Vortex singing in tip vortex cavitation under the effect of water quality

Xiaoxing Peng, Lianghao Xu, Mingtai Song, Yantao Cao
National Key Laboratory on Ship Vibration & Noise, China Ship Scientific Research Center, Wuxi, 214082, China
E-mail: henrypxx@163.com

Abstract. The phenomenon of vortex singing in tip vortex cavitation is studied experimentally in this paper. It is revealed that the vortex singing can be observed during the vortex cavity transfer from one phase to another in the same incoming flow condition. The state of vortex singing can only exist in a short duration from several seconds to several minutes. The sound of the vortex singing for different water qualities, including air content and nuclei populations of water are measured by a hydrophone. It is found that the tones of vortex singings are very different under different flow conditions and water qualities.

1. Introduction
The tip vortex cavitation is often found in marine propellers and draws consistent attention in ship design because of its potential to produce erosion and emit noise. This topic has been studied extensively by many researchers both in model scale experiments and full scale trials. Most of the existing works were focused on the formation of tip vortex cavitation and the scale effect of tip vortex cavitation inception, aiming to predict and suppress tip vortex cavitation. However, some works were made on developing vortex cavitation to explore the dynamics of tip vortex cavitation and its instability. Among these, the vortex singing in vortex cavitation is a very special phenomenon, which was first found in the 1990’s.

The noise emitted by blade tip vortex cavitation was investigated on model scale by Maines and Arndt. They observed the tone sound with special frequency, namely, “vortex singing”. In their description, the vortex singing can occur when the vortex was attached to the blade tip and only at a small range of cavitation numbers. In their experiments, the vortex singing seems related with a special flow pattern where a part of the boundary layer can still be laminar. But the physical mechanism of this phenomenon is still not clear. The recent attempt to analyze the problem was done by Bosshers, who derived a theoretical formulation to predict the occurrence of the vortex singing. However, the problem is that there are few laboratories which can repeat the special phenomena up until now.

In our paper, some recent experiments for the vortex singing are reported. The occurrence process of the vortex singing and the effects of water qualities, including air content in water and nuclei populations are emphasized in the study.

Correspondence author: Dr. Xiaoxing Peng, henrypxx@163.com
2. Experimental Setup
Experiments were conducted in the cavitation mechanism tunnel of China Ship Scientific Research Center (CSSRC). The tunnel has two exchanged test sections of circular and square shapes respectively as shown in Fig. 1. There is a large degassing tank installed in the downstream of the test section to control the air content of water. The tunnel is also equipped with a nuclei seeding system. In this study, the test section with a square cross section of $225 \times 225$ mm is used, and the maximum incoming velocity of this section can be up to 25m/s.

![Figure 1. Schematic diagram of cavitation tunnel.](image1)

The elliptic hydrofoil with section NACA 662415 was chosen as the test model. The model is 94.2mm and 112.5mm in maximum chord and half span respectively. The model was installed in the horizontal center of the test section with the tip in the centreline of the test section and the attack angle is $7^\circ$. A high-speed video camera with type of Photron APX was used to visualize the development of the tip vortex cavitation and a LED lamp was used as the light source. Both devices were set in the bottom of the test section. A hydrophone of B&K 8103 was installed in the side window with a cup filled with water. The arrangement of the experiment was shown in Fig. 2.

![Figure 2. Set-up of the experiments.](image2)

3. Vortex Singing Observations
During the experiments, strong tip vortex cavitations were set first with given incoming flows, and then the pressures were decreased until the vortex singing occurred. The vortex singing happens at a specific cavitation number range, which is narrow. On the one hand, in cases when cavitation numbers are lower than that range, the vortex cavitation is quite thick, with rotation stationary and stable even in the scenario which affected by the shedding of attached cavitation in the upstream. On the other hand, in situations where cavitation numbers are higher than the vortex singing range, the vortex cavitation is quite thin and departs from the tip.

We can observe the vortex singing when we hit a specific narrow cavitation number range. During the vortex singing, we keep the cavitation number unchanged while we observe three different cavity phases as shown in Fig. 3. The form of the vortex cavitation is unstable and keeps changing. In the beginning, the vortex cavitation is very similar to the pattern which usually happens at low cavitation numbers and the attached cavity around the tip is stable. In the second phase, the vortex cavitation starts to oscillate with synchronization of attached cavity and the distinct tone can be heard. This process can continue for the duration from several seconds to a few minutes with different test cases. When the vortex singing disappears, the vortex cavitation becomes very thin, which is similar to the cases which often happen at high cavitation numbers.
Noise measurements results are shown in Fig.4, where the noise spectra clearly show the characteristics of vortex singing. When vortex singing happens, resonance frequency and its second mode can be seen with very strong sound amplitude, which is over 30dB higher than non vortex singing. The interesting thing is that the two noise spectra of non vortex singing situations are almost the same while they are also consistent with the noise spectra of the vortex singing except for the resonance frequency and its second mode.

![Before singing](image1)
![In singing](image2)
![After singing](image3)

**Figure 3.** Form of tip vortex cavitation before, in and after vortex singing.

\((v=12.8\text{m/s}, \sigma =1.40, \frac{\alpha}{\alpha_s}=0.77, \text{no nuclei seeding})\)

**Figure 4.** Noise spectra of vortex cavitation before, in and after vortex singing.

\((v=12.8\text{m/s}, \sigma =1.40, \frac{\alpha}{\alpha_s}=0.77, \text{no nuclei seeding})\)

### 4. Effects of Water Quality on Vortex Singing

#### 4.1. Effects of air content

Three air content of water, 50%, 63% and 77% with different incoming velocity were tested to study the effect of air content on vortex singing. Fig.5 shows the results for the three different air content with the same incoming velocity of 12.8m/s. The cavitation numbers in the vortex singing change with different air content. With the increase of air content from 50%, 63% to 77%, the cavitation number of the vortex singing increases from 1.2, 1.33 to 1.4, while the resonance frequencies decrease from 525.3, 509.5 to 488.3Hz.

#### 4.2. Effects of gas nuclei population

Non nuclei seeding and three nuclei seeding conditions, namely “few”, “medium” and “rich” were tested to study the effects of nuclei on vortex singing. Fig.6 shows the results for different nuclei populations with the same incoming velocity of 9m/s. The cavitation numbers in the vortex singing change remarkably with different nuclei populations. With the increase of nuclei populations, the cavitation number of vortex singing increase from 1.35, 1.4, 1.8 to 1.85, while the resonance frequencies do not change much.
5. Conclusions
Extensive experimental research of vortex singing in tip vortex cavitation for the elliptic hydrofoil with section NACA 662-415 were carried out in this paper. Emphasis is made in the effects of air content and nuclei populations in water. Some conclusions can be drawn from the study.
1) The vortex singing can only exist in the transferring process between strong tip vortex cavitation and weak tip vortex cavitation.
2) With the increase of air content, the cavitation number of the vortex singing increases while the resonance frequency decreases.
3) With the increase of nuclei populations, the cavitation number of vortex singing increases while the resonance frequencies do not change much.

Acknowledgments
Authors wish to acknowledge the support from the State Key Program of National Natural Science Foundation of China (Project No. 11332009). Authors would also like to thank the anonymous reviewers for their helpful reviews and Mr. Haoruo Peng for the improvement of the writing.

References
[1] Maines B and Arndt R E A 1997 *ASME J. Fluids. Eng.* **119** 271
[2] Arndt R E A 2001 *Ann Rev. Fluid Mech.* **87** 965
[3] Bosschers B 2009 *Proc. NAG/DAGA Int. Conf. on Acoustics (Rotterdam)* 298