**Sixth International Symposium on Cavitation**
**CAV2006, Wageningen, The Netherlands, September 2006**

# RUDDER EROSION DAMAGES CAUSED BY CAVITATION

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## ABSTRACT

Due to increased power densities of propellers and speeds of large ships, cavitation erosion of propellers and rudders has become a great and a still growing problem. The exact mechanism of erosion and the relation between certain types of cavitation and erosion is not yet sufficiently understood. Based on experience the risk for erosion is linked to certain types of cavitation, predicted by calculations and/or model tests. Design guidance and remedies for damaged rudders are shown and different methods for the prediction of the risk for cavitation on rudders are discussed.

## INTRODUCTION

The shipping market shows a strong industrial need for merchant ships with very high efficiency combined with low levels of propeller induced noise and vibrations. An important criterion for such vessels is the largely increased need for higher speeds at sea and optimum manoeuvring performance in harbours or confined waterways. The increase in ships speed and propeller loading leads to an increased danger of cavitation on the propeller and the appendages mainly on the rudders, thus bringing additional problems into the focus of rudder design and analysis. Cavitation has not only a severe influence on noise and vibrations, but can additionally cause erosion resulting in severe material damage which may end even in a total loss of parts of a propeller blade or a rudder (Fig.1). Problems dealing with rudder erosion have generally been found to occur in a cyclic manner. In the 1970’s when the speed of container ships went up to 23 knots, rudders suffered from erosion damages resulting from cavitating propeller tip vortices impinging on and eroding the leading edges of rudder horns and in the pintle area of semi-balanced rudders (Kappel, 1982 / Kracht, 1987). No or only less damages were reported in the 1980’s because of the reduced speeds of the ships in response to higher oil prices. In the late 1990’s and till today ship speeds, sizes and powers have again increased. Examples are the fast and large single screw container ships with speeds up to 26 knots and Ro-Ro vessels with speeds up to 28 knots and higher (Mueller, 2005 / Mewis & Klug, 2004).

Newest results concerning erosion on ship propellers and rudders were found within the EU –Project EROCAV (Bark et al, 2004). This comprehensive study for ships and models, including computational studies, concentrated mainly on propeller erosion but also some information on rudder erosion was given. The research done within the project created an increased knowledge of some factors contributing to erosion damage. Additionally some deficiencies in the current prediction methods for rudder cavitation used in model testing, such as paint tests with stencil ink, were found. Preliminary design guidelines were developed within EROCAV and those guidelines were also adapted by the 24th ITTC Specialist Committee Report on Erosion (24th ITTC Report, 2005).

Fig. 1 Damaged Rudder

An accurate prediction of cavitation induced damage, especially on rudders, is very difficult. There are empirical methods to estimate the risk of erosion from very global parameters but they can only be used for a preliminary check. Some success has been reported in prediction of erosion by model experiments but in contrast to propeller erosion prediction methods our knowledge concerning the prediction of rudder erosion damages is less well developed. After more than 100 years of research in cavitation, the problem of scaling model damage data to prototype conditions is still unsolved. This is because cavitation damage involves both fluid and solid mechanics and at least for a rudder behind a propeller all this happens in an extremely complex flow region.

At the moment, the question how to improve the hydrodynamic and acoustic performance, namely, how to delay or suppress rudder cavitation and minimize erosion damages on existing rudders is subject of great concern in naval hydrodynamics.

## THE ROLE OF THE RUDDER

Ship manoeuvring performance is an important factor for the efficiency of a new ship, and it is also among the most relevant safety issues associated with waterborne transportation. Safety of maritime transport and especially the reliability of ship manoeuvres depend to a large extent on the manoeuvring system used. The course keeping ability of the vessel and its manoeuvring systems have an important influence on the overall performance of the ship. Therefore overall design considerations include not only manoeuvring properties, but also manufacturing costs, reliability, durability and fuel saving possibilities. And from the beginning propeller and rudder need to be considered as one propulsion unit. Up to now the conventional rudder is the main device used to control ship operation. Such a streamlined rudder system is an efficient device to guarantee the manoeuvrability of ships and other maritime transportation means. The conventional current rudder system consists of the rudder blade(s) and the rudder engine(s). The rudder blade itself is a hydrodynamic body (profile) inducing drag and generating lift forces. Rudders are hydrofoils pivoting on a vertical or nearly vertical axis. The cross section looks like an airfoil section shaped wing of relatively small aspect ratio. They are normally placed at the ship's stern behind the propeller(s) to produce a transverse force and a steering moment. Therefore ship rudders normally are subjected to propeller induced velocities and therefore induced flow angles that vary along the rudder span and chord.

