Paper to the International Symposium

WARSHIP 2001

FUTURE SURFACE WARSHIPS

The Royal Institution of Naval Architects
Institute of Directors, London
20th to 21st of June 2001

Cycloidal Rudder and Screw Propeller for Very Manoeuvrable Combatant

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Authors' Biographies

- Dirk Jürgens studied Naval Architecture and made a PhD-work on numerical hydrodynamic. Afterwards he took responsibility of special manoeuvring and propulsion concepts at Blohm + Voss / Jafo Technology located in Hamburg. Since 1999 he is Head of Research Department at Voith Schiffstechnik GmbH & Co. KG.
- Torsten Moltrecht is a Naval Architect at Voith Schiffstechnik GmbH & Co. KG. He is responsible for projecting VOITH SCHNEIDER Propellers and VOITH CYCLOIDAL Rudders. In 1995 he concluded his Naval Architecture and Ocean Engineering education at the University of Berlin.

SUMMARY

Based on the VOITH SCHNEIDER Propeller (VSP), which has been a hallmark of maximum manoeuvrability, minimum magnetism, least waterborne noise and best shock resistance for special mine counter measure vessels for decades, the VOITH CYCLOIDAL Rudder (VCR) is under development. It is a new propulsion and manoeuvring system for all ships requiring maximum manoeuvrability over the entire speed range.

During slow speed operation and manoeuvring the VOITH CYCLOIDAL Rudders operate in active mode similar to two bladed VOITH SCHNEIDER Propellers. This enables precise, quick and safe manoeuvres and best fuel economy.

At higher speeds, the two blades of the VOITH CYCLOIDAL Rudder operate like a conventional twin rudder while the conventional propeller drives the vessel. The lower drag resistance of the VOITH CYCLOIDAL Rudder increases the cruising efficiency of the vessel.

In outline, the advantages of the VOITH CYCLOIDAL Rudder for warships:

- Low resistance rudder for high speed operation.
- Improved manoeuvrability in comparison to conventional propulsion arrangement.
- As VCR is main propulsion for low speeds, CP-propellers may be replaced by FP-propellers.
- Redundancy of propulsion and steering (take home capability)
- Roll stabilisation even during stand-still of vessel is possible.
- High shock resistance, low magnetic signature, low radiated noise levels
- Ideal complement to advances propulsion systems

1 HYDRODYNAMIC PRINCIPALS OF CYCLOIDAL PROPULSION SYSTEMS

The idea of this unique propulsion and manoeuvring system was born by the Austrian engineer Mr. Schneider in 1926. In the following a short explanation of the hydrodynamic principle will be given.

The physical principle of the thrust generation by a VSP is comparable to a fish's fin or a bird's wing action. They are also producing simultaneously thrust and steering forces. Animals with such movements have the optimal adoption to their living environment.

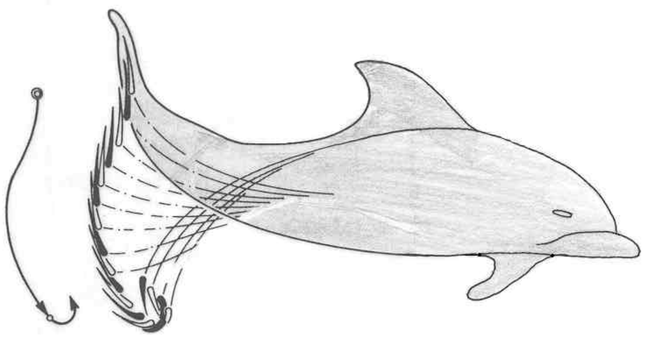


Fig 1.

On a cycloidal propulsor (VSP and VCR) the blades project below the ship's hull and rotate on a rotor casing about a vertical axis, having an oscillatory motion about its own axis superimposed on this uniform motion. The blade's oscillating movement - a non-stationary process in hydrodynamic theory - determines the magnitude of thrust through variation of the amplitude, the phase correlation determines the thrust between 0 and 360 degrees. Therefore an identical thrust can be generated in any direction. Both variables - thrust magnitude and thrust direction - are controlled by the hydraulically activated kinematics of the propeller, with a minimum of power consumption. Consideration of the processes on each blade position during one revolution provides the simplest explanation of the blades velocities and the resultant hydrodynamic forces.

