DP THRUSTERS - UNDERSTANDING DYNAMIC LOADS AND PREVENTING MECHANICAL DAMAGES

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Abstract

Despite the wide and successful use of mechanical azimuthing thrusters in various marine applications, such as dynamic positioning (DP), dynamic tracking (DT), bollard pull (BP), low speed manoeuvring, as well as high speed transit trips at continuous full power (then used as the ship’s main propulsion system), damages on the gears and bearings of mechanical azimuthing thrusters have been reported in many cases. According to the statistics of survey records of major classification societies (e.g. ABS, DNV and LRS), the failures of gears and bearings are among the first three major kinds of damages, where one of them is the propellers which are however exposed directly to a quite harsh environment in the water.

In order to help the industry to get an insight in the failures with respect to the external loads on the drives of thrusters, MARIN has been dedicated in studying the hydrodynamic loads on mechanical azimuthing thrusters in the past decades. Series of six-component transducers, with high-accuracy and high response frequencies, have been designed, manufactured and applied. Systematic model test campaigns and full-scale measurements in order to obtain dynamic loads to the higher frequencies have been carried out. Through investigations into extreme manoeuvring operations, thruster-thruster interactions, thruster ventilation and thruster-ice interactions, a thorough understanding on the characteristics and the amplitudes of the external loads in various operational conditions has been gained.

In this paper descriptions are given of test set-ups, used transducers, scaling laws and test procedures. Test campaign results have been reported, extreme loads have been identified and conclusions have been drawn. The test results and findings can serve as principle guidelines to prevent damages, which are important both for the thruster designers and manufacturers, as well as for the operators.

Introduction

Over more than half a century of practical applications, a considerable amount of mechanical azimuthing thrusters (traditionally a pushing type with ducted propeller and recently also a pulling type with open propeller) have been manufactured and installed in various types of vessels, which cover wide ranges of operational profiles. Superior position keeping capability and manoeuvrability, as well as excellent zero speed (DP and/or BP) operations, low speed operations and DT, and high efficiency at free sailing and transit conditions, etc. have distinguished them from traditional propulsion systems with fixed shafts. However, failures of gears and bearings have been reported after some of those thrusters were used in service operations, irrespective of the thruster manufacturers or ship operators. Obviously the operation of those mechanical azimuthing thrusters has exceeded the design constraints and limits, which are based on the present understanding of the hydrodynamic loads on thrusters and their shafting systems, including gears and bearings (Dang et al., 2013a).

Typical damages found in a mechanical thruster are one broken tooth of the bevel gear and burnt bearings of the pinion shaft. It is still not very clear which starts first and which is induced by the others. During the design stage, many safety factors have been already applied according to the present understanding of the static and dynamic loads on the shaft train, which often include appropriate safety factors for surface pitting damage, sub-surface fatigue, tooth root damage, loss of lubrication film thickness as well as the most hidden and catastrophic damage – the Tooth Interior Fatigue Fracture (TIFF).

TIFF starts as a small crack below the surface of the active flank of a tooth, most often within the transition zone between the case and the core material. During operation, the crack grows gradually inside the tooth towards the root area of the non-active flank, without notice. A single high transient load (overload), impurities in the material (material defect) or inconsistent material treatment (production error) may form the origin of the initial crack although it is still not very clear which one is the most dominant one. An example of the broken section of a tooth due to TIFF is given in Figure 1 (Coral, 2009).
Distinguished from a TIFF however, a blade root fracture, which starts typically from a small crack on the surface of the active (loaded) side and grows towards the non-active (zero load) side due to excessive bending moment at the root area. Practice shows that the bevel gears (often used for azimuthing thrusters) seem to be more vulnerable to TIFF than cylindrical gears.

According to the statistics of survey records of major classification societies (e.g. ABS, DNV and LRS), the failures of gears and bearings are among the first three major types of failures (see Table 1), together with the propellers that are however exposed directly to a quite harsh environment in the water. Within the gear damages, the TIFF damage and the scuffing damage of the gear surface are at the top of the list and next to each other.

<table>
<thead>
<tr>
<th>Components</th>
<th>Percentage of damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellers</td>
<td>24%</td>
</tr>
<tr>
<td>Gears</td>
<td>12%</td>
</tr>
<tr>
<td>Bearings</td>
<td>11%</td>
</tr>
<tr>
<td>Ducts</td>
<td>3%</td>
</tr>
<tr>
<td>Steering gears</td>
<td>0%</td>
</tr>
</tbody>
</table>

Although it is still arguable whether a material defect or a single dynamic peak load initiates the first crack in a tooth that results in TIFF, the static and dynamic loads on the shaft train of a thruster are responsible for the growth of the crack and final break-off of the tooth, for which very limited knowledge is available until very recently.

