative to their path. To achieve this, the steering centre is adjusted from \( N \) to \( N' \). Because the water flows in at an angle of attack \( \lambda \), there is a hydrodynamic lift force \( (A) \) and drag force \( (W) \) on the blade. The drag force has two components: the induced drag and the profile drag. Figure 9 illustrates the generation of thrust. The steering centre is varied by means of the kinematic system (Figure 5).

The VSP employs a two-stage thrust generation. As they revolve, the blades produce forces in the desired direction of thrust both in the forward and rearward half of the rotor. Figure 10 shows individual blade positions that contribute to thrust generation. Since the profiles are moving in opposite directions in the front and rear halves of the rotor, the VSP gives rise to hydrodynamic effects comparable to the interactions familiar from contra-rotating propellers [3].

Figure 11 shows the forces acting on the propeller in selected blade positions. There is continuous variation in the lift during each revolution owing to the non-stationary inflow to the propeller blades. The force-components acting transversely to the desired direction of thrust cancel each other out, while the force-components in the direction of thrust add up over the circumference of the propeller.
Figure 12 shows the lift conditions as a function of the cycloidal path for a stationary observer.

The physical principle involved in the generation of thrust by the Voith Schneider Propeller is that of hydrodynamic lift. Thrust generation differs in a fundamental way from that represented by the flow conditions of a paddle-wheel blade, where resistance forces are the decisive factor in thrust generation.

The thrust of the propeller is perpendicular to the line ON (in bollard pull conditions) or to the line NN’ (in open water condition). By shifting the steering centre N or N’ it is possible to produce thrust in any direction.

Figure 13 shows the effect of changing the steering centre N’. If it is moved toward the centre of the rotor from one particular observed starting point (Figure 13a), for example, the thrust is reduced (Figure 13b). Giving the steering centre a negative value x reverses the direction of thrust (Figure 13c). Simply by adjusting the steering centre, it is thus possible to reverse the thrust – without suffering the effects of unwanted transverse forces.

The zero-thrust condition can be selected at any time, making the ship very safe to handle.

Voith Schneider Propellers operate at very low number of revolutions – only about 25% of the number of revolutions of screw propellers of comparable size and power. The reasons for the low speeds can be summarized as follows:

- In certain installation conditions, the rectangular swept area of a VSP is approximately twice as large as that of a screw propeller (Figure 14).
Figure 13: Influence of the position of the steering centre N' on the direction and magnitude of thrust (a-f)

- The blades are arranged at the outer periphery of the rotor. The resulting inflow due to the rotation of the rotor and the speed of the ship is constant over the vertical length of the blades. With screw propellers, the inflow increases with the radius of the propeller.

- The flow conditions at the blade are non-stationary. They permit larger effective angles of attack without flow separation [4].

- The VSP generates the thrust in two stages – in the front and rear half of the rotor – in a manner similar to contra-rotating propellers (Figure 10).

  The low speed is associated with high torques, which call for robust design, although there is the disadvantage of greater weight.

  The advantages of the low speeds are:
  - Long service life, especially for the bearings and seals.
  - Reduced vulnerability to obstacles such as driftwood and ice. The blade generally strikes such obstacles with its leading edge, which means that the blade then has the maximum moment of resistance relative to the direction of attack of the applied force.
  - Low hydroacoustic signatures.
  - Components with very high safety factors.
Hydrodynamic characteristics of Voith Schneider Propellers

To illustrate the effect of rotational speed on the characteristics of the VSP, an analogy may be drawn with the diesel engine (low-speed, medium-speed and high-speed). There too, rotational speed has a decisive effect on the technical parameters.

The Reynolds number for Voith Schneider Propellers, based on the mean chord length c of a profile, is defined as follows:

\[ \text{Re} = \frac{c}{\nu} \cdot \sqrt{V_A^2 + u^2} \]

where \( \nu \) is the kinematic viscosity. Owing to the low number of revolutions of Voith Schneider Propellers, the Reynolds number obtained for a model propeller in propulsion tests is relatively low. It is therefore necessary to correct the results obtained with the model, and this can be done with measured values obtained by the Hamburg Ship Model Basin (HSVA) [5] or with validated correction factors obtained more recently by Computational Fluid Dynamics (CFD).