1.1 ACTUAL PATH OF ONE CYCLOIDAL PROPULSOR BLADE (CYCLOID)

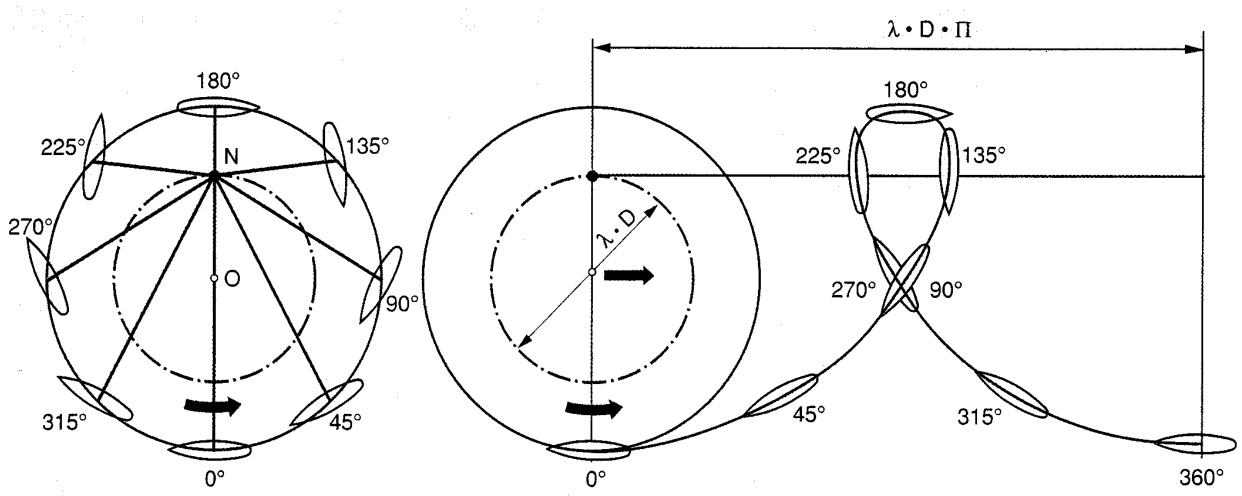
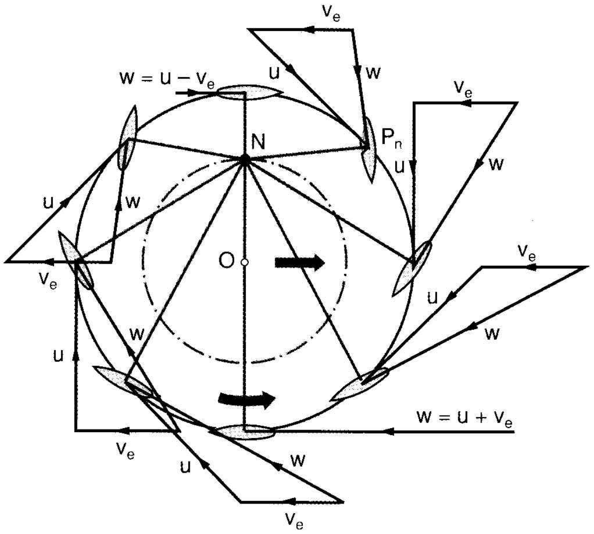


Fig 1.1. Cycloidal path

By superimposing the rotary movement of the rotor casing on a straight line perpendicular to the rotational axis (to represent the movement of the vessel), the blade of the cycloidal propulsor follows a cycloid. The rolling radius of the cycloid is equal to *?* x D/2 and the forward motion of the propeller during one revolution is therefore *?* x D x *p*.

1.2 VELOCITIES ON CYCLOIDAL PROPULSOR BLADE



O	propeller centre of rotation
N	steering centre
P_n	oscillating centre of the blade
u	circumferential velocity
v_e	speed of advance
w	resultant velocity
? =	v_e / u advance coefficient
D	blade orbit diameter

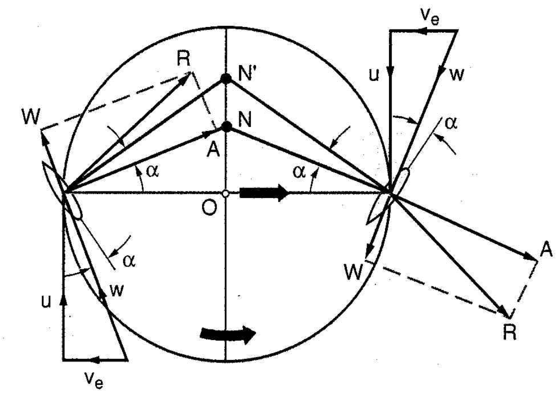
Fig 1.2. Velocities on cycloidal propulsor blade for no thrust condition

For the no thrust condition of the propulsor (the hydrodynamic lift is zero) the blades are set in such a manner that at each point the velocity w, resulting from the circumferential velocity u and the forward velocity v_e, is directed towards the profile axis (zero lift).

This basic law governs the motion of the blades: The geometric triangle NOP_n is similar to the velocity triangle uv_e w for all blade positions. The perpendiculars to the profile axes for all blade positions during one revolution must meet at one point, “the steering centre N”. During thrust generation the steering centre N is always displaced at the right angles to the resultant thrust direction by the dimension ON from the centre of rotation O (eccentricity). For the no thrust condition N’ coincides with N. (See Fig. 1.3.)