Rather similar to azimuthing thrusters, wind turbines experience also strong dynamic loads on their blades due to, for instance, the ground boundary shear flow, wind gusts, turbulence, their shaft inclination relative to the wind direction, system oscillations (when installed on an offshore barge for instance), etc., which are transmitted through the hub into the shaft trains with gears. To prevent damages and to improve the products, full-scale workshop tests of wind turbines for both static (Musial and McNiff, 2000) and dynamic (Hull and Bedwell, 2014) loads have been already in practice for decades, see Figure 2.
Besides the full-scale workshop tests for the wind turbine blades (structure tests), the dynamic loads on the shaft train system are often tested too, which includes typically drive train endurance tests, turbulent wind simulation tests, peak load event tests, component tests and gearbox tests.

However, during more than half a century of practical applications of azimuthing thrusters, a full-scale azimuthing thruster was rarely tested on dynamic loads on its shaft train system in a workshop before it was installed for service on board of a ship until very recently, see Figure 3 (Wärtsilä, 2013). Testing dynamic loads on full-scale azimuthing thrusters in a workshop is finally emerging and will certainly play an important role in developing reliable thrusters for the industry in the near future.

In order to help the industry to understand the dynamic loads on thrusters, to determine the scantling conditions for their designs, to avoid excessive loads during operations and to assist workshop full-scale tests, MARIN has initiated a series of Joint Industry Projects (JIP’s) and has also been involved in EU research projects in order to understand the physics, to gain systematic loads data, and to search peak load events. These include the projects within the Cooperative Research Ships (CRS) such as: CRS-Loads on Pods (dynamic loads on Pods), CRS-S-SHIPPEX (extreme ice loads on Pods when hitting ice ridges), CRS-ProPolar (ice loads on propeller blades, Hagesteijn et al. 2012); EU project STREAMLINE (propeller ventilation, Brouwer, 2014); MARIN JIP-SHARES (dynamic loads on thrusters, Dang et al., 2013a) and the related MARIN JIP-CD propeller series (on controllable pitch propeller series for DP and more, Dang et al., 2012 & 2013b). Alongside those cooperative research projects, commercial contract studies contribute also a lot to the understanding of the dynamic loads, to the development of the test set-up’s and to the test techniques at MARIN.

In this paper, descriptions are given of test set-ups used to study the dynamic loads on azimuthing thrusters, of transducers with high response frequencies, of scaling laws that need to be followed carefully and of test procedures to get the most reliable results with low uncertainties and low cost. Selected test campaign results are reported; extreme loads are identified and conclusions are drawn. The test results with an understanding of the physics, can serve as principle guidelines to prevent mechanical damages to thrusters, which are important both for the thruster manufacturers, for the classification societies as well as for the operators.

Test set-ups for hydrodynamic loads

Test set-ups

Various test set-ups of azimuthing thrusters have been built at MARIN, which include traditional thrusters with ducted propellers, pulling thrusters with open propellers, thrusters with tandem and contra-rotating propellers, etc. Two typical thruster test set-ups are shown in Figure 4.
The propeller blades, the thruster housings including struts and fins, and the propeller hubs are all made of aluminium in order to limit the influence of the mass and the mass moment of inertia of the models on the test results. A duct has been made partially from a PMMA (polymethyl methacrylate) block which is transparent, and partially 3D-printed from semi-transparent ABS plastics so that it is hollow and the transducer can be fitted inside the duct to measure the duct forces and moments.

The six-component loads (3 forces and 3 moments) at the total thruster unit, on the propeller shaft, on a single blade and on the duct can be simultaneously measured by separate six-component load transducers or frames.

**Load transducers**

Designing a six-component force transducer with high accuracy and high response frequency is known to be a great challenge. The requirements for the deformation of a transducer, in order to increase the sensitivity and improve the accuracy, often contradict to the requirements for a high response frequency. A loads transducer, together with the object, is in principle a mass-spring-damper system, as illustrated in Figure 5. To obtain valid hydrodynamic loads to a given high frequency, the natural frequency of the system needs to be much higher, so that the band of frequencies interested is far away from the frequency at which the resonance will occur, which magnifies the loads. A transducer should never be used to measure the loads at a frequency close to or higher than its natural frequency of the system.