The installation of a rudder behind the propeller which is very efficient in terms of ship manoeuvring creates several problems due to the non uniformity of the ship's wakefield in combination with the induced velocities of the propeller. This not uniform inflow is responsible for a change of the loading along the span. Additionally, the flow behind the propeller and in front or close to the rudder has large cross components causing – at least locally - high hydrodynamic incidences and therefore a danger of cavitation with all related consequences like noise, vibrations and erosion. The rudder additionally distorts the flow field, so that the propeller slipstream sometimes expands up the leading edge of the rudder.
The main task of a rudder is to produce a steering force to manoeuvre the ship. This steering force is the result of the pressure difference between the suction and the pressure side of the profile, and even for the above mentioned increased speeds, this force is expected to remain in the same range as for the lower ship speeds. But the larger ship speed and the higher propeller loading cause a lower ambient pressure level. As a consequence, the margin against cavitation inception becomes smaller. This is normally expressed using the pressure coefficient $c_p$ or the cavitation number $\sigma = \frac{p_{local} - p_{vapour}}{\rho V^2}$.
The smaller the cavitation number the higher the risk of cavitation.

## RUDDER CAVITATION AND RELATED EROSION DAMAGES

Cavitation is a complex physical problem, which depends on numerous parameters. It occurs in a number of applications and on very different scales. Examples can be found in areas such as space technology, medical equipment, chemical process and metallurgic industry, power plant industry, plants for distribution of tap and waste water, car industry, marine industry etc. Cavitation can occur anywhere in liquid flow or vibrating liquids, provided the local or temporal velocity or temperature is high enough at a given pressure. Typical devices suffering from cavitation are pipes, valves, pumps and hydraulic turbines, parts of diesel engines, propellers and rudders.
Cavitation starts when water evaporates at positions on a body where the pressure locally drops below the vapour pressure of the water. In reality cavitation occurs even earlier because of microscopic particles and dissolved gases in the water which promote the inception of cavitation. For a rudder this means, if at locations of high flow velocity the local pressure falls below vapour pressure, cavitation starts and the risk for erosion damages is given.

Fig. 2 Erosion Damages in the Lower Pintle Area and in the Gap of a Semi-Balanced Rudder

Cavitation on rudders can develop in a number of different forms and shapes, ranging from separated bubbles or cloud shaped structures to complex sheets. The effects of the various cavitation phenomena are different. Where strong developed sheet cavitation mainly leads to a reduced hydrodynamic performance the other forms may have effects such as severe erosion damages on the blade surfaces due to the rapid collapse of individual imploding bubbles in the associated pressure field. Erosion damages occur when small bubbles filled with vapour collapse on or near to the surface of the rudder. The impact causes small cracks and fatigue problems resulting in material erosion, which in sea water may be magnified by corrosion (galvanic loss of material). Cavitation is not necessarily erosive but if erosion occurs, the damage happens in many forms and at many different rates. The erosion damage first occurs at the collapse point of the cavities and at the reattachment point of clouds and not generally at the inception point of the cavity. Thus the travelling cavities are responsible for erosion, and as a consequence, bubble and cloud cavitation, rather than stable sheet cavitation, is considered to be most responsible for material erosion attack. The speed with which erosion can occur is variable, in some extreme cases significant material damage can occur as rapid as in a few hours whereas in other instances the erosion develops slowly over a period of months.

**Results of Full Scale Observations**

Experience with semi-balanced rudders on ships has a very long tradition. However within the last decade, especially container vessels have been considerably developed in size, power and speed and an extreme point, which was not known before, has been crossed. Latest reports from rudder inspections contain much more frequently then ever descriptions of erosion damages. For post-Panmax vessels, which require higher propeller loading to maintain the service speed, the rudder cavitation problem has become more severe. Periodic repair or replacement of the eroded rudders or shaft bracket arms also for fast twin screw RoPax-vessels increases the maintenance cost and decreases ship operational time. Rudder cavitation is a long recognized problem in shipping industry. Nevertheless we are still far away from practical final solutions to improve the situation.