The ratio of the distance ON to D/2 corresponds to the ratio of forward velocity v_e to the circumferential velocity u, “the advance coefficient ?”. As long as the propulsor generates no thrust the advance coefficient is identical to the pitch ratio.

1.3 FORCES ON THE CYCLOIDAL PROPULSOR BLADE

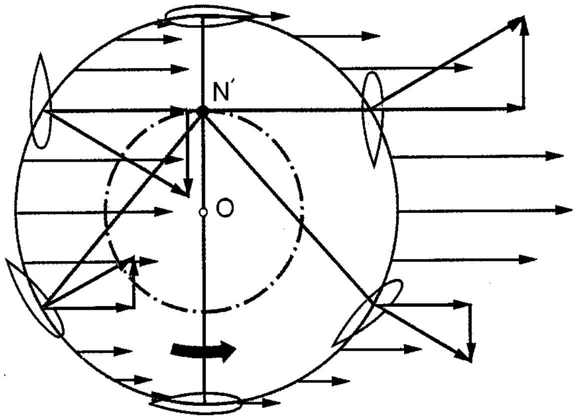


u	circumferential velocity
v_e	speed of advance
w	resultant velocity
α	angle of attack
O	propeller centre
N	steering centre
NN´	displacement of steering centre
A	hydrodynamic lift
W	induced and profile drag
R	resultant hydro. force

Fig 1.3.

To generate thrust the propulsor blade profile has to be turned against the blade path by the angle *a* by moving the steering centre from N to N'. The ratio ON' to D/2= ?$_o$ is the pitch ratio of a cycloidal propulsor. Through this angle of attack *a* hydrodynamic lift will be generated at right angles to the resultant velocity w, i.e. perpendicular to the cycloidal path. The magnitude of the hydrodynamic lift depends on the angle of attack *a* and the resultant velocity w.

1.4 THRUST GENERATION BY THE CYCLOIDAL PROPULSOR



O	propeller centre
N´	steering centre

Fig 1.4.

The hydrodynamic lift varies during the blade's revolution due to the "non-stationary" condition of the blades. Integration of the components of the lift forces created over the entire propulsor circumference shows:

- the lift components acting in the direction of motion result in the propulsor thrust
- the lift components acting at right angles to the direction of motion cancel each other out.

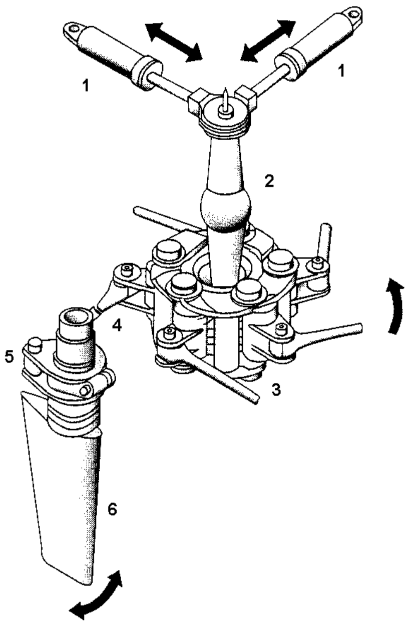
Consequently only the lift forces acting in the direction of motion generate thrust.

Since the thrust is always perpendicular to line ON’ (moored condition) or NN’ (free-running condition) thrust can be produced in any direction merely through movement of the steering centre N’. Due to the rotational symmetry of the cycloidal propulsor identical thrust can be generated in all directions. For moored conditions a circular thrust diagram is achieved through the possible movement of ON’ through 360 °. However, as thrust is perpendicular to NN’ for free-running conditions, a steering force can be produced additionally to longitudinal force up to available pitch limits.

The basis of thrust generation is the hydrodynamic lift acting on the blades. Unlike screw propellers, the speed through the water over the whole blade is constant. The effective propeller area of a cycloidal propeller is about 60% bigger than the area of a screw propeller. Therefore the VSP works with a very low speed of rotation. Rotation at speeds of about 20 % of those used in screw propellers for comparable thrust are common.

The hydrodynamic principle of the cycloidal propulsor is the basis that allows the control of thrust in magnitude and direction steplessly, precisely and quickly.

2 CONSTRUCTION OF CYCLOIDAL PROPULSION SYSTEMS



1	servo motors/actuators
2	control rod
3	lower spherical bush
4	connecting rod
5	actuating lever
6	blade

Fig 2.1 Kinematics for 5-bladed VSP

The hydrodynamic principle of the blade action is produced mechanically by the kinematics (Fig 2.1.) inside VSP and VCR. For reasons of compact construction the kinematics must produce the correct angular movement of the blades through an eccentricity smaller than the steering centre eccentricity ?$_0$ x D/2$_0$. On a modern VOITH SCHNEIDER Propeller this is achieved using crank type kinematics. The links of each blade actuating system are directly supported by the lower spherical bush of the control rod, which can be displaced eccentrically and connected to the crank, which pivots around the bearing pin fitted to the rotor casing. A connecting rod transfers this movement to the blade through the blade actuating lever. This crank type kinematics will be modified for the VCR to two blades.