**Figure 4** Left - A generic pulling thruster with Wageningen Series Propellers C4-70 at various pitch settings; Right - A generic pushing thruster with Wageningen Series Propellers D4-70 at various pitch settings in a 19A duct. (Dang et al., 2013a)

**Figure 5** Schematic of a mass-spring-damper system and its dynamic response (Dang et al., 2012)
The unit forces and moments on a thruster or a pod are often measured by a six-component frame at MARIN, as shown in Figure 6 (Bosman et al., 2014). This type of force balance consists of a framework with 6 force transducers. Normally there is a rigid metric frame or plate and a rigid non-metric frame or plate, with 6 force transducers in-between the two (see Fig. 4). Three force transducers are, for example, placed in the X direction, one in the Y direction and two in the Z direction. With the three transducers in the X direction also the moments around Y and Z axes are determined and with the two transducers in Z direction the moment around X axis is determined.

Dynamic loads on a thruster unit can be measured with this system too, however only to a very low frequency, giving the fact of a large mass and large added mass of a thruster model. The mass of a thruster model can in most cases not be scaled properly to represent a full-scale thruster. Typical dynamic loads that can be captured are the periodical flow oscillations generated by massive flow separations on a thruster unit or on the propeller blades when the thruster is given a large steering angle at high advance speed.

At MARIN, great efforts have been put on developing shaft transducers in order to measure shaft dynamic loads, valid up to a very high frequency. Figure 7 shows the inner works of the thruster models illustrated in Figure 4, driven by either an electric motor or a pair of right angle gears in the thruster housings.

To maximize the valid frequency band for the measurements, the blades were all made of aluminium. In addition, only one blade is connected to the metric side of the transducer and the other blades pass-by through a bridge (green part in the figure) to the non-metric side. A large number of teeth for the gears has been used in order to increase the gear meshing frequency beyond the natural frequency of the system. The non-metric side is connected to a big mass, either the rotor of an electric motor or a gear connected to a flywheel.
A unique force balance frame, consisting of two stainless steel rings, has been developed to measure dynamic loads on a duct (see Figure 8, Bosman et al., 2014), which is important to ensure the structural integration and to prevent deformation of the thrusters. Six small watertight standard MARIN force transducers are placed between the rings and inside the duct. Instead of measuring in the direction of the main axes, the transducers are placed in an angular array at every 120°. This results in a rotational symmetric design which usually gives good results and small linear crosstalk terms.

Thanks to small watertight force transducers, it is possible to place this concept inside a duct. Flexure hinges without any backlash are placed on both sides of the force transducers. This provides high stiffness in longitudinal direction and low stiffness in transverse direction.

The force balance has been well calibrated and evaluated with check loads. Uncertainty analyses have been carried out to prove that this ring-type force balance design results in a good performing and stiff measuring set-up (Bosman et al., 2014).

Natural frequencies and data reduction

The natural frequency of the measuring system can be easily checked by towing the test set-up in the tank, while randomly increasing and reducing the shaft rotation rate, the towing speed and the thruster steering angles in one test run. The set-up will encounter almost all hydrodynamic loads at all frequencies, including also the added mass effect of the system in water. The spectra of the loads provide enough information to judge the natural frequencies of the measuring system. An example is shown in Figure 9 for a generic pushing thruster test set-up with ducted propeller model (as shown on the right-hand side of Figure 4). Only the spectra of the propeller blade thrust, the duct thrust and the unit thrust of the thruster have been shown here. The other loads showed the same characteristics too.

A very high natural frequency of the key blade for its first mode has been found at about 750Hz in water, which is as expected from the FEM calculations and as designed for. The natural frequencies of the duct and the unit thrust have been found also at about 45Hz and 12Hz, respectively.

To obtain purely hydrodynamic loads and to remove any possible resonance of the model test set-up itself from the signal, a cut-off frequency at 500Hz can be applied to the blade loads, a cut-off frequency at 30 Hz can be applied to the duct loads and a cut-off frequency at 10 Hz can be applied to the unit loads for this test set-up. Low-pass filters have been applied, as shown in Figure 9, to remove the high frequency data which often includes noises from resonance, gears, shafts, towing carriage, motor, etc.
Raw and filtered signals of blade thrust

Raw and filtered signals of duct thrust

Raw and filtered signals of unit thrust

Figure 9 Dynamic response of the test set-up on model scale for shaft thrust, duct thrust and unit thrust as examples (Dang et al., 2013a)

Similarities and scaling

Simulating dynamic loads on mechanical azimuthing thrusters by model testing faces great challenge. Besides attention needed for test set-ups and load transducers that need to be carefully designed, calibrated and tested, attention needs to be paid to the similarities and scaling laws for model tests.

