# A SOURCE OF PROPELLER EXCITED BROADBAND VIBRATION ON A HIGH-SPEED TWIN SCREW SHIP

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## SUMMARY

The cause of the severe propeller excited broadband vibration on a twin screw ship's stern was investigated in a cavitation tunnel using conventional modelling methods. At first sight the results did not indicate anything untoward about the stern and propeller designs tested, apart from some unusual cavitation patterns in the propellers' slipstreams. The fluctuating pressure levels on the model hull varied considerably depending on the propeller designs and loading conditions used in the tests, but these did not provide an explanation for the vibration on the ship. Some unusual patterns in the relative levels of the harmonic pressures on the stern were noticed in addition to the presence of a large cavitation disturbance in a propeller trailing vortex that was captured in a single frame of a video recording. This latter observation led to a plausible explanation for the broadband vibration on the ship's stern.

## NOMENCLATURE

| | |
|---|---|
| $n$ | Harmonic number (n =1 to 5) |
| $p_n$ | Pressure of n$^{th}$ harmonic (Pa) |
| $\delta\tau$ | Time duration of pulse (s) |
| $\omega$ | Propeller speed of rotation (rad/s) |

## ABBREVIATIONS

| | |
|---|---|
| bpf | Blade Passage Frquency (n=1) |
| rms | Root Mean Square. See Appendix for definition |
| tdc | Top dead centre. Reference blade in the vertically-up position |
| bdc | Bottom dead centre. Reference blade in the vertically-down position |
| QPC | Quasi Propulsive Coefficient |

## 1. INTRODUCTION

The source of the vibration described in this paper occurred on a high-speed twin screw vessel typical of Container and Cruise Ships. It was fitted with open propeller shafts supported by brackets on either side of a centre-line skeg and twin rudders mounted abaft the propellers. Four bladed outward turning propellers were installed with tip skew angles in excess of 30° in what may be described as a compact after end design.

In service the vibration occurred in the after region and was notable because it was not directly related to the shaft or blade frequencies and their harmonics. In fact the vibration response of the ship's after structure was high level and non-periodic over a frequency range covering several harmonics of blade passage frequency (bpf). Furthermore there was a feature of randomness in the ship's vibration.

## 2. MODEL TESTS

In the course of producing the underwater ship design, conventional model tests were conducted in a towing tank to obtain the resistance and propulsion measurements and the nominal wake at the propeller position. On the basis of the nominal wake measurements outward turning propellers were selected. At that time nothing unusual was detected in the underwater hull design and the aft end in particular. The longitudinal clearances of the propellers in their apertures conformed to acceptable practice and it was only after the ship was completed that the vibration problem emerged. This led to further model tests being conducted in an attempt to discover the hydrodynamic cause of the problem after it was concluded it could not be overcome with local structural modifications.

Initially suspicion centred on the design of the propellers and their cavitation performance, but after modifications to the designs and repeating model cavitation tests it was realised that the problem was more obscure than anticipated, and cavitation tests in a large tunnel in which a complete model hull with its necessary appendages should be used. The primary advantages of a cavitation tunnel facility being that relatively high Reynold's numbers can be achieved and some control over the susceptibility of water to cavitate is available by adjusting its free gas content.

## 3. CONVENTIONAL FLUCTUATING PRESSURE MEASURMENTS

The fluctuating pressures on the model hull surface were recorded and analysed using established methods for dealing with periodic signals having frequencies at multiples of the shaft frequency. These methods with minor variations were, and probably still are, in common use at most of the main propeller cavitation testing laboratories. They presume that the recorded pressure fluctuations on the hull surface are periodic and that representative rms pressure levels and phases together with their dispersion statistics can be produced for harmonic frequencies up to, say, five times bpf. The cut off frequency in the measuring system can be quite low, depending on the frequency of the highest harmonic pressure of interest. This procedure is probably suitable for the vast majority of cases where the propeller(s) is the source of harmonic vibration excitation. However, when the vibration response on the ship is not of this simple form real-time analysers can be used to advantage in identifying more complicated signals producing results such as those described later.

Whilst the ship scaled rms pressure levels at bpf were often higher than desirable, those at twice, three times and even four times bpf were unusual as described in some detail later. It was clear, however, that at first sight these results could not be used to explain the source of the vibration on the ship.