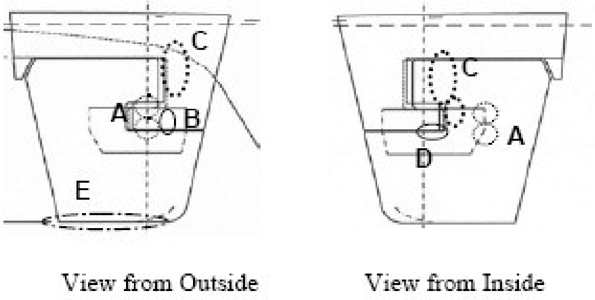


Fig. 3 Main Zones where Cavitation Occurs

Different classification societies and model basins have performed internal projects to investigate the damages and to elaborate possible countermeasures. Cavitation induced erosion on rudders is of interest mainly if it occurs within the range of rudder angles (± 4°) used for course keeping. Taking into account the damages reported over the last years, the unknown extreme point can be found around a ship speed of 23 kts with rudders operating in the propeller slipstream and a propeller power density $P/(\pi/4 \cdot D^2) > 800$ [kW / m²] (P - absorbed power of the propeller; D - propeller diameter). Rudder erosion damages can either be caused by self induced cavitation (Fig. 2) or by the cavitating propeller tip and hub vortices (Fig. 4). The main parts (Fig. 3) where erosion occurs are:

- Rudder horn and body (caused by the propeller tip vortex and the flow accelerated by the propeller)
- Pintle area (caused by rudder surface discontinuity and sometimes by hub vortices of the propeller.
- Rudder sole (caused by flow separation and a Cavitating vortex).

HSVA conducted several full-scale observations on semi-balanced rudders (Friesch, 2003), revealing quite dramatic cavitation occurrences and cavitation-induced erosion damages. During these investigations the cavitation behaviour was observed during daylight and at night with artificial lightning. Video sequences, showing dramatic cavitation occurrences, were taken. The basic behaviour and character of the observed cavitation phenomena did not change for the different speeds, only the intensity of the cavitation phenomena increased with increasing speed. The influence of small rudder angles on the cavitation phenomena was also rather small.

Fig. 4 Bursting Hub Vortex close to the Rudder Surface

Different types of cavitation occur on rudders, such as bubble, sole, gap, propeller tip-vortex cavitation, propeller hub-vortex cavitation and cavitation caused by surface irregularities. Those, very often production-related irregularities on the rudder surface can cause local cavitation phenomena resulting in local erosion damages which after a while can disturb large parts of the rudder blade surface. Principal emphasis must be given to the area around the pintle. There, details of gap size and geometry, as well as exact workmanship, are of paramount importance. Cavitating clouds, bubbles and sheet patches occur around all gaps, mainly at the upper and lower edge. Those types of cavitation are strongly fluctuating and they are known to be very aggressive. The clouds and bubbles collapse very rapidly and very irregularly, therefore here the most severe erosion damages occur.

Photos taken on a large containership within the EROCAV project showed, that mainly within the complicated flow field of such a ship, the tip vortex interacts with the sheet and is twisted violently. Additionally ring vortices are created around the core vortex, ending in a fine residue of fine vapour fog or mist (Fig. 5). When such a cavitating vortex (tip or hub vortex) hits the rudder, very often it wraps around the leading edge and the cavities collapse on the rudder surface. Systematic experiments with a model propeller showed, that the cavitating vortex is destroyed by the rapidly decreasing sheet cavitation and its roll-up process. The reason for this behaviour is expected to be the vorticity produced at the leading edge. Normally the erosion in the top area of the rudder is stronger than on the downstream side. Sometimes also the cavitating vortex core even passes along the rudder plating, causing damages more downstream on the rudder plating (Fig. 4).

For large rudder angles, cavitation is unavoidable, but normally not harmful due to the low number of operational hours.

Fig. 5 Tip Vortex Cavitation

## PREDICTION METHODS

There are various methods to predict cavitation but there are no real and practical methods to predict erosion or even the erosion rate and time.

A Modern numerical procedures such as computational fluid dynamics (CFD) can be applied to optimise a rudder design in relation to cavitation and sometimes to determine remedial measures.

B Model tests are another method to predict cavitation and related erosion problems.

C Full-scale measurements are very helpful but expensive, and they are mainly used for validation or to decide which remedial measures should be taken.

**Numerical Investigations**

The task to find the optimum rudder for a given ship needs to take into account all hull and propeller details, which influence rudder cavitation and rudder forces. Although the complexity of the problem calls for methods accounting for all effects, the need for optimising the designs requires fast and efficient methods allowing for reasonably accurate predictions within a limited time frame. Nowadays, the design of a new rudder system is still mainly based on experiences. The current state to project rudder systems contains normally calculations based on rules of the main classification societies. The rules cover the standard calculations for main parts and main components by using estimated forces and moments.