Although on model scale, Reynolds numbers for full scale can never be attained, leading edge roughness and roughened propeller blade surfaces ensure a turbulent flow on the blade surfaces. Roughness is also applied standardly at MARIN to the leading edges of the duct and any other appendages, including thruster housings with struts and fins.

Thanks to the Depressurized Wave Basin (DWB) of MARIN, the Froude law (governing the gravity similarity and free surface effects) and the cavitation number (governing the pressure similarity for cavitation and ventilation) can be fulfilled simultaneously over the whole depth of the basin, which is regarded as extremely important for the development of cavitation and ventilation bubbles on the blades. In addition, the DWB ensures good model tests at zero or low speed for both cavitation and ventilation tests, such as for DP, BP and low speed manoeuvring. At those conditions, a cavitation tunnel suffers from confined space and water circulation.
The cavitation number can be re-written as,

$$\sigma_n = \frac{p_a + \rho g h - p_c}{0.5 \rho D^2 n^2} = \frac{p_a - p_c}{0.5 \rho D^2 n^2} + \frac{h/R}{F_{RN}} \ ,$$

(1)

where $p_a$ is the ambient air pressure (or in the tank - the DWB), $p_c$ is the pressure in the cavity or ventilated bubble, $h$ is the shaft immersion and $F_{NR}$ is the propeller Froude number defined as,

$$F_{RN} = \sqrt{D \frac{n}{g}} \ .$$

(2)

When ventilation occurs, $p_c = p_a$, and the cavitation number is merely governed by the propeller Froude number $F_{RN}$, which is automatically fulfilled if a ship’s Froude number $F_R = V_s/\sqrt{gL}$ is simulated.

It is well known that the performance of a ventilated propeller is rather sensitive to the propeller Froude number, especially at low advance speeds and at high thrust loadings, such as the typical DP and BP conditions. Figure 11 shows how sensitive the loads on a propeller can be with respect to the propeller Froude numbers at low J values and at J=0 (the blue dashed curves in the figure).
To achieve a propeller Froude number $F_{RN}$ up to a value of 4 to 5 (necessary in some test cases), it is necessary to use a shaft rotational rate of over 1500 RPM in model scale for a propeller with a medium size, having a 25cm diameter, which is considered rather high for a thruster model and may impose some difficulties.

The surface tension of water has been found to play an important role for propeller ventilation, especially during the onset and the finish of ventilation events. Generally speaking, the surface tension of water is too high on model scale with respect to that in full scale. To simulate it correctly, an equal Weber number is required, which is the ratio of the fluid inertia to the surface tension:

$$We = \frac{\rho V^2 D}{\gamma} = \frac{\rho n^2 D^3}{\gamma},$$

where $\gamma$ is the surface tension of water. This requires also a rather high rotational rate of a propeller model during model tests, which is in most cases rather difficult to achieve.

However, the fluid inertia, the surface tension and also the pressure on the interface of the fluid-air determines the formation of air bubbles and their dynamics that play equally important roles in ventilation. Model tests in atmospheric conditions show the sensitive dependency of ventilation on the Weber numbers, which may have exaggerated the surface tension effects. Those effects on ventilation can only be well studied when the pressure is well simulated, such as in MARIN’s DWB.

With regard to ice load tests, model tests in an ice tank follow normally also standardly the Froude law. However, it is often not applicable to propeller-ice crushing studies and tests. Although the hydrodynamic loads and the fluid inertia are present during propeller-ice crushing and extrusion, their contribution is less significant than the ice crushing loads. Dynamic propeller-ice interaction is mainly based on continuum mechanism, meaning structure dynamics and structural strength which follow Cauchy’s scaling law. Cauchy scaling maintains the ratio of the ice floe inertia and the ice crushing strength $\rho_{ice} U / S$, where $U$ is the ice crushing speed and $S$ is the ice strength.

In addition, attention needs to be paid to the compressive strength rather than the flexural strength of the model ice floes. Making model ice with correct compressive strength can be rather difficult for some ice tanks who pay more attention to simulating correctly the ice flexural strength in the past for ice-going ships, rather than for ice crushing on, for instance, the offshore structures and/or propeller blades.

**Synchronized high-speed video recordings**

High speed video recordings have been proven to be very effective to help in understanding the physics, especially for the present context on thruster ventilation and interaction with ice. MARIN has developed various underwater systems for high-speed video recording systems. When the high-speed video recordings are synchronized with the loads measurements, the phenomenon on the dynamic loads can be easily revealed and understand. The high-speed videos play an important role in studying thruster ventilation and thruster-ice interaction. This will be further discussed and shown in the following chapters.