The hydrodynamic properties of Voith Schneider Propellers are primarily influenced by the following parameters:
- Blade angle of attack during revolution
- Profile geometry
- Ratio of chord length c to blade circle diameter D, (c/D)
- Relative thickness of the profile
- Blade shaft position
- Ratio of blade length L to blade orbit diameter D, (L/D)
- Shape of blade outline
- Design of the blade ends

With Voith Schneider Propellers, the ends of the blades can be optimized in a technically simple and very effective way (by using end plates or making the ends elliptical or swept back for example) to reduce the induced drag. Figure 15 shows a VSP blade with an end plate.

Figure 16 shows as example an open water diagram for a modern Voith Schneider Propeller. The propeller has been optimized for these conditions.
Selected results from model scale tests are shown in Figures 17, 18 and 19 [6]. The measurements were obtained with a model propeller on which the ratio of blade length to blade orbit diameter is just $L/D = 0.5$ and the ratio of chord length $c$ to blade circle diameter is $c/D = 0.176$. The major differences between this model propeller and the modern VSP are in the adjustment of the blades, the blade profile, the relative blade length and the relative profile thickness. Higher efficiency is achieved with modern VSPs.

The thrust coefficients (Figure 17) and figures for efficiency (Figure 18) are a function of the advance coefficient $\lambda$ and pitch $e$. There is a qualitative shift in the coefficients as a function of $\lambda$ and $e$, as is familiar from screw propellers with variable pitch. As the pitch increases, so does efficiency.

The effect of the number of blades is illustrated in Figure 19. The smaller the number, the higher the efficiency. On today’s VSPs, the number of blades is much less significant since the hydrodynamic interactions between the blades on the front and rear halves of the rotor are reduced by modification of the blade angle curve.

The profiles of Voith Schneider Propellers are optimized for each particular application. On a VWT, the bollard pull is optimized. High-lift profiles are therefore used on these ships. These correspond very largely to HSVA profiles [7] but have a modified leading and trailing edge. On VSPs optimized for conditions in open waters, convex blades are often used. On these propellers, the relative profile thickness is less than on tugs.
The side thrust of Voith Schneider Propellers increases with the increase of the advance coefficient. Figure 20 shows a corresponding diagram for various advance coefficient and steering angles. As the advance ratio increases, that is to say as the speed of the ship increases and the propeller speed remains the same, the steering forces also increase, as do the torques. Because the VSP is adjustable, it is possible to achieve a high steering force by means of a very rapid change in pitch.

For tests with models at towing tanks, Voith Turbo Marine can supply model propellers with 5 or 6 blades and diameters of 160 mm and 200 mm.

As with the calculation of flows around screw propellers, various methods have been developed for Voith Schneider Propellers:

- Simple calculation methods based on the theorem of momentum and simple, steady-state methods of hydrofoil theory [8]. These methods are simple to manipulate but yield inaccurate values when the pitch is relatively large and do not allow assessments of local hydrodynamic values, such as pressures and forces as a function of the angle of revolution.

- Methods based on the extended lifting line theory [9],[10], with all the free vortices moving at a constant velocity and exclusively in the direction of inflow. Variable inflow in the direction of the chord is not taken into account. It is possible to calculate local forces and torques.

- Discrete-time vortex lattice methods make it possible to allow for variable inflow in the direction of the chord and for the steady-state nature of the flow [11]. The position of the free vortices is calculated for each time step. Accuracy is comparable with that of vortex-lattice methods for screw propellers [12]. One advantage is the small amount of computing time required, relative to the capacity of today’s computers. On the other hand, there is the disadvantage that viscous effects can only be taken into account by using the outflow condition formulated by Kutta and Joukowski, with global corrections.

- Calculation methods which involve solving the Reynolds-averaged Navier-Stokes equations (RANSE). By adapting commercial codes for solving the RANSE, it is possible to calculate flows around Voith Schneider Pro-
pellers very accurately. There is very good agreement between the calculations and measurements. This method is also referred to as CFD (Computational Fluid Dynamics).

A brief description of how the flow around Voith Schneider Propellers is calculated by solving the Reynolds-averaged Navier Stokes equations is given below. The flow around Voith Schneider Propellers is calculated by solving the Reynolds-averaged Navier-Stokes equations. Turbulent effects are taken into consideration by using state of the art turbulence models. Voith uses the COMET Software. It is based on the Finite Volume Method, which ensures conservative handling of all flow variables. A detailed description of the theory is given in [13]. Figure 21 shows one example of a mesh for solving the RANSE. It divides the flow volume around a Voith Schneider Propeller into discrete elements. Figure 22 shows a calculated pressure distribution. This shows that high levels of thrust are generated, especially in the second half of the rotor. Although the effective angles of attack should be smaller in the second half of the rotor owing to the induced velocities of the first half, the pressure distributions tell a different story. The reason for this is to be found in the approximately 30% shaft position of the VSP blade.

