Experimental investigation of the effect of waves and ventilation in depressurised conditions on a POD-propeller of a cruise liner model

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ABSTRACT

Ventilation is a feared working condition of ship propulsors. Except for rare applications such as surface piercing propeller specially designed for this purpose, traditional propellers could suffer from a noticeable breakdown of thrust and torque once a sufficient amount of air is entrapped by the rotating propeller. Experience showed that the risk of ventilating propellers was negligently underestimated in traditional towing tank experiments but better predicted in depressurised towing tanks, where the ambient pressure is scaled down according to Froude similarity.

In 2012 MARIN has taken into service their Depressurized Wave Basin (DWB). This unique facility is the only in the world that is able to generate waves in a depressurized towing tank. This ensures correct representation of the pressure inside the enclosed ventilation bubbles and vortices, resulting into correct physical behaviour. The EU-funded Streamline project was the first project for which ventilation inception measurements were carried out in the DWB. The tests were carried out with a Poded Cruise liner model, sailing in waves and depressurised conditions.

In order to acquire detailed load measurements, MARIN used their in house developed 6 component and 5 component transducers. The 6 component transducer was used for measuring the omnidirectional propeller loads, while the 5 component transducer was used for measuring 2 blade forces and 3 blade moments. At the same time synchronised high speed video recordings were made to acquire insight in the occurring phenomena. In the present paper a description of the test set up will be presented. Furthermore one of the recordings and observations will be discussed in a detailed way, providing more insight in the complex phenomena that take place when cavitation and ventilation are originating and vanishing.

KEYWORDS
Ventilation, Waves, Dynamic forces, Propeller, POD.

1 INTRODUCTION

When ventilation occurs unpredictably and uncontrolled, the propeller starts racing due to the reducing torque in the ventilated regime. This might cause severe damage to traditional Diesel engines with at the same time imposing heavy efficiency losses as at the higher RPM of a racing propeller; the advance coefficient of the propeller is shifted into the unfavourable off-design regime. One of the claimed advantages of electric Poded propulsion is that the electrical engines can cope better with the dropping of torque, resulting in less engine damages. On the other hand the loading of the propeller bearings is more difficult to dimension due to the poor knowledge available, in the public domain, on Poded propulsors in service or more specific, seakeeping conditions.

During higher sea states the propeller loading fluctuates due to the variation in speed and the vertical motions of the vessel, which will result in different cavitation behaviour and inception speeds compared to the calm water conditions. Moreover, based on past experiments in MARIN’s Seakeeping Basin, it was seen that ventilation can sometimes occur on pods as well, a phenomenon which was observed to greatly affect blade forces and moments, and thus the shaft loading as well. The EU-funded Streamline project aimed at studying these ventilation effects in detail.

2 WAVES IN DEPRESSURISED CONDITIONS

Van Beek et. al. (2006) showed that the impact load of ventilating propellers depends upon the ambient pressure in an extensive study on the effect of ventilation on the spindle torque of CPP-blades. Moreover, entrapped air pockets are proven to behave differently at different scales (Lafeber et al 2012). Therefore, better predictions are achieved in depressurised towing tanks, where the ambient pressure is also scaled down according to Froude’s law of similitude.

In service conditions, waves also play a dominant role and will lead to increased inception of ventilation. Ideally, one would test for ventilation in both a depressurised basin and a wave basin. Unfortunately, the depressurised towing tank of MARIN was up to the last modification not able to test ships in full service conditions, i.e. with waves. With the installation of the wave generators in 2012 at the short and long side of the basin, the possibility to test ships in various seakeeping conditions and correctly scaled pressure became possible. Now cavitation
and ventilation phenomena can be observed simultaneously.

The refitted basin is now known as the Depressurized Wave Basin (DWB). This unique facility is the only in the world that is able to generate waves in a depressurized towing tank. This ensures correct representation of the pressure inside the enclosed ventilation bubbles and vortices, resulting into more correct physic behaviour.