The rotor casing of a VSP carries 4 to 6 blades, and of a VOITH CYCLOIDAL Rudder, two blades around its circumference. The blade axes lie parallel to the propeller's main vertical axis. The rotor casing is axially supported by the thrust plate and radially by a roller bearing. The roller bearing centres the rotor casing and transmits the thrust through the propeller housing to the ship's hull, while the thrust bearing supports the weight of the rotating parts and the tilting forces generated by propeller thrust and gear tooth pressure. A reduction gear flanged to the propeller housing and a bevel gear drive the rotor casing. The crown wheel is connected to the rotor casing through the thrust plate and the driving sleeve.

The control of the kinematics is achieved by the control rod, which is actuated by two hydraulic servomotors arranged at 90 degrees to each other. The speed servomotor controls the pitch component for longitudinal thrust (ahead and astern). The steering servomotor controls the pitch component for the transverse thrust (port and starboard).

Based on the success of the more than 3700 VSP delivered to date, which have been the hallmark of manoeuvrability and reliability for 75 years in the shipping industry, the VOITH CYCLOIDAL Rudder is now under development.

3 VOITH SCHNEIDER PROPELLER FOR NAVAL APPLICATIONS

3.1 VSP FOR SPECIAL MINE COUNTERMEASURE VESSELS

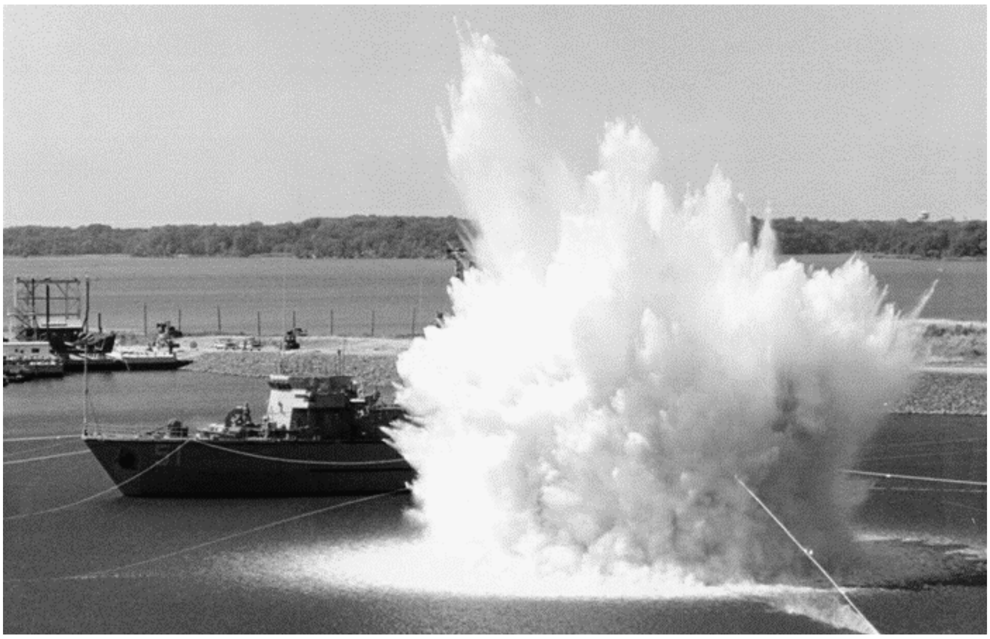


Fig 3.1. Minehunter during shock test (USS OSPREY)

On mine counter measure vessels (MCMV's) a combination of maximum manoeuvrability, least waterborne noise and best shock resistance is required. The VOITH SCHNEIDER Propeller combines propulsion and steering especially for minehunters as the main propulsion system operates at minehunting speeds with very low loads and resulting minimum waterborne noise. Special gear technology from Voith additionally ensures silent operation. The extremely low rpm characteristics require a very high torque gear design. In addition, using special materials, the propulsion system withstands very high shock loads. The former German Navy recognised the advantages of the VOITH SCHNEIDER Propeller in the late 1930´s and by the end of World War II more than 150 “R”-boats had been equipped with VSP. Today, most leading navies operate VOITH SCHNEIDER propelled minehunters.

Nowadays the Swedish Navy has seven minehunters with VOITH SCHNEIDER Propellers in operation (the so-called Landsort class). The Royal British Navy has 12 (Sandown class) with different VSP in operation. The US Navy operates 12 Osprey class minehunters and performed detailed research and full scale test with this vessels (see Fig.3.1). Further for example the Spanish Navy, Royal Thailand Navy, Singapore Navy, Saudi Arabia Navy and several other navies operate VOITH SCHNEIDER Propelled minehunters. For the Turkish Navy VOITH SCHNEIDER propelled vessels are under construction and other Navies have similar plans.