The higher velocities in the region of the profile’s trailing edge in the second half of the rotor give rise to high lift and even pressure distribution, as can be seen especially in Figure 23. It shows the calculated pressure distribution for a Voith Schneider Propeller with a nozzle plate. Like the nozzle for screw propellers, the nozzle plate has the effect of increasing thrust at bollard pull conditions. This section describes examples of the use of Voith Schneider Propellers on VWT’s, double-ended ferries and mine countermeasure vessels. Examples of other applications are given in [1].
Ships with Voith Schneider Propellers

6.1 Voith Water Tractor (VWT)

Ship-handling operations are an important link between land and sea transportation.

Ship-handling tugs are increasingly playing a key role in ensuring the safety of incoming merchant vessels right up until they are able to tie up at the terminal jetty. New dangers and risks due to the increasing size of seagoing ships, the huge increase in the transportation of hazardous substances such as crude oil, LNG and chemicals, and narrow channels in many harbors have made safety in ship assistance a decisive factor in risk assessment as applied to terminals and the environment.

In the currently understood sense, assistance to ships is necessary when a freighter’s own systems cannot provide sufficient manoeuvrability at low speed. It is also required in emergencies when, due possibly to the failure of the steering or propulsion system, a seagoing ship goes out of control and poses a risk to itself, to other shipping, to installations on land and to the environment.

Figure 24 illustrates when and where assistance from the ship-handling tug may be necessary. The efficiency of a ship’s rudder increases approximately in proportion to the square of the speed. Conversely, its steering capacity falls very rapidly as the speed of the ship decreases. Depending on the size and type of ship and on wind, and current conditions or conditions in a particular area, it may be necessary to provide assistance at relatively high speeds of as much as 6–8 knots. The Voith Water Tractor (Figure 25) covers all the above aspects. Thanks to the two possible methods of operation – direct and indirect – the VWT can assist a ship safely over a wide range of speeds. Its introduction has fundamentally eliminated the dangers associated with stern-propulsion tugs when used to assist ships. The distinguishing feature of the Voith Water Tractor is that the propellers are located in the bow section, where they are protected by an integrated nozzle plate. Other important elements are the aft stabilizing fin with the towing gear mounted above it, and the centrally mounted, logical controls (Figure 26).

Bow steering – i.e. location of the propellers in the bow section – was chosen for the Voith Water Tractor

- to enable the interactive hydrodynamic forces between the tow and the tractor to be counteracted, even at high speeds
- to obtain a stable equilibrium between the two forces acting on the tractor – propeller thrust and towing force

Tugs fast forward have a relatively low efficiency, and this falls as the speed at which assistance is provided increases. One reason for this
is that a considerable proportion of the tug’s power output is required to maintain its own speed. Another reason is that the force supplied by the tug is applied at or close to the hydro-dynamic centre of gravity of the seagoing ship, without any effective leverage. However, in some shipping areas it is impossible to avoid using a tug fast forward. When making fast, the interactive forces between the seagoing vessel and the ship-handling vessel are extremely critical.

There can be significant negative pressure due to the hydrodynamic interactions between the ships’ hulls, especially when the two vessels are close together. In addition, there is a risk to the stability of the ship-handling vessel from the transverse component of the tow-rope pull. With its propulsion arranged forward, a Voith Water Tractor can carry out this assistance manoeuvre safely. This was demonstrated by systematic tests on models carried out in the 1960s by the Hamburger Ship Model Basin (HSVA) [14].

An important consideration when providing assistance to a ship is the protection afforded to the propellers from unwanted contact at the side and from bottom contact. The nozzle plate arranged under the tips of the propeller blades to increase propeller thrust under bollard pull conditions serves simultaneously to provide them with reliable protection.

Another important aspect is the redundancy of the propulsion system, which is intended to eliminate the need to break off assistance immediately if one of the drivelines fails. In this context, system redundancy means not just the presence of two propulsion systems but also requires independent operation of these systems.