## 4. FLOW OBSERVATIONS

The observations of propeller cavitation under stroboscopic lighting showed wide arcs where blade back cavitation was present in the form of leading-edge vortex cavitation and some surface cavitation, whilst in the arcs void of back cavitation surface cavitation on the blade face was usually present. This was to be expected considering the propeller loadings tested, the nominal inflow wakes and cavitation numbers at the representative blade radius in the tdc position.

When looking downstream however, both near and far from the propellers, heavily cavitating propeller tip vortices were seen in the outboard arcs of the slipstreams extending from near tdc, 0°, to bdc, 180°, for both propellers. It appeared as though imaginary longitudinal vertical planes near the propeller shaft axes and parallel with them inhibited the presence of tip vortex cavitation on their inboard sides. This was unusual in the author's experience and noteworthy as in most cases where vortex breakdown has occurred with strongly cavitating tip vortices the vortices continued to cavitate through 360 degrees after the singularity.

Unfortunately it was not possible to obtain pictures of the downstream flow just described because of the awkward viewing situation. It could be seen by eye however, when articulating one's head and viewing at shallow angles through the tunnel's bottom windows.

Observations of the cavitation on the propeller blades and in the aperture space immediately ahead of the rudder were also captured using a video camera. At first sight these recordings simply appeared to confirm the observations made by eye under stroboscopic lighting, until a frame was found showing details not seen earlier, see Fig. 1. This shows a propeller blade on the Port side approaching tdc and the observer, with its accompanying back cavitation, and two cavitating helical tip vortices shed from preceding blades. The first of these shed vortices had reached the outboard side of the port rudder whilst the second was at the aperture just upstream of the rudder's leading-edge, where it had transformed into the large whitish-grey region which is believed to include the site of a cavitating vortex breakdown or collapse. The fact that this region is whitish-grey in appearance instead of translucent indicates it is a region of micro-bubbles reflecting the incident stroboscopic light back to the observer. This description is enhanced by the merger of the whiter interior region into the fuzzy light-grey region at the periphery where the density of the micro-bubbles has decreased presumably.

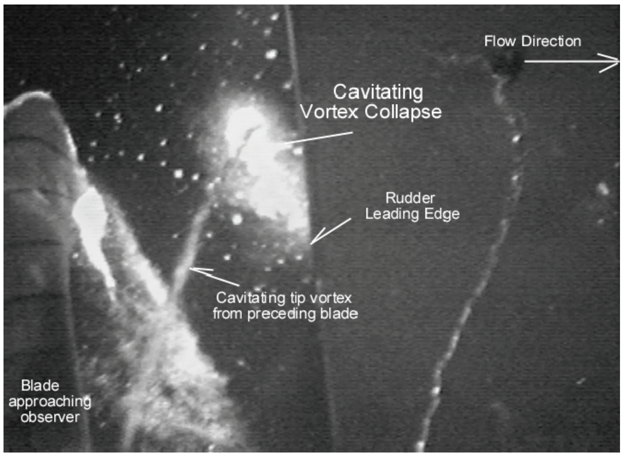

Figure 1. Cavitating Vortex Collapse

The vortex breakdown site itself is believed to lie within the overall whitish-grey region near the top where it is brighter than the remainder, which appears to include a trail of micro-bubbles following the helical path that the tip vortex and inboard helical vortex sheet would have taken had the tip vortex not collapsed.

This observation marks a notable difference between previous observations of model propeller tip cavitating vortex breakdowns where, after the disappearance of the cavitating vortex core for a short distance, the cavitating core re-establishes itself - as if the breakdown had not occurred. A similar observation was made by the authors of Reference [1] for a hydrofoil tested in the CalTech water tunnel. The disappearance of the cavitating cores of the tip vortices on their inboard sides in their respective slipstreams, referred to earlier, suggests the circulation of the downstream vortices had weakened to an extent that cavitation was not supported.