Figure 1: DWB from the inside, wave flaps visible at the left

MARIN, as the only operator of a depressurised wave basin tank, combines its knowledge how to operate depressurized towing tank and a seakeeping basin. In almost 40 years of experience it was learned that ventilation of model propellers is better observed in a depressurised regime rather than in a conventional towing tank. In other words, real ships suffering from ventilation are not correct modelled in normal towing tank tests. Therefore the DWB was chosen to perform a large part of the Streamline research on ventilation.

3 SHIP MODEL

For the study of ventilation and cavitation on Podded propulsors in service conditions, a ship model, including pod and propeller design had to be selected. Furthermore the test series serve to be as a validation case for CFD calculations.

The selected model was a cruise liner ship; however it didn’t have the typical ‘wave damping’ aft body that is seen on these ships since the last decade, but a more V-shaped one, see Figure 2. This makes it more comparable with other ship types, and reduces to a large extend the risk of slamming, which was regarded to be a not favourable condition to calculate with CFD-calculations and reduces the suitability of a benchmark case.

Figure 2: Aft body with the Podded propulsors.

The light loading condition of the vessel was used in combination with a series of wave periods, with the highest chance of ventilation.

The model is depicted in the harbour, just before entering the airlock to the depressurised part of the DWB in Figures 3 and 4. The model itself was free to heave and pitch.

Figure 3: model front fixation

The model’s surge motion was controlled by a linear motor which was programmed to re-enact a damper-spring system as if the model was being pulled by soft springs. The usage of a linear motor allowed for quick changes of the system’s behaviour and speed adaptive friction correction.

Figure 4: model aft fixation and engines

4 MEASURING VENTILATION

Measuring on phenomena which are very short in duration like ventilation can be very difficult. The dynamic range of the measurement device plays a dominant role in the ability to distinguish high frequent effects. See Hagesteijn et al (2012) for an elaborate explanation of the problem at hand. To ensure the registration of all phenomena or as much as possible
during a ventilation event, it is aimed to have the natural frequency of the measurement system as high as possible.

Based on past experience, it was decided a single blade should be instrumented and a new multi-component force-transducer needed to be developed. This way, a maximum natural frequency for the measurement device could be achieved, while asserting enough sensitivity of the transducer.

The starboard propeller was fitted with the single blade force-transducer or ‘key-blade’. Synchronised camera recordings were made with normal speed cameras and high speed cameras. Since the starboard propeller contained the ‘key-blade’ this was the propeller of main interest and where the camera’s were aimed at. The other propeller at portside was fitted with an existing multi-component force-transducer. This transducer has 6 degrees of freedom but was designed for use in a full propeller. While successfully used to measure blade loads in the past, the natural frequency of the setup would have been compromised if used for another key-blade measurement setup. Therefore the portside propeller measurements consist of multiple degrees of freedom forces, but do not contain as high frequency data as the ‘key-blade’ at starboard.

During development of the multi-component force-transducer for the key-blade, it was decided to sacrifice one component, being the centrifugal force component. Therefore the key-blade transducer became a 5 component transducer instead of 6. The final design of the key-blade transducer is shown in Figure 5.

Finite element calculations were used to determine the first natural frequency of the key-blade and its transducer, see Figure 6. The first natural frequency is used to identify the frequency that still can be measured. Measurements around the natural frequency are likely to be exaggerated. Above those frequencies, the setup acts like an analogue low-pass filter, obscuring any measurements that might be of interest. To prevent exaggerated measurements around the natural frequency, filtering is applied to the measured signals during post-processing of the data.