3.2 VSP FOR SHIPHANDLING VESSELS (TUGS) FOR WARSHIPS

Fig 3.1. Aircraft carrier handled by French VOITH Water Tractor

Generally, a shiphandling vessel should not be considered and/or assessed as an independent separate system, but always in conjunction with the ships it will handle, local area and environmental conditions. This principle applies to an even greater extent to a shiphandling vessel for warships. Although the shiphandling vessel does not necessarily belong to the actual combat fleet, it assumes a great strategic significance, because the availability for sea of the combant fleet, especially the capital ships, depends on the swiftness and reliability of the shiphandling service. Most warships are of extremely high value. Any shortcoming in reliability or sensitivity in the operation of shiphandling vessels involves the risk of damage. The consequences could be high repair cost and may jeopardise the readiness for action of a warship at a very decisive moment. When operations must be performed rapidly, the risk of damages due to overreactions is particularly serious. Advanced propulsion systems and sonar systems in the most modern vessels further increase the risks.

The characteristics of the VOITH SCHNEIDER Propeller in conjunction with the logical ship-design concept of the VOITH Water Tractor (well known in the naval world) ensures maximum manoeuvrability, highest safety, optimum ship-handling and effective operability in stationary and dynamic conditions. Considering the importance of a shiphandling vessel for Navy ships there is only one answer for such a craft: VOITH Water Tractor. Today most leading navies operate VOITH SCHNEIDER propelled VOITH Water Tractors inside their naval bases.

4 VOITH CYCLOIDAL RUDDER

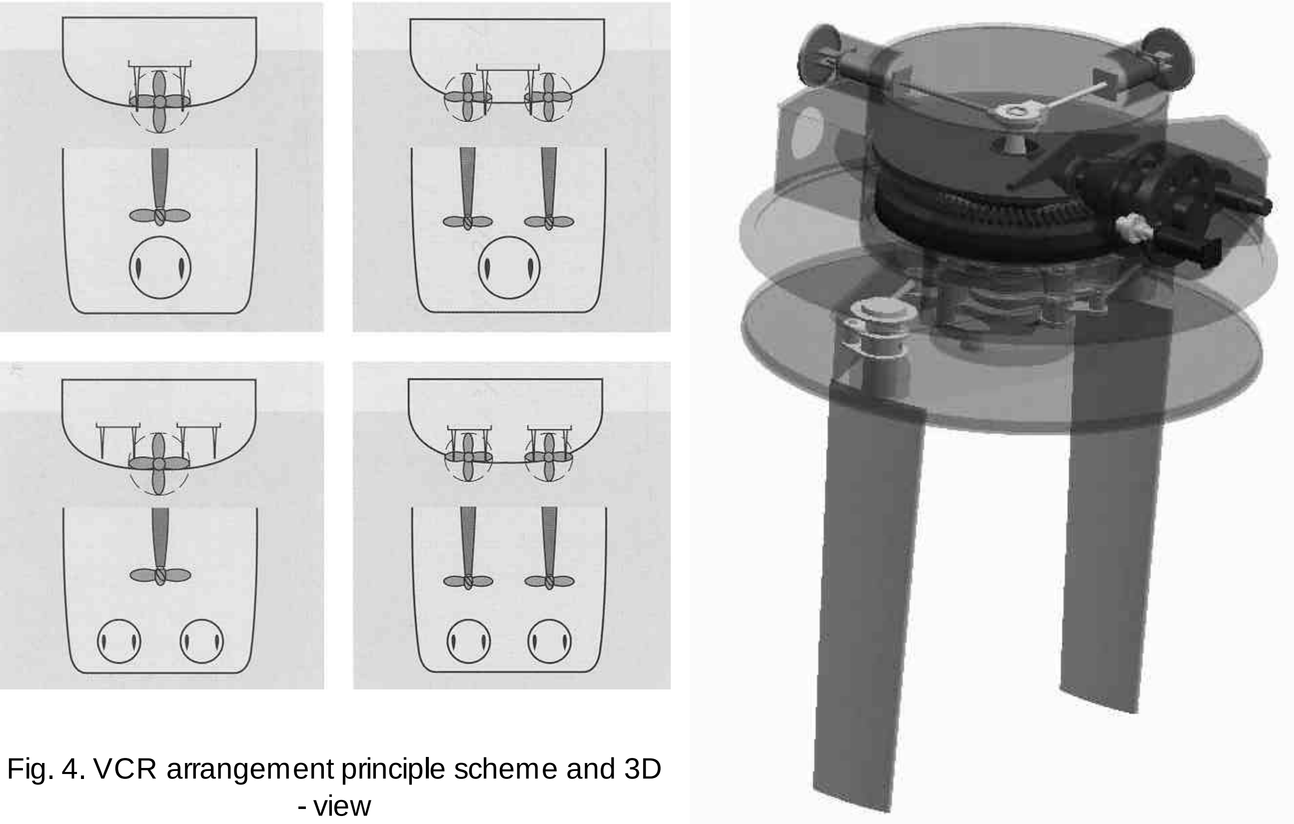


Fig. 4. VCR arrangement principle scheme and 3D - view

As with the VOITH SCHNEIDER Propeller, the VOITH CYCLOIDAL Rudder has a rotor casing with a vertical axis of rotation. Two rudder blades lying parallel to the axis of the rotor casing project from it below the vessel's hull. This rotor is turned via a reduction gear by diesel, gas turbine or electric motor.