## 5. OTHER SOURCES OF CAVITATING VORTEX BREAKDOWNS

(Excluding propeller-hull vortex collapse)

### 5.1 OSCILLATING HYDROFOILS

Cavitating vortex breakdowns in the tip vortices shed by oscillating hydrofoils, as described by C Brennan of CalTech and his collaborators, help to throw light on what is believed to be taking place in the case of the cavitating propeller tip vortices in this example. For instance, the position of tip vortex cavitation where it becomes a cavitation cloud, consisting of a region of densely packed micro-bubbles, is responsible for the very high pressures experienced in the fluid on its collapse. The cloud of micro-bubbles is unstable and collapses extremely rapidly in a coherent manner, when intense impulsive pressures are created at the collapse site. For example, in the water tunnel facility at CalTech it was found that positive pressure pulses on the upper low pressure surfaces of the cavitating hydrofoil had amplitudes of the order of tens of atmospheres and durations of the order of tenths of milliseconds [2]. An observation concerning the pause in the cavitation of the hydrofoil tip vortex as it passed the trailing edge of the foil was also observed linking it with propeller observation described above.

### 5.2 CAVITATING VORTEX GENERATOR

Other tests in a Cavitating Vortex Generator (CVG), an experiment rig designed especially for determining the collapse pressures and durations of cavitating vortex breakdowns, has estimated a sample mean pressure of 900MPa (9kbar) and an extreme pressure of 2,200MPa (22kbar), the latter occurring in a time interval of tens of microseconds [3]. These pressures and timed events were determined with novel and elaborate techniques unlike using conventional strain gauges, for example. Repeated impulsive pressures of these magnitudes in the close vicinity of hard metals are known to cause erosion and metal fatigue. The vast difference in the collapse pressures obtained in the CVG and the Caltech water tunnel on hydrofoils is noteworthy and perhaps can be explained by the higher velocities in the CVG and the greater tensile strength of the water there, as well as the mechanism used for initiating the solitary vortex breakdowns and ensuing bubble clouds.

## 6. FURTHER CONSIDERATIONS

The two-dimensional shape of the whitish-grey region seen in the aperture upstream of the port rudder in Fig. 1 does not give its athwartships position in relation to the entrance to the passageway formed by the closure of the ship's centre-line skeg, the hull above and the inboard side of the port rudder. The flow approaching this passageway is highly irregular and it is conceivable that the static pressure in the vicinity of the rudder's leading-edge had increased locally above that present in a uniform stream causing the cavitating vortex to collapse. This is a conjecture that could not be explored, but it was found that moving the rudders outwards by a small distance made little difference to the results. Also, it was noticed that when comparing the propulsive coefficients for this ship design with those of two similar type twin-screw ships all tested in the same towing tank using an identical thrust identity testing method, the relative rotative efficiency was lower for this vessel compared with the other two. However, the overall propulsive efficiencies, QPC's, of all the vessels were acceptably close taking account of the uncertainties present in ship model propulsion testing, Reference [4], and the scepticism held in some quarters regarding the breakdown of Propulsive Efficiency into its component parts.

It can be deduced, albeit subjectively, from the levels of the blade rate pressures recorded in these experiments, that the pressures associated with the collapse of large cavitation clouds like that shown in Fig 1 did not occur at successive blade passages, since if they had the blade rate pressures would have been exceptionally high. This points to the likelihood that the broadband vibration experienced by the ship was caused by shock pressures at random time intervals. This may have been confirmed if instrumentation for observing the real-time pressure transducer signals in the model experiments had also been installed which unfortunately it was not.

The size of the breakdown cloud in the current propeller example appears be of the order of 0.1R across in the image plane, R being the propeller radius, which would categorise it as being large, if not very large, and a non-linear event in mathematical terms. However, it will be appreciated that at the instant of recording the image the breakdown cloud could be growing or collapsing and therefore its maximum size was likely to be greater.

Interestingly R E Apfel [5], using simple physical reasoning, described how the pressure intensity of a cavitating bubble at collapse depends on the sudden release of the potential energy stored in the liquid during the growth stage, being relatively larger for big bubbles than small ones.

Due to a delay in receiving the image in Fig. 1 and because the experimental programme had progressed the opportunity to investigate it in more detail did not arise.

Reference [6] contains some interesting pictures of cavitating ships' propellers in different modes of operation, including one showing a cavitating propeller tip vortex breakdown emanating from a sheet or clump of cloud cavitation on the back of a blade near the tip. A common feature in these pictures and others of full scale merchant ship propellers is that invariably the cavitating tip vortices in the propeller slipstream have a cloudy whitish appearance, in common with the full scale pictures in [7] and those at model scale in [8] and Fig 1 of this paper. From a modelling viewpoint cloud cavitation should be present in the trailing tip vortices, as distinct from cavitation with a translucent appearance, because collapsing cloud cavitation produces strong impulsive pressures and noise [1].

