Sound signature of propeller tip vortex cavitation

Pennings, PC; Westerweel, J; van Terwisga, TJC

DOI
10.1088/1742-6596/656/1/012186

Publication date
2015

Document Version
Final published version

Published in
Journal of Physics: Conference Series

Citation (APA)
Pennings, PC., Westerweel, J., & van Terwisga, TJC. (2015). Sound signature of propeller tip vortex cavitation. *Journal of Physics: Conference Series*, *656*. https://doi.org/10.1088/1742-6596/656/1/012186

Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Sound signature of propeller tip vortex cavitation

To cite this article: Pepijn Pennings *et al* 2015 *J. Phys.: Conf. Ser.* **656** 012186

Sound signature of propeller tip vortex cavitation

Pepijn Pennings[1,2], **Jerry Westerweel**[2] **and Tom van Terwisga**[1,3]
1 Laboratory for Ship Hydrodynamics, Delft University of Technology, Mekelweg 2, 2628 CD, Delft, The Netherlands
2 Laboratory for Aero & Hydrodynamics, Delft University of Technology, Mekelweg 2, 2628 CD, Delft, The Netherlands
3 Maritime Research Institute The Netherlands, Haagsteeg 2, 6708 PM, Wageningen

E-mail: `p.c.pennings@tudelft.nl`

Abstract.
The design of an efficient propeller is limited by the harmful effects of cavitation. The insufficient understanding of the role of vortex cavitation in noise and vibration reduces the maximum efficiency by a necessary safety margin. The aim in the present study is to directly relate propeller cavitation sound to tip vortex cavity dynamics. This is achieved by a dedicated experiment in a cavitation tunnel on a specially designed two-bladed propeller using a high-speed video camera and a hydrophone. The sound signature of a tip vortex cavity is not evidently present in the sound spectrum above the tunnel background. The addition of a simulated wake inflow results in a high amplitude broadband sound. With a decrease in the free-stream pressure the centre frequency of this sound decreases as a result of a larger vortex cavity diameter. In the near future each blade passage in the high-speed video will be analyzed in detail. The frequency content of the cavity dynamics can then be directly related to the measured sound. An analytic model for vortex cavity dynamics resulting in a cavity eigenfrequency using a vortex velocity model can finally be evaluated as a design instrument for estimation of broadband sound from propeller cavitation.

1. Introduction and experimental setup

The design of an efficient propeller is often limited by various forms of cavitation. Of these forms sheet and cloud cavitation are closely related to the blade passage frequency and are relative well understood. The measures taken to prevent this type of cavitation nuisance however, appear to stimulate the occurrence of vortex cavitation. Vortex cavitation is expected to be responsible for a broadband contribution to the pressure fluctuation spectrum, typically between 40 to 70 Hz for a full-scale propeller [1].

A previous study on the dynamics of steady tip vortex cavitation trailing a stationary lifting surface shows that a vortex cavity has a distinct eigenfrequency [2]. When excited by a matching frequency this has the potential to generate high amplitude sound [3]. This principally tonal component is expected to be spread over a range of frequencies mostly by signal variability between blade passages [4] and changes in vortex cavity properties.

The main aim of the experiment under consideration is to show that understanding of vortex cavity dynamics can be applied to estimate the sound production of propeller tip vortex cavitation using a few basic properties such as cavity size and vortex strength. A simultaneous registration of high speed video and hydrophone measurements is used to obtain the properties of the dynamics of the tip vortex cavity and the resulting sound. As the detailed analysis of

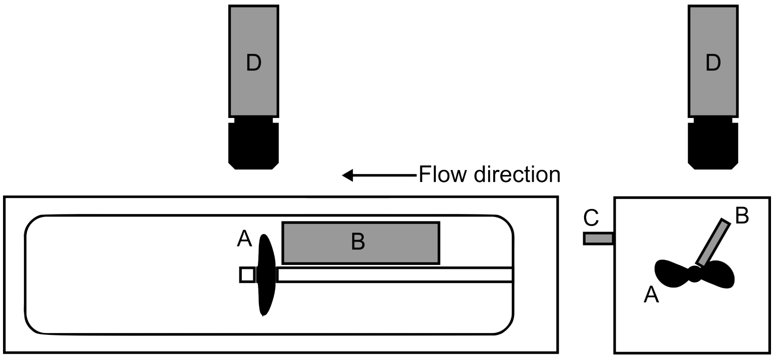

Figure 1. Sketch of the experimental setup with; A the propeller, B the wake generator, C the hydrophone and D the high speed camera. Left is a side view of the test section with on the right a cross section looking from upstream on the suction side of the propeller.

the high-speed video is not yet completed at present, some general trends based on the cavity images and sound spectrum are presented.