**Test procedures**

**Type of tests**

Dynamic load studies for mechanical azimuthing thrusters are mainly focused on extreme loads. These include typically extreme manoeuvring open water tests of thrusters in inclined flow; thruster-thruster interaction tests; thruster ventilation tests and thruster-ice interaction tests.
There is very limited information on the dynamic loads on thrusters, during extreme manoeuvring (Oosterveld and van Oortmerssen, 1972), until very recently when systematic tests were carried out for a series of propellers working over 360 degrees steering angle at various advance ratios (Dang et al., 2013a). Systematic investigations have also been carried out (Dang et al., 2013a) for the thruster-thruster interactions, both with a pulling thruster with Wageningen C-series open propellers (Dang et al., 2013b), and also with a pushing thruster with Wageningen D-series ducted propellers (Dang et al., 2013b).

The type of tests and results, that are discussed in the present paper, are mainly on the thruster ventilations and the thruster ice interactions.

Data analysis

The measured dynamic loads are defined in 6 degrees of freedom in various coordinate systems, as shown in Figure 12. O-XYZ is a ship-fixed coordinate system. o-xyz is a thruster-fixed coordinate system which coupled to the steering angle $\delta$ of the thruster but doesn’t rotate with the propeller shaft. To study the loads on a single blade, an o-xtr coordinate system is used which is fixed to the key blade and rotates with the propeller shaft.

![Figure 12 The coordinate systems and the forces and moments](image)

The forces $F$ and thrusts $T$, and the moments $M$ and torques $Q$ are non-dimensionalized by the following formulae:

$$ K_{F,T} = \frac{F, T}{\rho n^2 D^4} \quad (4) $$

$$ K_{M,Q} = \frac{M, Q}{\rho n^2 D^5}. \quad (5) $$

Often, the sampled discrete points are fitted with Fourier series, as given in the following formula:

$$ K = \sum_{k=0}^{N} \left[ A_k \sin(k\delta) + B_k \cos(k\delta) \right] \quad \text{for } -180^\circ \leq \delta \leq +180^\circ \quad (6) $$

Quasi-steady test technique

Until computational fluid dynamics (CFD) are well developed to be able to capture all the details on flow separation, ventilation and ice-impact on a thruster efficiently (Koslowska et al., 2011 & Peddle et al., 2012), model tests are still indispensible. Building a test set-up with high quality for thruster model tests is often expensive. However carrying out series of tests with the built set-up at various conditions are considerably cheaper than doing large sets of CFD calculations. To reduce the testing cost even further, advanced test procedures and techniques have been developed and studied, leading to reliable and accurate new test techniques, such as the quasi-steady test method (Dang et al., 2012 & 2013b).
Figure 13 shows a test result as an example for using quasi-steady open water test technique for a propeller in 2-quadrants through varying either the towing speed of the carriage or/and the propeller shaft rotation rate in a single test run (the solid curves). Figure 14 shows a test result as an example for using quasi-steady test technique for a thruster at a given advance ratio, through varying the thruster steering angle continuously, covering 360 degrees in a single test run too (the solid curves).

Both sets of results have been compared to the results of the traditional steady tests, as shown in the figures by the circles (o) for the mean values and by the plus signs (+) for the 95% occurrence intervals. The quasi-steady test technique has shown and is proven to provide exactly the same results concerning both the mean values and also the fluctuations, as those determined by the conventional steady methods (Lafeber et al., 2013).

![Comparison of the filtered raw data from quasi-steady tests to the steady test results with their 95% occurrence intervals, sinusoidal variations, for a propeller at its design pitch setting (Dang et al., 2012)](image1)

![An example of unit dynamic thrust measured by quasi-steady test technique (solid curves) and compared to the mean values (o signs) and their 95% occurrence intervals (+ signs) of the steady-state measurements for a thruster at a given advance ratio, steering angle between -180° and +180°](image2)
Results and discussions

Series of test campaigns have been carried out in the past decades at MARIN to try to understand the dynamic loads on azimuthing thrusters at various conditions, which include extreme manoeuvring, thruster-thruster interaction, thruster ventilation and thruster-ice interactions, etc. Large databases with systematic results have been built-up and a thorough understanding of the physics and the characteristics of dynamic loads have been gained (Dang et al., 2013a).