The main characteristic of the VCR is that it has two different modes of operation: Passive and active. These two modes enables the VCR to give the ship very unique manoeuvring and propulsion features.

4.1 PASSIVE MODE OF OPERATION

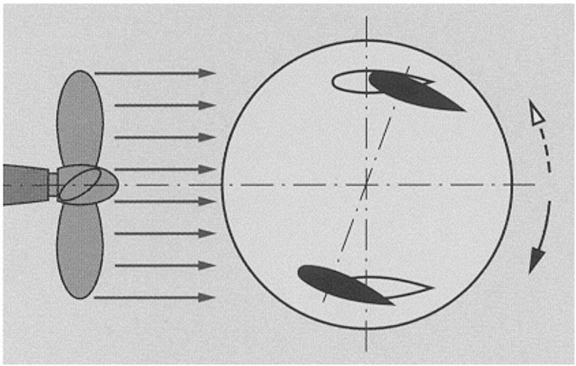


Fig 4.1. Passive mode of operation

In passive mode, the rotor casing does not continuously rotate but instead is slightly rotated from the longitudinal to produce steering forces much like a conventional rudder. Thus the locked rudder blades are adjusted relative to the inflow and transverse forces for steering are generated.

The passive mode of operation of the VOITH CYCLOIDAL Rudder is identical in principal to a conventional ship's rudder and is used at cruising speeds. But conventional rudders are designed for producing sufficient rudder forces with small inflow forces and at high vessel speeds the rudder area is oversized because of the squared dependence of rudder force to speed and produces additional drag resistance. But as this passive mode for VCR is used only for high speed operation, rudder area may be designed much smaller and appendage losses will be greatly reduced. Due to the reduction of rudder area, acoustic noise radiation will also be influenced positively.

4.2 ACTIVE MODE OF OPERATION

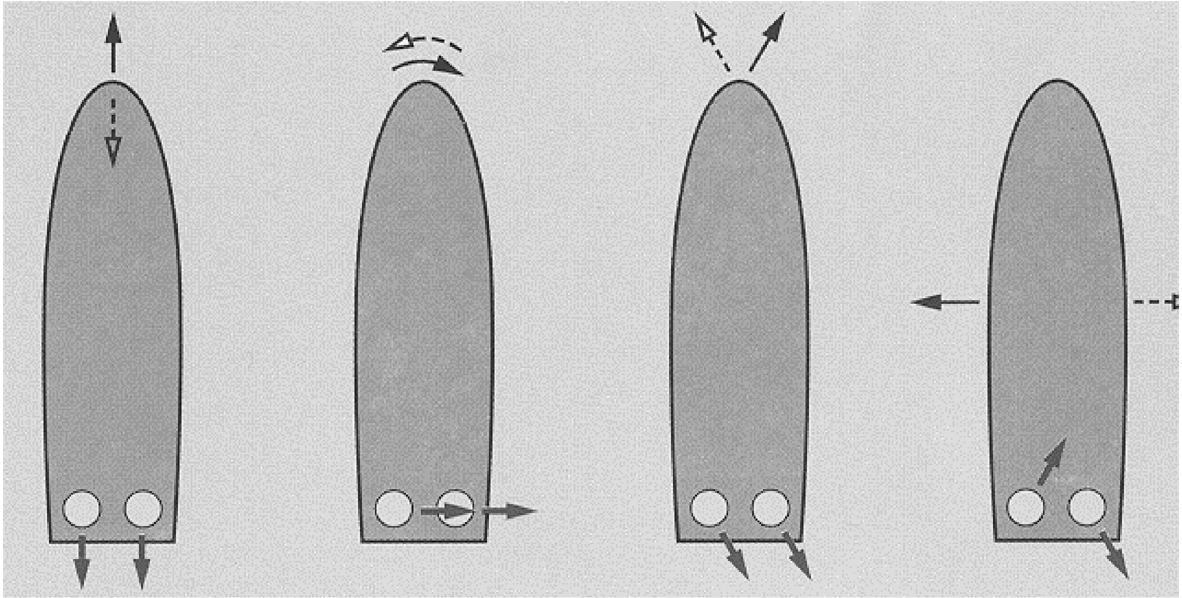


Fig 4.2 Active mode of operation

In active mode of operation, the VCR rotor casing is rotated and the system functions like a VOITH SCHNEIDER Propeller as described earlier in this article. Controllable thrust, stepless in direction (0-360°) and magnitude is produced. Therefore an identical thrust can be generated in all directions. Both variables - thrust magnitude and thrust direction - are controlled by the hydraulically activated kinematics of the VOITH CYCLOIDAL Rudder with a minimum of power consumption. Main propulsion can be reduced to stand-by condition, CP-propellers may be in sailing mode while FP-propellers can be windmilling.