It is the special feature of the Voith Schneider Propeller with its ability to supply variable thrust according to X/Y coordinates that are identical with the ship’s coordinate system which opens up this option.

The steering characteristics of the Voith Schneider Propellers ensure that the Voith Water Tractor can be steered in an equivalent way with one or two propellers, i.e. there is a fall-back option but no change in the handling characteristics. Thanks to the forward position of the propulsion system, the towing gear on the Voith Water Tractor can be positioned well aft so that the two main forces – propeller thrust and tow-rope pull – acting on the ship are directed away from its centre of rotation, and a constant stable equilibrium is established between these forces – a significant safety feature compared with stern-propulsion tugs.
People are a significant component in any safety system. Experience shows that a very high percentage of accidents are due to human error. The way in which people operate safety systems is therefore very important. The steering provided by the Voith Schneider Propeller meets this safety requirement. The logical arrangement of the control on the bridge permits intuitive steering in any situation. There is no need for a change in approach when switching from operation fast forward to operation fast aft, from the direct to the indirect method or from one to two propellers. This prevents serious errors due to stress in emergency situations.

With its relatively large skeg propeller guard and nozzle plate, the Voith Water Tractor is equipped with two hydrofoil systems that have a damping effect on its movements due to swell. The skeg reduces the rolling motion and the guard plate damps pitching and heave motions. The vertically arranged, rotating VSP blades likewise have a damping effect on the swell-induced motion of the ship.

The skeg and the active VSP blades of the Voith Water Tractor ensure good directional stability. Since all seagoing ships are driven and steered from the stern, it makes the most sense to place an assistance vessel at the ship’s stern when replacing or supplementing these systems. Thanks to the equilibrium between the tow-rope pull and the propeller thrust, the Voith Water Tractor can operate behind the ship while secured to the tow-rope.

If the VWT has to produce forces opposed to the direction of motion of the seagoing ship while in this position, the VSPs are subjected to a negative approach flow. They then operate with a negative advance coefficient. The propellers may also be subjected to severe additional loads by the propeller wash of the ship to be manoeuvred. Such complex flow conditions pose relatively few problems for the VSP because:

- the VSP has a vertical axis, and the rotating propeller wash has less effect on the inflow to the blades than in the case of interaction between two screw propellers
- the VSP’s large wash area evens out such effects
- the pitch control allows precise adaptation to a variable approach flow and thus prevents overloading of the propulsion system

This enables engine power to be converted immediately into active braking force in any phase. Here too, the operating redundancy of the systems guarantees safety,
Ship Assistance
with Voith Water Tractor

Figure 28: Steering forces in the direct method

Figure 29: Stability and remaining freeboard in the direct method

ensuring that assistance operations are not put at risk if one of the propulsion systems fails, even at high speeds.

For steering at low speed, i.e. to supplement the rudder force of the seagoing ship, the installed power of the Voith Water Tractor is employed via the thrust of the propellers – the direct method.

The forces that arise while pushing a seagoing ship are illustrated in Figure 27.

While the optimum position of the Voith Water Tractor for pushing at a speed of 0 is 90° to the axis of the seagoing ship, as would be expected, this changes with increasing speed, and the angles of incidence become smaller (Figure 28). The diagrams in Figures 28 and 29 are based on the following ship's parameters:

- \( \text{Lwl} = 33.50 \text{ m} \)
- \( \text{B} = 10.50 \text{ m} \)
- \( \text{Thull} = 2.8 \text{ m} \)
- \( \text{D} = 4.2 \text{ m} \)
- \( \text{Disp.} = 598 \text{ t} \)
- \( \text{GM} = 210 \text{ m} \)
- \( 2\times\text{VSP 32R6/210} \)
- \( \text{PB} = 2\times2450 \text{ kW} \)

Due to the hydrodynamic action of the fin, the Voith Water Tractor is capable of maintaining the maximum steering force from a speed of zero to about 6 kn, the maximum practicable speed for the direct method. Whereas the Voith Water Tractor leans into the flow initially with increasing speed, as would be expected, leading to a reduction in the freeboard, the ship is already beginning to right itself at a speed of about 4 kn (Figure 29). This effect is governed by the high transverse propeller thrust required. At higher speeds in the direct method, therefore, the freeboard increases to beyond that when the ship is
floating upright. The assistance manoeuvres can therefore be carried out with a high degree of safety within the speed range outlined. Figure 30 shows the optimum push positions of a Voith Water Tractor as a function of speed.