Numerical tools become more and more powerful and many hydrodynamic effects can be predicted numerically meanwhile. Propeller flow predictions for industrial maritime applications are predominantly based on potential flow methods. Potential flow codes are a standard tool for propeller designers to calculate the propeller characteristic (efficiency, RPM-thrust- and RPM-torque-relation) and to calculate the time depending cavitation extent on the propeller blade. They are also used routinely for rudders. In an early design stage CFD calculations can be used to check the cavitation behaviour of different rudder designs. The design and optimisation of rudder profiles is usually based on two dimensional potential flow calculations. The calculations yield the influence of the profile geometries on forces, velocities, pressure distribution and cavitation danger. Thickening of the profile in the pintle area (Fig. 6) is still often observed - mainly because of strength consideration - and leads to significant low pressure drops in the region of the pintle bearing. This is the most critical area of the rudder, and 3D viscous-flow calculations reveal a very complicated flow behaviour in this region. The water is sucked into the gap between rudder horn and rudder blade, comparable to the behaviour of a scoop. Here viscous flow calculation can help to check the influence of a change of the geometry in front of the gap or even inside the gap.

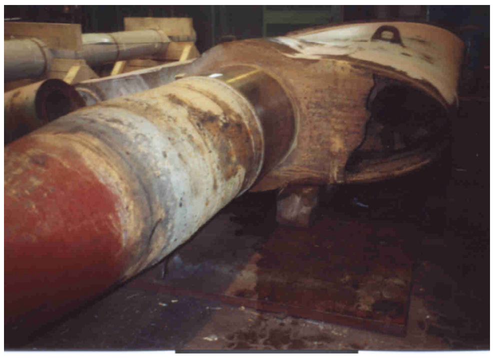

Fig. 6 Profile Thickening in the Pintle Area

Potential flow codes neglect all effects caused by the viscosity of the water and they are based on the simple assumption that cavitating rudder areas are those

areas where the numerically calculated local pressure falls below vapour pressure. These tools are not able to predict the character of the cavitation and they also fail when cloud and vortex cavitation are involved. While the cavitation number, as shown above, can be used as an indicator concerning the occurrence of cavitation, the better solution would be to model the phase change associated with cavitation. The most promising and general way to model these features computationally is based on Reynolds-averaged Navier-Stokes (RANS) equations. The methods theoretically offer the possibility to solve the free surface viscous fluid flow around a manoeuvring ship with working propeller. Still the effort associated with accounting all phenomena and effects, e.g. the free surface, will require massive computational effort not necessarily available during the development phase. Highly sophisticated numerical methods such as RANSE (Reynolds averaged Navier Stokes equation) solvers, and multiphase and large eddy flow codes are in development to allow proper prediction of cavitation aggressiveness and vortex cavitation inception, but up to now they are still away from routine application within the rudder design process. Supplementary to a robust and accurate numerical framework, the major challenges are concerned with the ability to accurately mimic streamline-curvature effects, turbulence and cavitation. Concerning cavitation HSVA employs a cavitation model based on a combination of the VoF methodology - which is the preferred approach of hydrodynamic free surface computations - and a traditional pressure-correction approach to model the influence of cavitation. The fluid is decomposed into a vapor phase and a water phase. Using the VoF methodology to model the cavitation is slightly more complex than a free-surface VoF model, since transient phase changes between vapor and liquid need to be resolved. The latter is addressed by an additional source term in both, the VoF-transport equation and the pressure-correction equation. First validation steps for the described cavitation model have been made. Fig. 7 shows the result of such a calculation for one of the rudders described earlier. The results are encouraging and demonstrate the capabilities of RANSE based cavitation modelling (Schmode et al, 2006.).
But nevertheless cavitation tests at model scale are still indispensable to avoid subsequent problems in full scale.

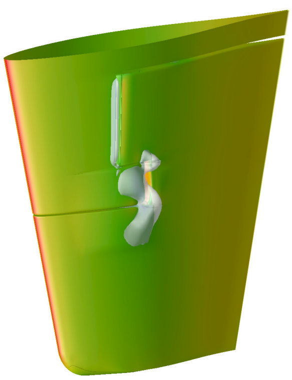

Fig. 7 Results of a CFD Calculation

**Model Tests**

Flow Measurements

To make a good and reliable rudder performance prediction in an early design stage needs a detailed knowledge of the flow to and around the rudder. This need has implied a rising interest on detailed measurements of the propeller flow field, to be used for both: for a detailed analysis of existing designs and for new rudder designs like for example twisted rudders (Löhmer, 2004.). Such detailed experimental investigations provide data to improve theoretical prediction methods and to support the flow modelling and the validation of computational codes like BEM, RANS, LES. The experimental analysis of the flow field around a propeller-rudder configuration should be performed by means of LDV or PIV methods and additionally flow visualization with a high speed camera are recommended. The objective of the PIV-technique is to study details about the flow and to deliver 3D information around 3D bodies. PIV is a whole flow field technique providing velocity maps. Using a stereoscopic approach with two video cameras, the system provides all three flow components over the whole measuring plane such detecting easily for example vortices. Using these techniques, wake features, with particularly emphasis on the tip vortex trajectory, can be measured along transversal planes in front, parallel and behind the rudder.