To minimise disturbances in the measurement signals caused by gears, bearing etc., direct drive units are used for the Pods. These units consist of a small electric engine in the Pod-housing similar to real Pods. For the propeller shaft, space is very limited in a direct drive unit. Also, the geometrical constraints are different from regular propeller shaft sensors. The 6-component force-transducer was already designed for use with the direct drive method. The thrust of the propeller is directed along the shaft and causes tension and compression of the shaft. To measure a longitudinal force in a slender body like the shaft which also experiences torque and side forces, is quite challenging. Nevertheless the concept as shown in Figures 7 and 8 are capable of measuring these forces for a key-blade full propeller respectively.
For both the 5 component key-blade and the 6 component propeller transducer, multiple independent measurement channels are measured. Deriving these high sampling frequency signals from a rapid rotating shaft is a challenge on its own. A very small slip-ring set with 24 channels, specially designed for this purpose, is used to bridge the sensor data from the rotating shaft to the rest of the setup for both Pods. All the strain gauge bridges in the transducer have their individual power supply channels and their individual measuring channels.

To prevent imbalance issues at the starboard propeller, the blades mounted directly on the shaft side of the transducer are equipped with balance weights to counteract any weight deviations caused by the key-blade.

To gain a better understanding of the measurements it is required to record high speed video during some of the measurements. The cameras buffer a few thousand frames constantly. When a manually controlled trigger pulse is send, the cameras keep on buffering up to its full capacity and stops filming once the complete buffer is filled. The high speed camera windows can be observed in Figure 2. The oval shapes in front of the starboard Pod are the windows.

5 TEST RESULTS

A series of tests were carried out which started as a systematic matrix, which was deformed during the execution of the tests to capture sufficient conditions in which ventilation occurred. Tests with interesting events were carried out both in depressurized and atmospheric conditions. During all measurement runs it was aimed to capture normal video and high speed video recordings. However, due to the relatively short buffer length of the high speed video and the large data sizes created by it, it was not possible to captures all events on high speed video. The combination of high speed video with high frequency transducer signal measurements, enables a unique and detailed investigation into the development, the growth and stability of ventilation phenomena.

In Figure 11, the model is shown during one of the tests. The waves are irregular head-waves with a significant height of 4 m full scale. Two wave probes are seen mounted near the bow of the model.

For the initial search for ventilation standard video recordings with an underwater camera positioned behind the ship model are used. An example of such a recording is shown in Figures 12 through 14.
Figure 12: cavitation inception

Figure 12 shows inception of cavitation due to decreasing hydrodynamic pressure when the water surface is moving down in a trough. The cavitation is only present on the top of the blades passing through the upright position. The water surface is close to ventilating, but needs to be lower for this to start.

Figure 13: ventilation inception

Figure 13 is taken just moments later then Figure 12. Now the water surface is lowered further due to the wave trough and breaks down. Air, though depressurised, is being caught by the propeller and a ventilation event is started. Figure 14 shows the air being thrown out aft of the Pod the next moment.

Figure 14: model sailing in waves

When propeller ventilation or another interesting phenomena was observed, a high speed video recording was made for a duration of about 4 seconds. High speed video camera observations turned out to be a very valuable tool for the analysis of the differences between depressurised and atmospheric conditions with regard to differences in ventilation behaviour.

In Figure 15, two frames from a similar event are combined and show the same situation in depressurised and atmospheric conditions. The left frame shows the depressurised situation and the right frame the atmospheric situation. The synchronised time traces of the measured forces are plotted at the right side of the figure for both situations with Froude scaled values for full scale. The white marker indicates the synchronised moment of time. Thick lines are for the depressurised measurements and thin lines for the atmospheric ones.

The test for which Figure 15 is constructed was performed while sailing forward in a regular wave with 0 degrees Pod angle. In this particular situation the time traces of the forces are very similar though the inception of cavitation was present under depressurised conditions. This is visible at the left side of the figure between blades 2 and 3. Small differences, especially in the low frequent content (periodicity above 0.2 s full scale) can originate from small differences in the exact inflow into the propeller.

In Figure 15, the breakdown of the water surface in front of the pulling Pod blade can be clearly distinguished. This brake down will swiftly turn into a closed air pocket which is sucked in and moved downstream along the Pod.