The direct method cannot be used at higher speeds because the force required to drive the tractor itself reduces the tow-rope pull accordingly and, depending on the speed, there is only a reduced tow-rope force available. The Voith Water Tractor therefore marked the introduction of the indirect method. In this method, the hydrodynamic lift forces of the ship’s hull and the fin are introduced into the ship via the towing rope (Figure 31). In the indirect operating method, the propellers are essentially used only as steering gear to position the Voith Water Tractor’s hull at the correct optimum angle of attack and to adjust the port- or starboard-side steering position relative to the ship. As a result, the maximum steering or braking forces are effectively generated to meet the requirements for assistance [15]. In this application, a heeling moment on the Voith Water Tractor is consciously accepted and increases as the square of the speed. The design of a Voith Water Tractor must take account of this moment-related requirement by optimizing the principal dimensions, the shape parameters, weight distribution, dynamic stability and arrangement of the towing winch.

Serious accidents with tankers have led to a demand for safe escort vessels.

Following the most severe tanker accident to date, that of the "Exxon Valdez" off Alaska, safe escort ships were prescribed by law in hazardous waters such as Prince William Sound, the Strait of Juan de Fuca, San Francisco Bay etc. All tankers with a dead weight of above 5,000 tDW must be escorted by a suitable tug [16].

In many sea areas where escort ships are required, such as Valdez, Alaska and Placentia Bay, Newfoundland, Canada, attempts have been made to describe the complex behavior of the Voith Water Tractor escort together with a tanker. In various risk scenarios involving the parameters of the largest tankers entering these areas and extreme weather conditions, permitted turning circles were laid down as limits within which the tanker had to be brought under control if the steering or main engines of the tanker failed [17], [18].

In Scandinavia, on the other hand, the maximum steering forces to be produced by an escort tug to secure an at-risk tanker are defined in complex risk assessments for individual terminals. Tugs designed for such escort duties are given an "Escort Rating Number (n, v)",

Figure 30: Optimum push positions of a Voith Water Tractor as a function of speed

Figure 31: Forces acting on a Voith Water Tractor in indirect method
which expresses the maximum steering force \( n \) in tonnes at an escort speed \( v \) in knots [19]. As with the requirement for the maximum time to put the helm over from hard to port to hard to starboard, the escort tug must be able to change position within 31 seconds. If the actual manoeuvring time from one position to the opposite one exceeds the prescribed value, the “Escort Rating Number” is reduced accordingly. The area criterion of the leverarm curve is decisive for the assessment of stability. Between equilibrium and the maximum heel of 20°, the area of the leverarm curve under the righting to heeling lever must be at least 25% above the value for the area of the heeling lever. Moreover, the total area of the righting levers up to the critical inflow opening, or at most 40%, must be 40% greater than the area of the heeling levers [19].

The escort tug must also have a "self-tension" towing winch so that it can handle the considerable overloads during dynamic oscillation of the tow-rope forces at sea. If the tow-rope force is more than 50% of the breaking strength of the tow-rope, the towing winch must automatically release it. If the force falls below this value again, the winch must draw in the rope to its original length. The breaking strength of the tow-rope must be at least 2.2 times the average maximum measured tow-rope force.

There are many different ways of optimizing the system to increase the maximum steering forces, by maximizing the under water lateral area and the transverse force coefficient of the tug through variation of its shape [20].

The steering forces of a Voith Water Tractor can be maximized by:

- choosing high-lift profiles for the fin
- using hydrodynamically optimized appendages on the ship's hull and end plates on the fin
- the position of the A-frame relative to the hydrodynamic point of action of force
- the angle of attack of the ship relative to the towing direction
- balancing the moments about the A-frame [21].
Voith Turbo Fin (VTF)

The transverse thrust component of the Voith Schneider Propeller required to ensure equilibrium should be as small as possible. The ship’s design must provide the Voith Water Tractor with sufficient stability and freeboard to enable it to safely accept the maximum tow-rope forces. The results of optimizing the ship in this way can be depicted by a "butterfly" diagram [22]. Figure 32 shows by way of example the steering and braking forces that can be achieved over the entire speed range of the Escort Voith Water Tractor "Ajax" [21]. The principal data for this ship are as follows:

- LWL = 38.20 m
- B = 14.20 m
- THULL = 3.8 m
- D = 6.25 m
- Disp. = 1276 t
- GM = 2.98 m
- 2*VSP 36GII/270
- PB = 2*3460 kW

The serious accident involving the tanker "Aegean Sea" at the entrance to the Spanish port of La Coruna was one of the reasons why the Voith Water Tractors used in Spain are designed for escort duties. The same applies to the water tractors used at Southampton, Cork, Antwerp, Ravenna and Venice. To meet the requirements for high steering forces while retaining the compact dimensions of a harbor tug, Voith has developed the Voith Turbo Fin (VTF). For this purpose, the familiar rotor rudder system [7] was adapted to the fin on the Voith Water Tractor. On the nose of the fin profile there is a rotating cylinder which can be activated by the captain as and when required in indirect operations. By selectively altering the boundary layer, flow separation is delayed and the steering force of the entire VWT is increased by up to 18%, allowing it to be positioned at greater angles of attack (Figure 33a, b). The diameter of the rotating cylinder is about 50% of the maximum thickness of the fin profile. To get the best results from the VTF, the velocity of the cylinder’s circumference should be about 4 times the ship’s speed. The captain activates the Voith Turbo Fin by means of a pushbutton at the helm. When he turns the wheel to generate steering forces to port or starboard, the cylinder begins to turn in the corresponding direction of rotation. With the Voith Turbo Fin, Voith Water Tractors corresponding in size to conventional harbor assistance tugs for escort duties can generate steering forces of over 100 t. This considerably enhances the multipurpose character of these ships.
6.2 VSP Double-Ended Ferries

The steady increase in the proportion of the total costs of a product accounted for by transportation, storage and handling has always exerted enormous economic pressure on the productivity of transportation by water. At an early stage, seasonal fluctuations in passenger numbers led to great interest in carrying commercial loads such as cars, trucks, heavy goods and railway wagons. Transporting such commercial loads rapidly became a factor in the profitability of ferry links. In recent years, in particular, ferries have become an efficient element in complex integrated transport systems. In contrast to the requirements of other types of shipping, ferry links over short distances are of a completely dynamic nature. Operations thus have to flow as continuously as possible, with short journey times and economically acceptable propulsion power. The shorter the distance between ferry ports, the more significant the following factors:

- loading and unloading times
- the berthing and unberthing of the ferry
- acceleration and deceleration of the ship in the ferry port

and the less significant the achievable speed in open waters. To keep to the fixed timetable for every modern short-distance ferry, every minute that can be saved in loading and unloading and manoeuvring at the ferry port means a reduction in the required speed in open waters and a corresponding reduction in the required propulsion power and significantly reduced operating costs. Figure 34 shows the fuel consumption, installed power and required speed of a double-ended ferry in comparison with single-ended ferries. The comparison is based on the following parameters:

- loading time: 15 min
- manoeuvring time: 2 min
- additional manoeuvring time for single enders: 1 min

Principal data of the double-ended ferry:

- \( Lwl = 31.5 \ m \)
- \( B = 15.0 \ m \)
- \( Thull = 1.6 \ m \)
- \( D = 2.60 \ m \)
- \( Disp. = 700 \ t \)
- \( v = 12 \ kn \)
- \( 2^*VSP \ 16KG \)
- \( PB = 2^*470 \ kW \)

With their "roll-through" load-handling capability and minimal manoeuvring at the ferry port, double-ended ferries undoubtedly offer the best foundation for economic short-haul ferry operations. The compromise that the shipbuilding engineer has to make with regard to resistance and somewhat higher power requirements when designing a
Mine Countermeasure Vessels (MCMV) with VSP

The large swept area of the Voith Schneider Propeller means that the thrust loading on the propeller is low and, coupled with its controllable pitch characteristic, enables it to produce extremely high braking forces (Figure 35).

6.3 Mine Countermeasure Vessels (MCMV) with VSP

The Voith Schneider Propeller was first used for military applications in the early Thirties on the first Type M1 and M2 minesweepers. By the end of the Second World War almost 120 minesweepers had been built. The aircraft catapult ships "Falke" and "Bussard" likewise had Voith Schneider Propellers as their main means of propulsion. Thanks to the positive experience with minesweepers, military use of Voith Schneider Propellers in the post-war period was focused on modern mine-hunters – mine countermeasure vessels (MCMVs).