Cavitation Tests

Model tests in a cavitation tunnel can help in the early stage of design, especially when they are performed in a sophisticated test facility. Rudder cavitation is not only influenced by the geometry of the rudder, but also by the inflow to the rudder and propeller. Therefore, tests in 3D inflow, behind the whole ship model, to give full propeller/hull interaction, are necessary to obtain a clear view of the cavitation behaviour.
Several erosion prediction techniques have been investigated in the scope of the EU project EROCAV (www.erocav.de). Some were new when applied to the field of rudder cavitation erosion prediction. The paint test method, which predicts the erosion area for propellers very accurately, fails for rudders, due to the influence of the low Reynolds number if it is applied on model scale components, investigated in a cavitation tunnel. If the danger of cavitation-induced erosion is large for specific areas such as the pintle, additional tests in a smaller tunnel with higher Reynolds numbers are recommended. The reason is to get a sufficiently high Reynolds number in the model test, which can only be achieved if the scale for rudders comes close to 10 or even lower. A consequence of that would be that only a part of the rudder can be installed in a cavitation tunnel and no appropriate propeller model would be available in front of this partial rudder. This means that in such a test the role of viscosity would be much better represented, but in an at least questionable inflow condition. Therefore, combinations of model tests with whole ship models in a large cavitation tunnel (Fig. 8a) with investigations of

parts of the rudders (Fig. 8b) in a high speed cavitation tunnel are recommended. Unfortunately as mentioned above, the paint test method up to now does not give reliable results for the prediction of cavitation induced rudder erosion. Further research is needed to develop an adequate paint. Therefore the only way to judge the danger of erosion on rudders is to observe the cavitation phenomena very carefully. The most promising visual method to investigate rudder cavitation is the **High-Speed Video Technique** (Johannsen, 2001 / Tukker & Kuiper, 2004).

The objective of this method is to study details about the dynamics of cavitation, and therewith to gain additional insight into possible mechanisms of erosion. As a result the phenomenology and mechanisms influencing the development of more erosive cavitation are more precisely defined. The high-speed video technique is applied both in model tests, as well as in full-scale observations. Use is made of an ultra fast digital video recording system with the ability to record up to 4500 frames per second. High-speed video requires a continuous light source of high power. To catch the (irregular) shape of the cavities properly, light from various directions is needed. It has proven to be a powerful tool with regard to the judgement of the erosive ness of cavitation, because the rate and the position of the cavity collapse can be investigated in much more detail.

However, video techniques in general and for cavitation erosion on rudders in particular are not an objectively acting tool which enables a full reliable damage prediction. The phenomenology and the mechanism of erosion are still not fully understood. Therefore the results depend on the experience and skill of the person in charge who is evaluating the video sequences. Further investigations and research are necessary to fully understand the mechanisms responsible for the erosion process. This is necessary to define objective criteria for the damage prediction and to develop more sophisticated cavitation models for CFD tools.

### Acoustical Measurements

One of the main disadvantages of visual observations in investigating rudder cavitation induced erosion is, that no information is given on the focussed energy resulting from cavitation impacts. Additionally those observations give no answer concerning the rate of erosion, which will determine the time available for corrections. Here acoustic emission techniques offer the potential for quantifying the energy involved in the process. Using acoustic emission analysis gives the possibility to locate the crack propagation zone. Acoustic emissions (AE) are the elastic stress waves produced when metals absorb and release strain energy under stress. Stress waves result from the sudden release of strain energy due to micro-fracture events in metals. The primary source of an acoustic emission event in metals is the crack growth, which is a discrete energy release mechanisms on a crystalline microstructure scale. The development of this method has been driven mainly by the industry, looking for a new tool for non-destructive testing. It has been applied successfully by Lloyds Register of Shipping in the offshore sector in order to predict crack propagation and also the remaining life time. The application on cavitation erosion is a new one. First results are reported in (Carlton et al, 2006.).

## DESIGN STRATEGY

To minimize the danger of erosion damages on rudders for high-powered, high speed ships, a careful design strategy should be considered. This strategy should include both, numerical calculations and model tests.