Another example of such a comparison is seen in Figure 17. This time the Pod was turned under an angle of 30 degrees. Again the low frequent components of the force measurements are found to be very similar, but due to the strong interaction of cavitation and ventilation, higher frequency oscillations are now seen as well in the depressurised signals. The effects that occur in this transmission regime have been described by Brandt (1973), who used the UT2 of VWS for systematic research of ship propellers close to the free surface in
depressurised conditions at different cavitation numbers. The atmospheric situation is very close to ventilation as well, but is slightly less likely to ventilate. When it does though, no high frequency oscillations, as in the depressurised condition, are observed.

Other observations during the test campaign were that for sailing conditions with forward speed, a constant presence of a cavitating tip vortex was formed before ventilation would incept. Therefore ventilation and cavitation were sometimes hard to separate from each other. Furthermore it was observed that during a local passing wave trough, a phase difference is observed in the development of the cavitation and the ventilation. The cavitation generally forms earlier then the ventilation while the ventilation can hold longer than the cavitation. Therefore it can be concluded that not only local pressure is of importance, but also flow direction for these phenomena.

Figure 15: similar ventilation event in depressurised (left frame, thick lines) and atmospheric conditions (right frame, thin lines)

Figure 16: similar ventilation event in depressurised (left frame, thick lines) and atmospheric conditions (right frame, thin lines)
6 APPLICATION POINT OF FORCES

Apart from the magnitude of the ventilation/cavitation impacts, also the point of application of these forces is of interest for load and fatigue calculations. With the forces and moments of the key-blade known, an application point can be determined for this force. More accurately, a line of application can be determined which intersects with a surface. The surface chosen is a 2D representation of the blade for easiness of calculation. The line of application is defined as the line were the translated force vector would have a minimized (or zero) resulting moment left. The direction of this line is always parallel to the direction of the force vector itself. The intersecting point with the surface is determined by finding the solution with zero moments applied perpendicular to this line. However the moment applied over the longitudinal direction of the line itself stays the same, regardless of the position of this line in space. Therefore the minimum total moment found can be different from zero.

In Figure 17, an example of application point calculations is shown. There are actually two points and corresponding force vectors shown. The measured data is split into two parts. One part contains the low frequency data which contains frequencies only slightly above the rate of revolution. This low frequency part resemble the ‘normal’ inflow condition and still contains the dynamics from the motion of the blade during a single revolution and the changing inflow during this revolution. The other part, or high frequency part only has a significant value during periods in which high frequent oscillations occur, as during the inception of ventilation and cavitation. The application point technique is able to identify the position of these high frequent phenomena. In Figure 18, the low frequent force and application point are denoted by the yellow arrow. The high frequent part is denoted by the red arrow. The low frequency arrow is found where the normal hydrodynamic forces are believed to act upon the blade. The high frequency arrow able to identify the region where the high frequent oscillation originates from, namely the location where sheet cavitation resides and due to ventilation, air is being drawn into for this instance.

![Figure 17: forces and their application point during a combined cavitation and ventilation event, low frequent in yellow, high frequent deviations in red](image)

CONCLUSIONS

Research on ventilation is very important since ventilation damage is expected to occur regularly and the current knowledge is not sufficient. One of the big difficulties was that until recently nobody was able to measure ventilation on model scale under all the right circumstances. With the opening of MARIN’s DWB facility new research possibilities are introduced.

In the DWB model test were performed in waves and depressurised conditions for the first time in the world. Many ventilation events were registered on a fully instrumented model of a cruise liner ship with two pods. One of the pods was equipped with a multi component force-transducer which combined with high speed video footage gave insight in the occurrence, build up, and dynamics involved of ventilation events.
Utilising the application point technique enabled to not only register the strength of the applied force, but also to the location of this force. Splitting the frequency content of the signals on top of that enabled even the identification of local disturbances in the flow.

The EU-funded Streamline project succeeded at studying ventilation effects in detail.

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