The discussions on the results of the study in this paper will be focused on several selected important aspects of thruster ventilation and thruster-ice interactions.

Ventilation inception

Propeller ventilation is a rather complicated phenomenon, which depends strongly on thruster geometry (propeller, duct, struts, ship hull, thruster location, etc.), loading, advance speed, shaft immersion as well as time duration. However, two basic types of ventilations are dominant: one is vortex induced propeller ventilation and the other is propeller blade suction induced ventilation.

In general and as lifting surfaces, propeller blades generate a lot of vortices in the flow around it. Those vortices can be accumulated in time and form a few large strong vortices with very low pressure in the vortex cores. Those accumulating effects are often strengthened by a duct and the sharp corners at the connection of the duct to the vertical strut of a thruster. When a vortex finds a connection to the free surface, it funnels the air down onto the blades. Three screen shots of a video shows the inception of a vortex induced propeller blade ventilation in Figure 15.

![onset](onset) ![developing](developing) ![fully-developed](fully-developed)

**Figure 15** An example of vortex induced ventilation in bollard pull condition, thruster with ducted propeller (screen shots of video’s recorded with stroboscopic lights)

When a vortex induced propeller ventilation occurs, it can go very deep in the water. Increasing the immersion of the thruster may not easily stop the ventilation. However on the other hand, the vortex induced ventilation needs time to build-up a strong vortex. This occurs often in steady operations with high power setting on a thruster, rather than in intermittent and unsteady operations during continuously changing power settings and thruster steering angles in time.

The vortex induced ventilation is more often seen for a pushing thrusters with a ducted propeller rather than a pulling thruster with an open propeller.
To prevent vortex induced propeller ventilation, the connection of the vortex to the free surface should be blocked. This may be easy for many DP thrusters fitted in the bottom of a ship with a vast flat plate on top of them. In this case, the vortices will end on the surface of the ship’s bottom. However, blocking a vortex for a ship with thrusters for the main propulsions can be difficult because the thrusters are often located close to the sides or ransom of a ship. Placing a pushing type thruster with ducted propeller close to the transom of a ship and under the blunt ending of its headbox with a dead water area right above the propeller has been proven to be a problematic configuration design with respect to the vortex induced propeller ventilation, both for operations at zero speed and for operations during transit.

The other type of ventilation inception is related to low pressure generated on the suction side of propeller blades of a thruster, when it is close to the free surface. The blades suck down the water surface until the air breaks in and fills the low pressure areas on the propeller blades. Figure 16 shows the event of this kind of ventilations on an open propeller blade in one surface wave period in the DWB of MARIN in atmospheric condition.

![onset](image1.png) ![fully-developed](image2.png) ![retrieving](image3.png) ![finishing](image4.png)

**Figure 16** An example of blade ventilation in waves, pulling thruster with open propeller at low advance speed, selected frames from high speed video's, atmospheric condition

For both types of ventilation, the process from the onset to full-ventilation is normally accomplished within a very short period, typically within one revolution of a propeller. Once a blade is fully ventilated, the ventilation bubble will still stay attached to the blade, after the bubble is already disconnected from the free surface, for several tens or even hundreds of revolutions before the air bubbles are broken down gradually and washed away completely.

Ventilation inception on a pushing thruster with ducted propeller in waves is often a combination of the above-mentioned basic types of ventilations. Figure 17 shows screen shots of selected moments during one period of the surface waves in atmospheric condition for a thruster in DP operation. The onset of the ventilation starts almost always at the corner of the connection between the duct and the vertical strut by a vortex. The air fills first and quickly into the leading edge of the duct, before the propeller blade ventilation starts. Due to the combined effects of the vortex and the suction of the propeller and the duct, a huge funnel will be formed which draws the air onto the propeller blades, which results in full blade ventilation.

It seems that the air bubbles entrained at the leading edge of the duct are very difficult to be washed away by the flow. At the finishing stage when the ventilation is disconnected from the surface, the ventilation bubbles at the duct leading edge stay for a rather long period at the lower half of the duct. This results
from the elevation of the wave surface that generates an upward flow to the duct and a low pressure area along the inner side of the lower half of the duct by the orbital motion of the water particles in waves.

Figure 17 An example of duct and blade ventilation in waves, a pushing thruster with a ducted propeller at DP condition, selected frames from high speed video’s, in atmospheric pressure

Alternate blade ventilation

Similar to a pump impeller where alternate cavitation may occur when the impeller has even numbers of blades, e.g. 4, 6 or 8-bladed, alternate ventilation on propeller blades can take place if a propeller has an even-number of blades too. This can occur on both open propellers and also on ducted propellers.