A steady tip vortex cavity trailing a propeller without excitation is not expected to produce sound with significant amplitude above the tunnel background. Therefore a simulated wake field with a sharp dip in the axial velocity component is generated upstream using a series of plates with narrow spacing. The flow aligned plates retard the flow locally resulting in a local higher loading of the propeller blade passing its wake. The consequence is a locally stronger tip vortex with a larger cavity diameter potentially followed by collapse and rebound after the blade passage. This excitation of the vortex cavity is expected to be sufficiently strong to result in audible pressure fluctuations. As the required excitation frequency is unknown the narrow wake is chosen such that it contains a broad range of frequencies. The experimental results in this study show the effect of a varying cavity size on the resulting sound by looking at the difference in sound power density spectrum between a uniform inflow and simulated wake field.

The experiments are performed in the cavitation tunnel at Delft University of Technology. The details of the tunnel can be found in the thesis by Foeth [5] while the recent modifications are described in the thesis by Zverkhovskyi [6]. The tip vortex cavity is generated by a specially designed right handed two-bladed skewed propeller with reference number 7359. The diameter is 0.15 m with a constant pitch-to-diameter ratio of $P/D = 1.0$ over the span with the detailed geometry freely available upon request. The projections of the propeller geometry can be seen in the sketch of the experimental setup in figure 1.

The wake field is generated by 5 plates 2 mm thick, 100 mm high and 300 mm long with 3 mm spacing, that is mounted at 30 degrees from vertical and 10 mm upstream of the propeller hub. The field of view of the high-speed video camera is chosen to include the propeller shaft and tip. The hydrophone is mounted in a water filled cup to the side window of the test section at 50 mm upward from the shaft axis at the stream-wise location of the propeller tip.

2. Results

Figure 2 shows three experimental conditions for varying the free-stream pressure while keeping other parameters constant. At a constant blade angle the images on the left are for a uniform inflow and on the right for the simulated wake inflow. The power density spectrum of the sound is shown below the cavity images.

From the sound spectrum it is clear that a steady tip vortex cavity in uniform inflow does not contribute significantly to the sound above the level of the background noise of the cavitation tunnel. This is evident in the equal power density in the first blade passage frequency at 76 Hz