This mode of operation is selected for slow speed operation when high manoeuvrability is needed, e.g. during man overboard, search and rescue, going alongside or in the harbour, both in narrow channels and while mooring and getting underway. Further with excellent manoeuvrability crossing of mine fields in clean corridors is possible. Manoeuvring inside harbours without infrastructure and tug assistance will be possible. In emergency situations including loss of main propulsion, the VOITH CYCLOIDAL Rudder guarantees take home capability.

Unlike fin-stabilisers, VOITH CYCLOIDAL Rudders allow roll stabilisation even without vessel forward speed. The thrust direction of active VCR may be electronically controlled to oppose roll motion. As thrust direction can be varied quickly and precisely, excellent station keeping allows ROV operation and helicopter landing in sea-states much higher than today's operational limits.

4.3 STATE OF DEVELOPMENT OF VCR

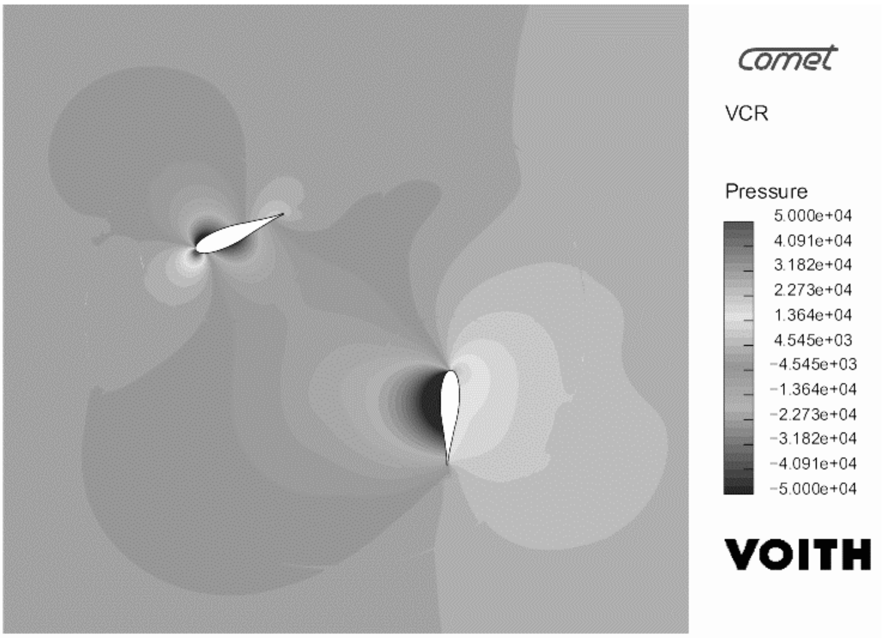


Fig 4.3.a Results of CFD-Calculation for VCR

To get a deeper insight into the physics of the VCR Voith Schiffstechnik is using the CFD technology and experimental techniques. The use of the modern Computational Fluid Dynamics (CFD) Technology enables the calculation of the forces acting on the VCR. The solution of the Reynolds Average Navier Stokes Equation (RANSE) is possible due to the application of the parallel CFD-code (COMET). Only the parallel CFD code makes the calculation of the non-stationary flow field of the VCR in an acceptable time possible. The results of the CFD-calculation are used for the design of the VCR and for the prediction of the active and passive propulsion and steering forces.