Owing to the enormous technological progress in the effectiveness and disguising of modern and very cost-effective sea mines, mine hunting has become a very dangerous and complicated defensive military operation. MCMVs fitted with VSPs have a single propulsion system for operations mine hunting, for clearing sea mines with mechanical, magnetic or acoustic sweeping equipment and for traveling in open waters to the area of operations. To clear designated sea areas, high directional stability combined with extreme manoeuvrability, good dynamic positioning ability and very short stopping distances are required. During mine hunting, the ship must not emit any signals to which the sensitive sensors of the mines could respond. This is a matter of minimizing the underwater noise caused by the propeller combined with air- and structure-borne noise levels from all sources of noise in the ship, which can be radiated into the water via...
the ship’s structure. The low operating speed of the VSP (see Section 3) is a significant contributor to the acoustically favorable behavior of the Voith Schneider Propeller because its sound pressure is proportional to the product $\sim n^3D^4$ [25].

The magnetic signature of each individual component of the ship is subject to strict controls. The Voith Schneider Propellers for MCMVs are manufactured with up to 90% non-magnetic steels and the magnetic components that are required to enable it to operate are degaused or magnetically neutralized. During mine hunting, there is always the possibility that a mine will detonate close to the ship. The Voith Schneider Propeller has to withstand such extreme shock loads, without operational restrictions or major damage (Figure 36).

Over 70 modern MCMVs fitted with Voith Schneider Propellers are in use by leading navies worldwide.

7. Voith Cycloidal Rudder (VCR)

The Voith Cycloidal Rudder (VCR) is a new type of multi-functional means to manoeuvre. It represents an adaptation of the technology behind the Voith Schneider Propeller to other areas of application. The VCR is used in combination with conventional screw propellers (Figure 37a, b). The basic idea of the VCR is to modify a VSP with just two blades in such a way that it can be used for a dual purpose. There is a passive mode, in which the VCR acts like a conventional rudder, and an active mode, in which the VCR acts like the tried-and-tested VSP ([26], [27], [28]). The two modes are summarized as follows:

**Passive mode**

Figure 38 shows the VCR in passive mode behind a screw propeller. The blades are stationary and only the rotor casing has been turned, through about 30°.

**Active mode**

In the active mode, the VCR acts just like a VSP. The direction of thrust is infinitely variable over 360°. The active mode is used when the ship is moving at low speed. In this case, the effects of a passive rudder are very slight owing to the quadratic dependence of the rudder forces on the inflow speed. At low speeds, the VCR gives high manoeuvring forces, thus simplifying the ship’s handling and enhancing its safety.
What advantages are there in using the VCR:

- The ship's rudder can be made smaller. Ships' rudders are often over-dimensioned for high speeds because the required rudder forces at low speed dictate their area. With its two modes, the VCR provides the choice of a smaller rudder area entailing less drag. At low speeds, the active mode ensures manoeuvrability.

- As a result, the ship is highly manoeuvrable. The VCR allows all important ship's manoeuvres, such as forward and reverse motion, turning on the spot and, when two VCRs are fitted or in combination with a bow thruster, pure traversing manoeuvres as well.

- In terms of propulsion, the VCR is a redundant system. If the main propulsion system fails, the VCR enables the ship to be moved safely on its own, provided that the power supplied to the VCR is independent of the main propulsion system.

- Roll motion can also be reduced with the VCR. Like a rudder roll stabilization system [29], the VCR can damp the rolling motion of a ship. This is possible because thrust forces can be transferred very quickly from port to starboard in the VCR's active mode, it is also possible to reduce the rolling motion while the ship is stationary.

The VCR is currently at an advanced stage of development. Numerical simulations, model and full-scale tests have been carried out. For the full-scale tests, Voith Turbo Marine has worked together with the marine educational establishment (Seefahrtschule) in Leer. Seefahrtschule Leer operates the “MS Aurora” as a training ship. This is a former buoy layer, which is fitted with two VSPs size 14. For test purposes, a VSP was converted to use as a VCR, as shown in Figure 39.

The VCR can be used with advantage on a very wide range of ships, e.g. ferries, passenger ships, navy vessels, container ships, offshore supply vessels and research vessels. The VCR's ability to act as a redundant propulsion system is also a way of increasing the safety of ships carrying hazardous loads.
Bibliography


[16] Oil Pollution Act (OPA 90), Rules on Escort Vessels, November 17, 1994