**The first step** should include model measurements oft the flow field generated by ship and propeller. Then a first rudder geometry should be designed based on potential theory. If the pressure distributions look critical, a 3D viscous flow calculation for the critical parts like the pintle area on semi-balanced rudders, should be performed. If no measured data are available, results of CFD-calculations for ship and propeller should be used for the first outline of the rudder geometry.

**The second step** should be a test in a cavitation tunnel with the whole ship model or at least a dummy model in front of rudder and propeller. During these tests a remote controlled rudder engine should allow rudder angle variation at any time (Fig. 8a). The tests need to be performed at as high tunnel speeds as possible to achieve high Reynolds-numbers. The tests should not only be performed for the design condition, but realistic off-design conditions need to be specified and the tests should be done for these conditions additionally. During these tests it is important to check how the normal range of auto-pilot settings is influencing the cavitation behaviour, mainly the character and the dynamics of the observed cavities. Main emphasis needs to be given to the area around the pintle housing.

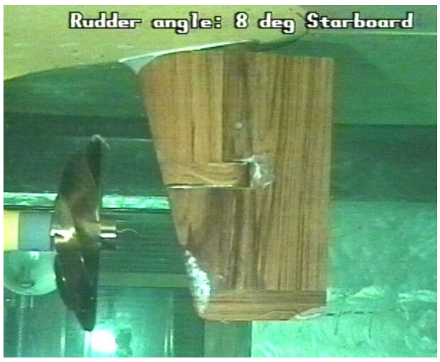


Fig. 8a Moveable Rudder behind the Ship Model in HYKAT

If dangerous cavitation phenomena will be seen in the tests performed during step 2 in **a third step** large scale model tests with a partial model should be performed to estimate the full scale behaviour in all critical areas, mainly around the pintle and in the gap between the moveable rudder blade and the rudder horn. Those tests should centring particularly on the mid-region of the rudder to minimise scale effects mainly in the gap regions (Fig. 8b).

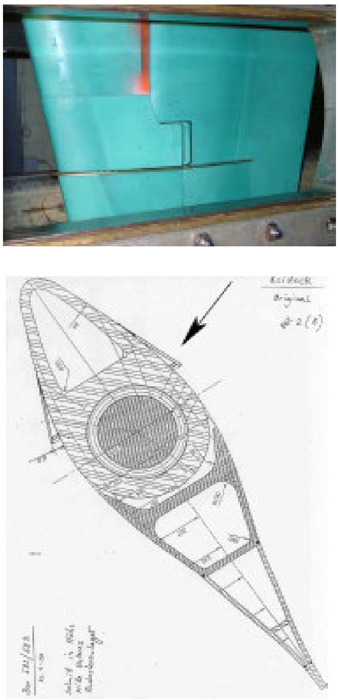

Fig. 8b Investigations of Details of the Rudder Geometry in a larger Scale at even Higher Re-Numbers

The tests during steps 2 and 3 should be accompanied by paint tests, if validated data is available at the institute performing the tests. Paint tests, even if not always successful in rudder cavitation testing are still the most used erosion investigation technique during model tests.

If the results were not satisfying this model test phase should be followed by a second iteration. During this iteration geometrical changes should be done based on the detailed knowledge about the cavitation gained during steps 2 and 3 mainly for the pintle area and all the different gaps. Also the introduction of contoured leading edges should be evaluated, to get the best cavitation free operating range.

If the changes are large a second loop of cavitation tests could become necessary.

At present model experiments are still considered the most accurate way to arrive at a full scale rudder cavitation prediction, despite the fact that scaling issues always produce some uncertainty. Large models are in general better to reduce scale effects such as for instance laminar flow over the body. Full scale trials need to be a vital part of the development work at model basins to correlate results and to further improve the predictions. Present service procedures of model basins follow a combination of an initial set of calculations completed by a more limited set of experiments. This is still and will for some time be the best method to solve questions concerning rudder cavitation and related problems. The role of calculations will further increase, but the time that calculations will fully take over the role of model experiments is still far from being reached.

In **a final step** careful attention during the fabrication process of the rudder should be given to all details of gap geometry, keeping tolerances mainly for all the different radii and gap sizes, to assure that the tested geometry is really build.

## DESIGN GUIDANCE

Under circumstances where the cavitation process is not fully understood, practical solutions to minimize cavitation erosion have to be based on experience. In practice, solutions can be categorized into two approaches:

1. Control the hydrodynamic characteristics by altering the inflow and/or geometry and

2. Increase the material resistance against the erosion without any change of hydrodynamic characteristics.

Sometimes these solutions can be applied concurrently.