Figure 18 shows a typical case for a pulling thruster fitted with a 4-bladed open propeller. When one blade is fully ventilated, it changes the inflow to the next blade downstream. The ventilation on the second blade can be totally suppressed then. This phenomenon may repeat on the consecutive blades, thus resulting in alternate blade ventilation. This kind of ventilation can stay very stable due to the fact that the propeller has an even number of blades.

When alternate ventilation occurs, the load fluctuation on the shaft during the ventilation will increase due to the un-balanced loads on each blade, especially for the shaft bending moments. To prevent the alternate blade ventilation, a propeller with odd-numbered blades can be considered, such as a 5-bladed propeller fitted to a thruster.
Dynamic loads during ventilation

Propeller blade ventilation results in strong dynamic loads on both single propeller blades and on the propeller shaft. With carefully-designed transducers, the dynamic loads can be measured up to a very high frequency. To remove any noise and any response related only to the model itself and to obtain only the hydrodynamic loads, low-pass filters can be used.

Figure 18 An example of alternate blade ventilation on the propeller of a thruster with even-numbered blades, resulting in even stronger load fluctuations on the shaft train, at atmospheric condition

Figure 19 Blade dynamic loads in 5 wave periods, open propeller P/D= 0.8, thruster steering angle 0 degrees, advance ratio 0, shaft immersion 1.5R, cavitation number $\sigma_n=2.0$, wave amplitude 1R, period 2 seconds
A selected set of test results on the key blade of an open propeller fitted to a pulling type thruster is shown in Figure 19 as an example, where the blade thrust $T_{bx}$, the blade shaft torque $Q_{bx}$ and the blade spindle torque $Q_{br}$ are plotted against time for 5 periods of the surface waves. Every spike represents each revolution of the propeller shaft. Some notes are given only on the blade thrust $T_{bx}$ in the figure, which are however also valid for the shaft torque $Q_{bx}$ and the blade spindle torque $Q_{br}$.

At the wave peak, the propeller was immersed deeply under the water surface and no ventilation occurred although limited cavitation was found on the blade surfaces. With the drop of the wave height, the static pressure reduced and the cavitation volumes on the blades increased, resulting in slightly stronger load fluctuations on the key blade. When ventilation occurred, the blade loads dropped suddenly within one single revolution. The mean load reduced further to the lowest level in the wave trough. Recovery of the mean loads and finishing of the ventilation took a long time: several tens of revolutions of the propeller.

During the ventilation, strong load fluctuations have been measured on the key blade with a lot of high spikes. The highest single spike indicates that the loads can be double those of the values at non-ventilated condition. In addition, ventilation may result also in negative thrust and torque which depends on the balance of the pressure on the ventilated side of the blade with that on the non-ventilated side.

Unlike the blade thrust and torque, the mean blade spindle torque doesn’t change that much during ventilation, however the fluctuations are rather pronounced.

When the measured loads on the key blade are applied to other blades by shifting the phase of the measurements, the total propeller shaft dynamic loads can be composed. The non-dimensionalized 3 forces and 3 moments on the propeller shaft are plotted in Figure 20 as examples for the same event as discussed above and shown in Figure 19.

![Figure 20 Non-dimensionalized shaft loads in one wave period, propeller pitch ratio 0.8, thruster steering angle 0 degrees, advance ratio 0.0, shaft immersion 1.5R, cavitation number $\sigma_n=2.0$, wave height 1R, wave period 2 seconds](image-url)
The dynamic load fluctuations are less pronounced on the shaft than on the single key blade. This is because that the loads on different blades cancel and balance each other, partly. However, the load fluctuations during ventilation event are still very significant. Besides the sudden drop of the propeller thrust and torque, the propeller shaft bending moments $Q_y$ and $Q_z$ change also suddenly when ventilation occurs. These horizontal and vertical bending moments on the shaft at the propeller have been considered to be the most important components of bearing and gear loads of a mechanical azimuthing thruster that determine the size of the equipment.

**Propeller-ice impact loads**

The shaft transducer with high response frequency and high accuracy makes the study on the ice impact to a propeller blade possible, which is quite similar to that of the blade ventilation event which occurs in a very short of time period. Combined with synchronized high-speed video recordings, many details of the phenomenon can be revealed and studied.

In the following figures, Figures 21 through 23, three screenshots of an ice impact event on a propeller blade of a pulling thruster are shown at three most representative moments during an ice floe impact on a propeller blade, where the thruster was in BP condition and a prescribed disc-shaped model ice floe was fed into the propeller. The measured blade forces and moments were synchronized with the high speed video recordings and are shown in the below figures with coloured curves.

