Bubble-induced sheet cavitation inception on an isolated roughness element

Martijn van Rijsbergen and Jesse Slot
Maritime Research Institute Netherlands (MARIN), P O Box 28, 6700 AA Wageningen, The Netherlands
E-mail: m.v.rijsbergen@marin.nl

Abstract. The nucleation process on an isolated roughness element, located at the point of minimum pressure of a NACA 0015 hydrofoil was studied experimentally and computationally. The objective of this study was to investigate the working mechanism of bubble-induced sheet cavitation inception. High-speed micro-scale observations show the generation of a streak of cavitation—attached to the roughness element—in the wake of the bubble. Below its critical diameter, the bubble can detach from the streak cavity and travel on while the streak cavity remains. The solutions of a Rayleigh-Plesset equation along a streamline extracted from a RANS calculation show strong similarities with the experimental observations, but a factor 5 to 10 higher frame rate is needed to validate the calculations.

1. Introduction
Sheet cavitation inception does not necessarily occur on foils and propellers when the local pressure decreases below the vapour pressure. The condition of inception is also dependent on the characteristics of the fluid, the solid surface and the local flow. Although seeding the flow with micro bubbles and applying leading edge roughness with a Reynolds-dependent grain size is adequate in most cases [1], the detailed working mechanism of the sheet cavitation inception process is not fully understood. A hypothesis formulated in [2] states that a roughness element causes a very local but significant additional pressure decrease in which a micro bubble can expand and induce a streak of cavitation. This local pressure decrease is dependent on the thickness of the boundary layer compared to the height of the roughness element and therefore also dependent on the Reynolds number [2].

High-speed micro-scale observations were made on a hydrofoil to investigate the nuclei-induced sheet cavitation inception process in more detail. The first analysis was focussed on the diameter, form and trajectories of the nuclei [3]. In the present study, a further analysis is made of the nucleation process on an isolated roughness element caused by free stream bubbles. To obtain the pressure and velocity distribution around the roughness element, the foil with the roughness element were numerically modelled and the steady wetted flow was solved using a RANS code. To study the bubble dynamics, a variant of the Rayleigh-Plesset equation has been solved along calculated streamlines passing close to the roughness element.

2. Experiments
The experiments were carried out in MARIN’s high speed cavitation tunnel with a rectangular test section of 80 mm height and 40 mm width. A 2D NACA 0015 section with a chord length of 60 mm was placed in the test section at an angle of attack of 6.0 degrees. High-speed cameras were used to
observe the leading edge of the foil from the side and the top at a frame rate of 15 kHz. The shutter times of the top and side cameras were respectively 9 and 1 µs. Further details on the test set-up can be found in [3] (corrigendum: the height of the roughness element is 60 µm).

Figures 1 and 2 show a series of combined “photo finish” images of the nucleus from the top (left) and side (right). The numbers indicate the corresponding instances of the side and top camera images. The contour of the roughness element is highlighted with a white line (right). The initial bubble diameter \(D_0\), indicated by number 1, is determined from the side camera image with an estimated uncertainty of 5 µm. The estimated uncertainty in the diameters determined from the top camera images is 60 µm. The cavitation number \(\sigma\) and Reynolds number \(Re\) of the two cases can considered to be equal within the estimated experimental uncertainty of 5%, only \(D_0\) is different with more than a factor 2. In both cases, the bubble expands and deforms when approaching the roughness element, generates a streak of cavitation on the roughness element, expands further and passes on. In case 1, the bubble passes on the side of the roughness and generates a longer streak than in the bubble in case 2. It also stays attached to the streak for a longer time than the bubble in case 2. The measured diameters are shown in Figures 6 and 7.