## 7. PROBABLE CAUSE OF THE SHIP VIBRATION

The deductions drawn from the model experiments, including the image of the large model cavity and the hull surface harmonic pressures, together with the vibration measurements on the ship suggest that transient high impulsive pressures were created in the water from each propeller at random, relatively infrequent time intervals compared with blade passage times. Each shock pressure pulse can then be approximated by a solitary step pulse of unknown but high amplitude and short duration in a time domain of infinite extent. The actual shape of these pulses is not critical [9], and can be represented by rectangular ones enabling the Fourier pressure spectrum to be drawn. This is seen to be almost flat over a frequency range including several harmonics of bpf. The Fourier frequency spectrum for such a pressure pulse is well known and has the form $\sin x/x$, where $x = \omega\delta\tau$, For the limiting case when $\delta\tau \rightarrow 0$ this function, known as the Dirac or delta function, takes the value of 1, or, in other words, the frequency spectrum is flat for all $\omega$. For small finite pulse-time increments of $\delta\tau$ representative of blade passage times the Fourier frequency spectrum plotted against frequency has a very slowly drooping characteristic and vibration is just as likely to occur at all frequencies. In practice, however, vibration can be expected to occur when local resonances in the plating and inboard structure are excited.

For a solitary pressure pulse of 100μs duration, i.e. midway between the values mentioned previously for the oscillating hydrofoil and the CVG experiments, the frequency spectrum remains effectively flat up to the 5th harmonic of blade rate and beyond.

Hull pressure pulses for the cavitating pictures in [6] are not provided, but the author gives a short dissertation on the subject concluding that to gain an understanding of cavitation rather more than a Fourier-based curve fitting algorithm is necessary. This view is contrary to that given in [9], for example, for simple mechanical shocks to which collapsing cloud cavities can be likened when the period of the pressure pulse, in the lower tens of microseconds, is small compared with the natural period of the ship's stern structure of the order of $10^6$ times this.

## 8. HIGHER HARMONIC PRESSURE LEVELS

In the search of further evidence in support of the conclusion that it was the collapse of the propeller cavitating tip vortices that caused the broadband vibration on the ship, it is informative to review the distribution of the higher harmonic pressure levels measured on the model compared with their corresponding bpf levels. An inspection of these rms pressures obtained for the two contending model propeller designs at the ship's main operating conditions, of which there were three, led to the following observations.

In nearly a quarter of the results the 2nd harmonic rms pressure levels were greater than the corresponding bpf levels, whilst in nearly a third of the results the 3rd harmonic pressure levels were greater than the 2nd but not necessarily greater than the corresponding bpf levels. Fig. 2 shows two fairly extreme examples of these results in which both 2nd and 3rd rms harmonic pressure levels were greater than the bpf levels. These harmonic pressure distributions are unusual and resulted presumably from the shock pressures created by the collapsing cavitating vortices.

After the publication of [8] some scepticism may have existed concerning the experimental finding that higher harmonic pressure levels could exceed the blade rate values, but this was dispelled by the publication of [10], in which the author's showed theoretically it was possible.