The main focus should be given to avoid obvious mistakes in an early design stage by a careful rudder design from the beginning. The common requirement for rudders is that self-induced cavitation must be avoided. This should include:

1. Make the gap size as small as possible and round all edges mainly those around the gap. Consider the use of a spade rudder where no gap at all is present. Assure that the velocities through the gap are low. Check for separated flow regions using CFD.

2. Consider the use of flow adapted rudders.
The flow behind a propeller always contains kinetic energy due to the axially accelerated water as well as the rotation in the slip stream. The rudder can recover some of this energy and therefore asymmetric rudders, full spade or semi-spade, are in use. For minimizing early cavitation inception and related ship vibration a twisted rudder can be used with profiles along its entire span that are aligned with propeller induced non-zero flow angles from the rudder's root to the rudder's tip. Moreover, each individual rudder section may be twisted in the chordwise direction to substantially align the individual sections with the incoming flow along the entire chord from the rudder's leading edge to the rudder's trailing edge. Early in the year 2005 the first very large container vessel fitted with a rudder

featuring a twisted leading edge entered service. Many others followed the “Savannah Express” built by DSME and fitted with a TLKSR-rudder from Becker Marine Systems. The decision for the twisted rudder was supported by a comprehensive test campaign at HSVA including CFD-calculations, ship powering, cavitation and manoeuvring tests. Based on these test results, accompanied by full scale observations, HSVA developed their new twisted rudder TW05.

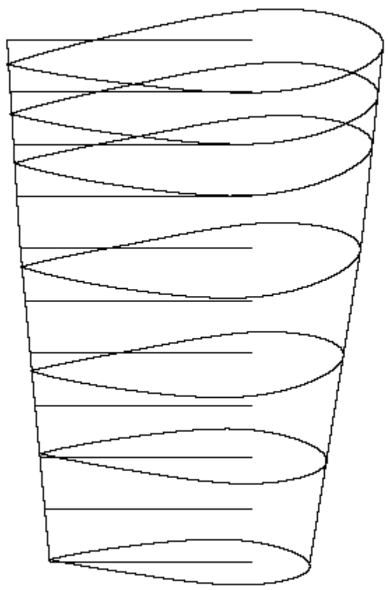

Fig. 9 HSVA TW05 Rudder

In the design philosophy for this full spade rudder HSVA put special emphasis on a smooth resultant flow at the leading edge, which finally led to a yet uncommon realization of twist. Step one of the design was to calculate the resultant flow at the rudder as the sum of the velocity components in the ship’s wake and in the propeller slipstream. In a second step, a smooth entrance of the flow to the rudder was assured by a combination of twist (i.e., an inclination of the nose-tail line) and camber. The sections below and above the propeller shaft height are twisted to different sides. The same holds for the direction of camber. The camber line shows a constant curvature all along the section from the nose to the tail (Fig. 9). The camber supports the local inclination of the nose, which assures that enough load is left on the rudder to regain rotational energy from the propeller slipstream. Propulsion tests at HSVA confirmed that the TW05 rudder concept indeed leads roughly to a 2% reduction of the power demands. A rudder bulb introduced to establish a tight connection between rudder and propeller was found to have only negligible influence and was finally omitted. It is evident from the numerical analysis and proven by cavitation tests, that the rudder can withstand high ship speeds without showing cavitation (Fig. 10). The general design concept of the HSVA TW05 allows the adjustment of the geometry to a demanded range of cavitation free rudder angles.

3. Minimize sole cavitation by bending the base plate upward at its front end and rounding the welding at this location.

4. Use appropriate profile shape and thickness. This may well require use of CFD analysis. An appropriately shaped large leading edge radius should be chosen in order to widen the cavitation bucket and to be able to cope with changes to the incoming inclined flow. Use a rudder profile with a sufficiently small absolute value for $C_p$ at moderate angles of attack (typically maximum thickness should be 35% - 40% behind leading edge and the pressure distribution should be smooth). At high speed onset flows, sections like HSVA MP-71-xx have been found more suitable. Avoid extreme variations in profile shape.

5. Minimize tip and hub vortices and cavity shedding from the propeller which can produce cavities in the onset flow to the rudder. This may cause additional cavitation and also implosions of the cavities on the rudder surface accompanied by erosion.

6. The mounting of the rudder stock must not lead to a local expansion of the rudder profile (Fig. 6). It is essential to make sure that the mounted rudder stock fits within the local profile thickness. If this is not the case use another more appropriate profile (higher thickness to chord length ratio $t/c$).