![Figure 1](image1.png)

**Figure 1.** Case 1, \(D_0 = 86 \mu m, \sigma = 2.15, Re = 5.0 \times 10^5, V = 7.9 m/s\)

![Figure 2](image2.png)

**Figure 2.** Case 2, \(D_0 = 37 \mu m, \sigma = 2.15, Re = 5.3 \times 10^5, V = 8.2 m/s\)

3. Calculations

A CAD model has been made of the test section with the hydrofoil and the roughness element as described in section 2. The 3D geometry of the roughness element was modelled as closely as possible using the available images. On the hydrofoil, as well as on the upper and lower walls of the tunnel, a no-slip condition is applied. A symmetry condition is imposed on the side walls of the tunnel as well as on the symmetry plane intersecting the roughness element. At the inlet the velocity is set. On the outflow plane a constant pressure is imposed. Figure 3 shows the grid topology around the roughness
element on a very coarse grid, used only for visualization. The viscous-flow CFD code ReFRESCO has been used to solve the incompressible flow using steady RANS equations, complemented by the k-ω SST 2003 turbulence model [4]. No wall functions were used.

The numerical uncertainty of the solution for Re = 3.6x10^5 is determined using the procedure by Eça et al. [5] using 7 grids ranging in size from 6.9M to 37.2M cells. For the third finest grid with 23.4M cells, the numerical uncertainty of $C_{P\text{min}}$ was 0.3%. Since this is sufficiently small, this grid was chosen for the Reynolds study. Next to the numerical uncertainty there is a modelling error which might be significant on the leeward side of the roughness element. Studies on the flow around 3D hills have shown that RANS is capable of prediction the location and the magnitude of $C_{P\text{min}}$. But a little further downstream the RANS solution—in terms of the starting point of the flow separation, the size of the separation zone and downstream pressure recovery—deviates considerably from measurements [6], [7], [8].

Figure 3. Grid distribution on hydrofoil and symmetry plane. Inset shows close-up of grid on roughness element. For illustration purposes a very coarse is shown.

Figure 4. Minimum $C_p$ as function of Reynolds number for a NACA 0015 foil in a cavitation tunnel without (dots) and with (x) roughness element.

Figure 4 shows that a roughness element can decrease $C_{P\text{min}}$ up to 60% at Re = 1.0x10^6. The effect reduces strongly at lower Reynolds numbers.

To analyse the behaviour of the bubbles described in section 2, the local pressure along a streamline passing at a distance of 30 µm above the roughness element has been extracted from the solution for Re = 3.6x10^5, see Figure 5. The value of 30 µm has been estimated on the basis of the side view images. The ambient pressure has been scaled to fit the experimental conditions.

Figure 5. Local pressure coefficient along streamline passing 30 µm above roughness element. $t = 0$ corresponds with the moment when the bubble is at location 1 (see right hand sides of Figures 1 and 2). The tracer path passes over the roughness element at $t = 0.47$ ms.
A variant of the Rayleigh-Plesset equation—described in [9]—has been used to calculate the response of the bubble radius to the pressure history in time. The results are shown in Figure 6 and 7.

Although the local pressure is far below the critical pressures of the bubbles, they do not reach their critical diameters (respectively 835 and 250 μm for the 86 and 37 μm bubble) due to the fast pressure decrease and recovery around the roughness element. The agreement between the calculations and experiments is acceptable. The bubble resonance can clearly be seen in the calculations, but the experimental data lacks temporal resolution to resolve this phenomenon. A factor 5 to 10 higher frame rate would solve this.

4. Concluding remarks

- The experiments show that an attached streak cavity can be formed on an isolated roughness in the wake of a free-stream bubble which travels on after the moment of inception. The largest bubble generates the largest streak.
- The calculations show that the bubble starts to resonate but does not reach its critical diameter.
- The numerical modelling can be improved by imposing a no-slip condition on the side tunnel walls and solving an equation of motion to determine the path of the bubble in the viscous flow more accurately.
- Future experiments with frame rates of 100 to 150 kHz and a factor two higher spatial resolution are expected to reveal more details on the generation of an attached streak of cavitation by a free-stream bubble and the dynamic behaviour of the bubble.

References

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