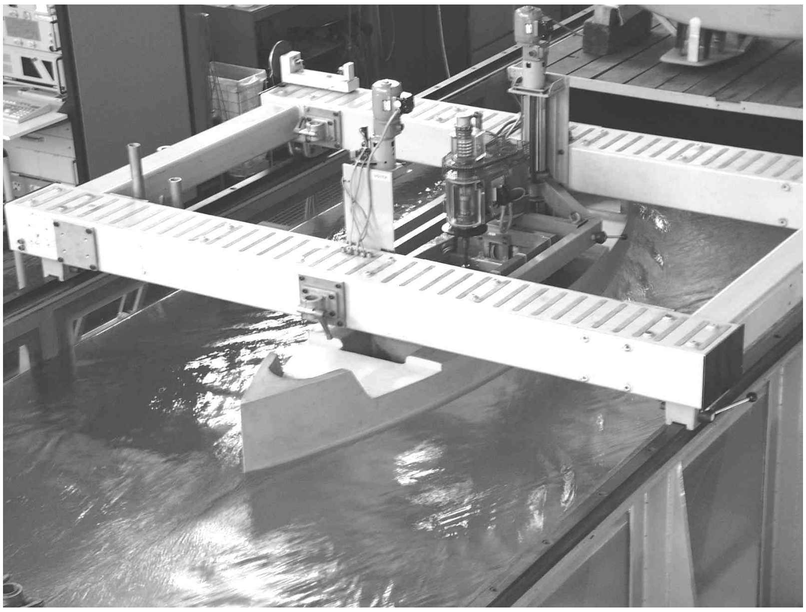


Fig 4.3.b VCR model test performed in VOITH circulation tank

VOITH has performed detailed model experiments with VOITH CYCLOIDAL Rudder in its own circulation tank for active as well as passive mode of operation (Fig. 4.3b). Blade profile, blade shaft position as well as scale effects have been varied. Based on the model experimental results and the CFD calculation a program for predicting forces/thrust in project stage was developed.

As the mechanical construction of the VOITH CYCLOIDAL Rudder will be based on several thousand practical approved VOITH SCHNEIDER Propellers, even the prototype can be seen as proven technology. Detailed discussions with classification societies of the concept signals principal approval. At this moment control and interface is the next focus of the development.

4.4 OPERATIONAL ASPECTS OF VCR FOR WARSHIPS

The dual mode of operation of the VOITH CYCLOIDAL Rudder provides a number of important properties that are important for warships. The operating area must be reached quickly, but in operation slow speed with minimum noise and maximum manoeuvrability may be necessary.

Conventional rudders are designed for producing sufficient rudder forces with small inflow speeds. At high vessel speeds rudder area is oversized because of the squared dependence of rudder force to speed and this produces additional appendage resistance. As a consequence of the alternative modes of operation of the VOITH CYCLOIDAL Rudder as active rudder (slow speed) and passive rudder (cruising speed) the required rudder area can be designed for service speed much smaller. Especially for higher speed combatants this reduces significantly the appendage resistance of the rudder. Due to the reduction of rudder area acoustic noise radiation will also be influenced positively.

Redundance of propulsion and steering by installing the VOITH CYCLOIDAL Rudder, which is completely independent from the main propulsion is also important for Navy vessels' safety. In case of loss of main propulsion, the active mode of the VOITH CYCLOIDAL Rudder is emergency propulsion securing full manoeuvrability and guarantees take home capabilty.

The VOITH CYCLOIDAL Rudder may not only act as emergency propulsion but also as propulsion for slow-speed operation. For fast combatants it is often difficult to operate in restricted channels at reduced speed. These vessels maintain relatively high speeds even with main engine power reduced to minimum. Reducing the speed requires special propulsion arrangements.

During patrol, low noise radiation operation is important. On a vessel with VOITH CYCLOIDAL Rudder, main propulsion may be switched off during patrol and active VCR may propel the vessel, resulting in much lower radiated noise.

High manoeuvrability is of major importance if a combatant has to cross mine fields in clean corridors. With a VOITH CYCLOIDAL Rudder this manoeuvrability is available from low noise and non magnetic propulsion device. As the VOITH SCHNEIDER Propeller for special applications VOITH CYCLOIDAL Rudders will be available in special non-magnetic re-inforced and re-silent version. More than 90 % by weight can consist of non-magnetizable material. Special gear technology will assure silent operation. The design of the VOITH CYCLOIDAL Rudder will be based on the proven design of the VOITH SCHNEIDER Propeller. The shock resistance of the VOITH SCHNEIDER Propeller has been proven at full scale shock tests (Fig. 3.1).

With the manoeuvring capabilities of the VOITH Cycloidal Rudder, movement astern, turning on the spot and lateral movement with stepless transition inside harbours is possible (Fig. 4.2). This is of major importance in harbours without adequate tug fleets. The swiftness of harbour manoeuvres is of great strategic significance, because it may influence the readiness for action of an entire naval formation.

Unlike fin-stabilisers, VOITH CYCLOIDAL Rudders allow roll stabilisation without vessel forward speed. The thrust direction of active VCR may be electronically controlled to oppose roll motion. As thrust direction can be varied quickly and precisely excellent platform stability allows ROV operation and helicopter landing at sea states much higher than today’s operational limits.

In outline the advantages of the VOITH CYCLOIDAL Rudder for naval combatant ships:
☐ Low resistance rudder for high speed operation.
☐ Improved manoeuvrability in comparison to conventional propulsion arrangement.
☐ As VCR is main propulsion for low speeds CP-propellers may be replaced by FP-propellers.
☐ Redundancy of propulsion and steering (take home capability)
☐ Roll stabilisation even during stand-still of vessel is possible.
☐ High shock resistance, low magnetic signature, low radiated noise levels.
☐ Ideal complement to advanced propulsion systems