7. The size and shape of cathodes for protection will require specific attention with respect to location and fitting in the propeller slipstream.

8. Grind all welding seams from the leading edge up to the position of maximum thickness. No welding seams to be located in areas where cavitation may occur.

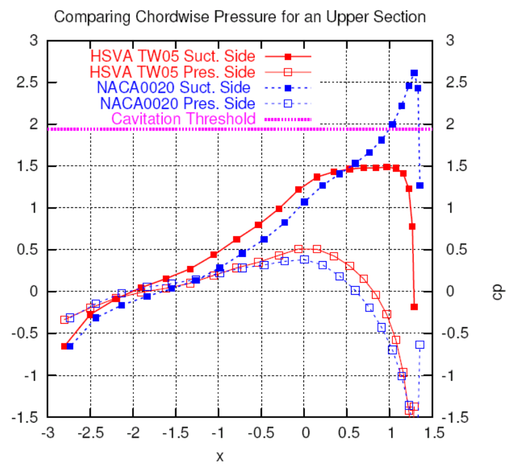


Fig. 10 Improved Pressure Distribution at the Nose

## REMEDIAL MEASURES TO IMPROVE IN SERVICE CONDITIONS

Since cavitation induced erosion can have several sources, knowledge on the type of cavitation (propeller or self induced), cavitation location, development and convection of the cavities is necessary. This information should be gained - if possible - by full scale cavitation observations of the rudder. Then the following measures can be taken:

1. Use of erosion resistant material:
   One possibility is the introduction of a material with a higher resistance against erosion (Junglewitz, 2003.). This is simply a reinforcement of the material with respect to the erosion fatigue problem. Stainless steel can be introduced by clad welding or using explosion cladded parts. But also the opposite philosophy works: the introduction of soft covers. Experience has been gained using neoprene, epoxy based coatings or "liquid metals" as a repair solution for a couple of months. The soft coatings are able to absorb energy to some extent and to avoid erosion in a passive way. This works well for weak erosion.

2. Scissor Plates
   They are helpful to guide the flow and close the horizontal gaps between horn and rudder and pintle and rudder for semi-balanced rudders. If propeller tip vortices enter gaps of an upper pintle bearing or flap moving mechanisms, a horizontal guide plate could keep them down (Fig. 11)

3. Coating
   A number of single weak erosion markings, especially in the first third of the rudder chord indicate that the erosion is probably due to tip and hub vortex cavitation of the propeller and / or bubble cavitation on the rudder blade. As long as the erosion is weak, a simple cover could improve the situation. Hard covers (compared with conventional hull dye) such as ice breaker hull coating (mostly epoxy based) as well as soft covers (neoprene) can be used.

3. Spoilers
   Such devices (Friesch, 2003) have been used to change the flow, mainly in the area around the pintle housing. For examples they have been applied at the lower end of the upper vertical gap (upstream of medium horizontal gap) and on the lower pintle, in order to direct cloud cavitation away from the rudder surface. (Fig. 8b)

Fig. 11 Scissor Plates on a Semi-Balanced Rudder

## SUMMARY

Cavitation induced rudder erosion has become a major concern within the last years, especially for semi-balanced rudders, due to the increased ship speed and propeller loading. Numerous attempts have been made by ship owners, yards, model basins and classification societies to find short term practical solutions as well as improvements in the design. The problem, that countermeasures work well in some cases and in other applications not, is still not solved due to the lack of a full understanding of the erosion mechanism. However, a number of countermeasures is available to improve the situation. At the moment the experience is still not sufficient to guarantee that the rudder survives a class period of five years. Such experience will be available in a few years, based on the results gathered with different applications of countermeasures currently introduced. In the design stage the following recommendations should be fulfilled:

- The propeller/rudder/appendages must be designed as a unit with the same design effort in order to reduce the potential of cavitation erosion.

- Off-design ship operating conditions are important and need to be considered to reduce the risk of cavitation erosion.

- Geometrical and material specifications must be followed more carefully in manufacturing to reduce possible cavitation erosion.

- It is recommended to do more documentation of the observed full-scale cavitation erosion patterns not only to improve correlations to model scale tests and predictions but also for the improvement of the design methodology to reduce potential cavitation erosion.

- The mentioned guidelines to reduce cavitation erosion are only qualitative and more research into the physics of cavitation structures/material interactions is required before damage rates at full-scale can be quantified.

Designer and ship owner expect that the problem is solved by a complete theory and respective cavitation erosion prediction methods in connection with CFD tools. For this purpose essential efforts with research projects and model / full scale investigations are necessary and are going on at the moment in a combined action of owners, model basins and classification societies.

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