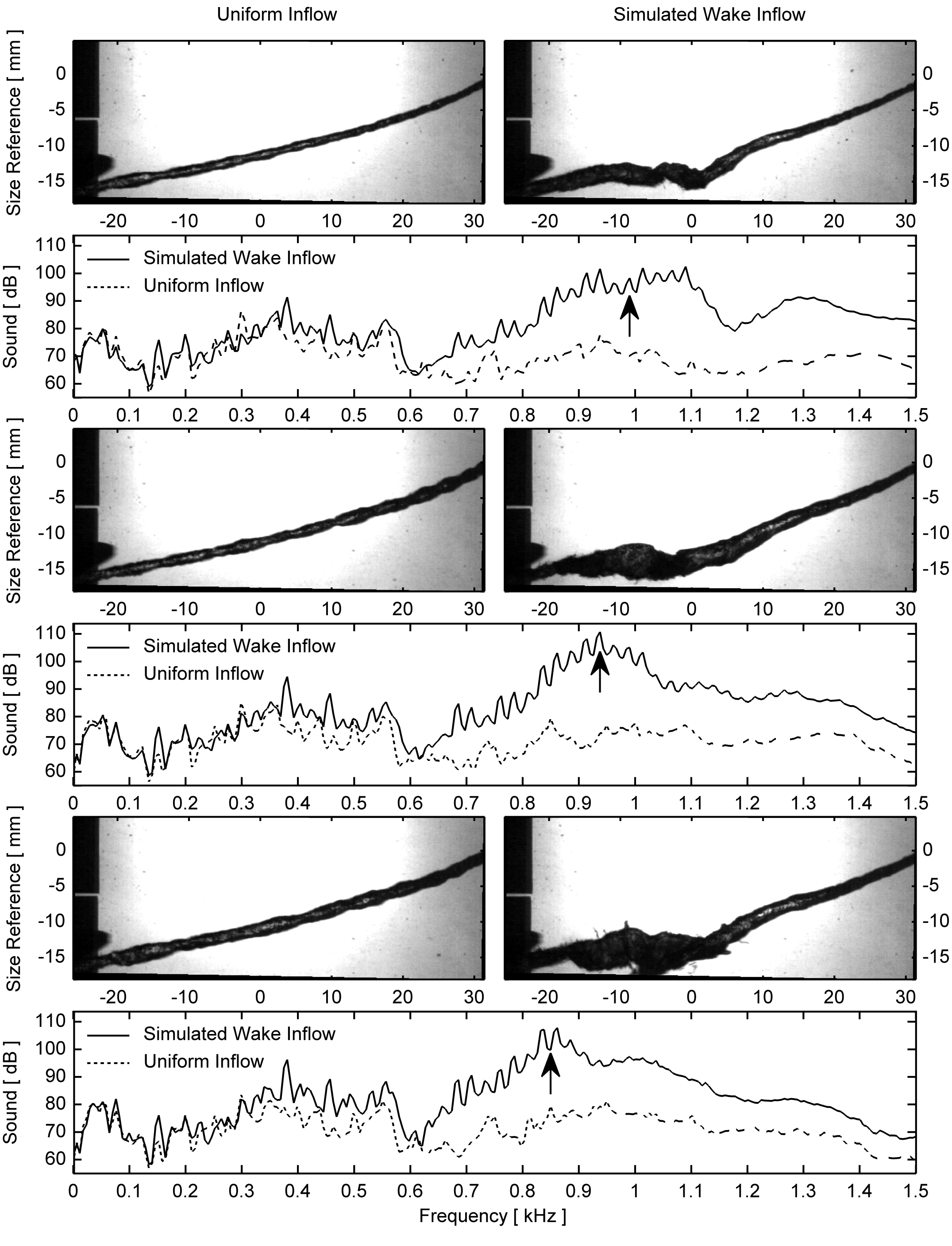

Figure 2. Tip vortex cavity images of uniform inflow (left) and behind a simulated wake (right), that are accompanied by a power density spectrum with reference value 10^{-12} Pa^2/Hz. Flow from bottom to top. Left in image; hubcap, propeller hub and a small portion of the propeller tip trailing edge. The gap in the shaft is 42 mm downstream of the wake. Common conditions; free-stream velocity 3.2 m/s, rotation rate 38 Hz, advance ratio $J = 0.56$, thrust coefficient $K_T = 0.18$, torque coefficient $10K_Q = 0.27$, Reynolds number at 70% radius 6.5 $\times 10^5$. Cavitation number at 70% radius varied from top to bottom to 1.16, 1.07 and 0.98. Arrows indicate high amplitude contributions that decrease in frequency consequently.

and the range between 0.6 and 1.5 kHz. The cavitation tunnel conditions do not allow a reference measurement without cavitation on the propeller. When the sound spectrum of the tip vortex behind the plates is considered it is observed that the cavity grows and apparently excited the rest of the tip vortex cavity. The reduced axial flow also alters the path of the vortex cavity centreline. The result in sound is a high amplitude broadband contribution as much as 30 dB in power density above the uniform inflow signal. The centre frequency of this feature is related to the cavity diameter. For lower pressures thus larger cavities, a lower frequency is found. Only the 5th and 6th blade passage frequencies increase in amplitude in the presence of the wake but significantly less than the broadband part.

The broadband character of the high amplitude contribution varies with decreasing pressure. The middle case shows highest amplitude and is thus expected to contribute to the sound over a larger portion of the blade rotation resulting in a more narrow-band signature.

The simultaneous registration of the high-speed video images recorded with a frame rate slightly above one data point per degree of rotation enables a more detailed time-frequency analysis. This can be used to directly link the dynamics of the vortex cavity to sound emission.

3. Conclusions and future work

A tip vortex cavity in the wake of a propeller in a uniform inflow does not produce sound with significant amplitude to be detectable above the tunnel background. The addition of an obstruction in the inflow of the propeller results in a significant broadband contribution to the measured sound. The range of this frequency band strongly correlates with the size of the tip vortex cavity; for larger cavities the range shifts to lower frequencies. Finally the high-speed video is of sufficient resolution in time and space to study in detail the cavity growth, collapse and rebound of the vortex cavity behind and besides the wake plates.

The analysis described here is only a preliminary first step preceding a detailed analysis of the high speed video of the individual blade passages and the corresponding contribution to the sound by the tip vortex cavity. The main goal is to find tip vortex cavity properties which correspond to the broadband sound centre frequency. Potential candidates are the mean cavity size in the undisturbed section of the flow and the cavity size downstream of the wake plates. The frequency content of the cavity will then be compared to the time-frequency sound signal to break down the broadband sound in individual elements at several blade angle ranges. Finally the sound generating condition of an analytic cavity wave dynamics model [2] combined with a viscous vortex flow field will be used to form an engineering method for estimation of the broadband sound from tip vortex cavitation.

Acknowledgments

This work is funded by the Lloyd's Register Foundation as part of a cooperation in the International Institute for Cavitation Research

References

[1] Wijngaarden E, Bosschers J and Kuiper G 2005 *Proceedings of the ASME Fluids Engineering Division Summer Meeting and Exhibition* (Houston, Texas, USA)
[2] Pennings P, Bosschers J, Westerweel J and Van Terwisga T 2015 *Journal of Fluid Mechanics* DOI: 10.1017/jfm.2015.379
[3] Maines B and Arndt R 1997 *Journal of Fluids Engineering* **119** 271–276
[4] Bosschers J 2009 *Proceedings of the First Symposium on Marine Propulsors* (Trondheim, Norway)
[5] Foeth E 2008 *The Structure of Three-Dimensional Sheet Cavitation* Ph.D. thesis Delft University of Technology Delft, The Netherlands
[6] Zverkhovskyi O 2014 *Ship Drag Reduction by Air Cavities* Ph.D. thesis Delft University of Technology Delft, The Netherlands