![Image: Ice blockage effect](image)

**Figure 21** An example of propeller flow blocked (but not touched) by an ice floe, resulting in sudden increase in blade thrust $F_X$ and torque $M_X$, minor influence on blade spindle torque $M_Z$, synchronized results

Figure 21 shows the moment when the ice floe is coming towards the key blade of the propeller – the one with line marks on selected radii, but just before hitting the blade. The loads on the key blade increased suddenly at that moment. This is a very well-known effect called the ice blockage effect. The ice blockage effect can increase the blade loads to a level higher than bollard pull loads. However only the key blade, which is extremely close to the floe, feels the blockage effect. The loads on the other blades are hardly affected.

When the key blade starts to crush into the ice floe, as shown in Figure 22, the crushing process results in a high pressure on the suction side of the blade. This high pressure will reduce the blade thrust. In many cases, the blade thrust can be reduced to even a negative value. This crushing on the suction side of the blades depends not only on the compressive strength of the ice floe, but also on the change of its momentum – meaning the size (mass) of the ice floe and the speed change of the ice floe.
Figure 22 An example of ice impact on the suction side of a blade when the blade cuts into the ice, resulting in a strong negative peak of thrust $F_X$, torque $M_Y$ and blade spindle torque $M_Z$, synchronized results.

Once the propeller blade cuts into the ice floe, it will extrude the crushed ice from the leading edge on the pressure side of the blade, resulting in a sudden increase of the blade thrust due to the high pressure on the pressure side of the blade. This is clearly shown in Figure 23 at the moment of the ice extrusion.

The positive thrust and torque on the blade during the extruding of the crushed ice depends also on both the size (mass) and the relative speed of the crushed ice. The higher the propeller pitch and the propeller shaft rotational rate are, the higher the ice extruding loads will be.

Figure 23 An example of an ice floe being cut-off and extruded from the pressure side of a blade, resulting in a high positive peak of blade thrust $F_X$ and torque $M_Y$, and fluctuations of blade spindle torque $M_Z$, synchronized results.

At both moments when the ice impacts on the suction side of a blade during ice crushing and when the ice impacts on the pressure side of a blade during ice extruding, the ice generated negative and positive loads on the key blade become so dominant that the hydrodynamic loads become relatively insignificant.
Concluding remarks

Dedicated model tests carried out at MARIN in the last decades have resulted in fruitful understandings of the dynamic loads on azimuthing thrusters during all possible operations, including thruster ventilation and thruster-ice interactions. The lessons learnt and the experiences gained can be summarized in the following conclusions and remarks.

- In order to capture the hydrodynamic loads and limit the noises to the measuring system, carefully-designed load transducers with high accuracy and high response frequency are essential. The signal close to and above the natural frequency of the system should be filtered, which either represents only the model test set-ups or comes from the system noise.

- Test conditions and scaling laws are very important to ensure that the test results represent real-life full-scale situations. Besides Reynolds and Froude laws, cavitation and Weber numbers need to be considered carefully. MARIN’s Depressurized Wave Basin (DWB) provides a unique facility in the world where most of the scaling laws can be fulfilled and the cavitation and ventilation events can be tested together with surface waves, which prevent also flow circulations during DP/BP testing.

- Test procedures, such as the quasi-steady test technique, make it possible to conduct the tests with a high accuracy in a very efficient way, so that quality results can be obtained with low budget. Compared to the traditional methods, the quasi-steady method save test time by a factor of 8 to 10. Therefore systematic studies can be carried out, which support the thruster design strongly, with respect to the scantlings of the parts.

- Both the dynamic loads during extreme maneuvering and the thruster-thruster interaction, and also the dynamic loads during thruster ventilation and ice-impact are thoroughly studied at MARIN by conducting model tests, with a typical pulling thruster fitted with an open propeller and with a typical pushing thruster fitted with a ducted propeller.

- When the measured dynamic loads are synchronized with high speed video recordings, a lot of physical phenomena can be revealed and understood. This helps the industry to understand the details of the dynamic loads and to prevent possible damages already during the thruster design stage.

The findings of the present study provide detailed information on the dynamic loads on mechanical azimuthing thrusters to support the determination of the strength of the mechanical parts and to guide the full-scale workshop testing, which are not only important for thruster designers, manufacturers, classification societies, but also for the operators in order to prevent damages to mechanical thrusters in service.

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