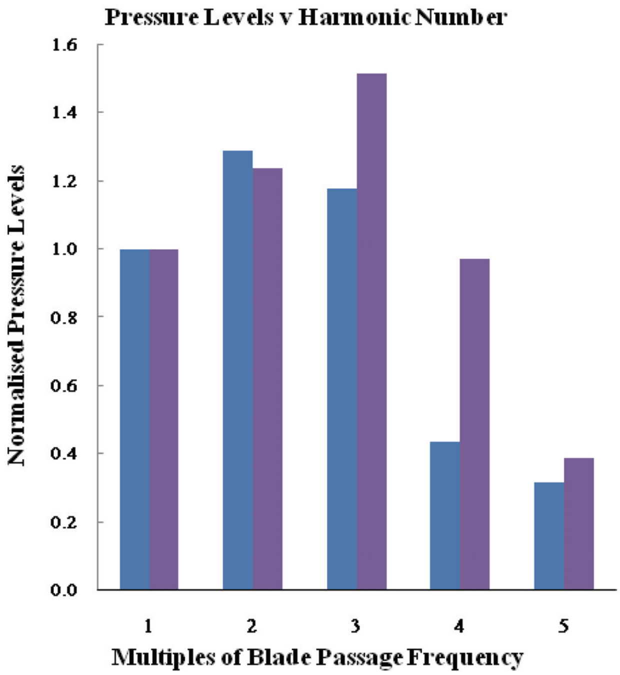


Figure. 2. Normalised Harmonic Pressures

An engineering means of gauging the activity of the higher harmonic pressures is to calculate the quadrature sums of the harmonic pressures for each transducer and compare these values with those obtained from tests on a similar ship model that did not suffer a significant propeller/cavitation induced vibration problem. This has been done using the following expression. With n = 5 this led to maximum values close to 2 for many transducers positions on the model of the as-built ship compared with a similar figure of 1 for the acceptable vessel.

$$\frac{1}{p_1}\left[\sum_{2\rightarrow n} p_n^2\right]^{1/2}$$

## 9. CONCLUSIONS

- Experiments on the underwater form of a model high-speed twin screw displacement ship in a large cavitation tunnel produced evidence, both visual and measured, that led to a plausible explanation for the source of the broadband vibration on the ship.

 

- Part of the visual evidence took the form of sightings by eye, under stroboscopic lighting, of the cavitation on and near the propellers and far downstream in their slipstreams. The propeller blade cavitation was extensive but not unusual whilst the cavitation in the slipstreams, both near and far downstream, was quite unusual. This was because cavitating tip vortices were present in the helical arcs on the outboard sides of imaginary vertical planes passing close to the centre-lines of the propeller shafts, whilst it was absent in the arcs on the inboard side of these planes.
- It seems that the circulation of the helical tip vortices suffered discontinuities in strength occurring at the top and bottom of the imaginary vertical planes near the shaft axes.
- A single frame from a video recording showed an instant in the life of a large cavitation disturbance near a rudder's leading edge. The cavitation emanated from a cavitating propeller tip vortex and probably marked the commencement of the curious vortex behaviour observed in the slipstreams, referred to above. The term *'cavitating vortex collapse'* seems more appropriate for this behaviour than 'cavitating vortex breakdown', where the cavitating tip vortex is present after the singularity.
- The absence of exceptionally high rms pressure levels at bpf implies that similar large cavitation disturbances did not occur regularly at each blade passage. An inspection of the video recording, covering many model propeller revolutions supports this view. Indeed, the capture of this image was fortuitous and lent weight to the belief that this phenomenon occurred relatively infrequently and randomly on the ship and model. This suggested that the large transient impulsive pressures caused by the formation and collapse of cavitation disturbances, similar to that captured in the video recording, could be approximated by solitary pressure pulses of very short duration in time frames of infinite extent. It is this understanding that points to the source of the broadband vibration experienced by the ship.
- It is known that when propeller cavitating tip vortex breakdown or collapse occurs, the pressure levels at higher harmonic frequencies of blade rate can exceed the bpf pressures. These experiments also showed that rms pressure levels at three times bpf can exceed the pressures at twice bpf and bpf.
- The model experiments showed that the quadrature sums of the rms higher harmonic pressures, normalised by their bpf pressures, were about twice as high when cavitating vortex collapse was present compared with when it was not.
- The instrumentation commonly used for recording and analysing the pressure signals in model propeller/hull cavitation tests is suitable when the signals are of the continuously varying periodic type. However, when shock occurrences take place these are unrecognised. In order to detect the presence of transient impulsive pressures real-time signal recorders and analysers should also be installed.

## 10. ACKNOWLEDGEMENT

The author is grateful and indebted to Christopher E Brennen, recently retired as The Hayman Professor of Mechanical Engineering at Caltech, for supplying several cavitation references, amongst them [1], [2] and [3]. I suggest anyone with an interest in bubbles, cavitating or otherwise, would enjoy reading his Article, "The Amazing World of Bubbles", Engineering and Science, California Institute of Technology, LXX1, 30-41, available on the Internet.

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**APPENDIX:** Defining RMS

The root mean square, rms, of a continuous pressure versus time waveform having a period T is the square root of the integrated sum of the squares of the ordinates defining the waveform divided by the period T. It is an effective mean value as opposed to a simple mean in which negative contributions to the integral diminish the positive ones, leading to the misleading result of zero for a sinusoidal waveform over a single period T.