Observations of cloud cavitation on a stationary 2D profile

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Abstract. The generation of noise by a cavitating ship propeller is strongly determined by the collapse of cavity clusters. In this study, the formation of these bubble clusters is studied by observing a cavitating 2 dimensional hydrofoil under steady inflow conditions. It is found that a re-entrant jet develops. In certain conditions, this can cause a regular shedding of large bubble clouds. In other cases a more irregular pattern of cavity structures is shed, still basically caused by the presence of a re-entrant jet.

1 Introduction

Cavitation is important in the design of ship propellers, regarding the production of noise and erosion of the propeller blade surfaces. Both effects are caused by the same process; the implosion of cavities, which goes with a very high peak pressure in the final stage. In this study we are mainly interested in the aspect of noise radiation by cavitating ship propellers. The noise radiated by a ship propeller has a frequency spectrum roughly like in figure 1.

Although the collapse of single cavity bubbles explains the generation of high frequency noise, it is not adequate to explain the high sound level at frequencies around 1 kHz. It is shown in previous research, that this part of the spectrum can be explained by the collective collapse of a cluster of bubbles: a bubble cloud. A review on this is given by Van Wijngaarden (1993) in these proceedings.

Cavitation on a propeller or a hydrofoil can roughly be divided into three types: bubble cavitation, sheet cavitation and vortex cavitation. We direct our attention to sheet cavitation. When the pressure along a blade sharply decreases below vapour pressure (e.g. at the leading edge of a propeller blade), the flow can detach at a fixed position and reattach at a downstream position, thus forming a rather flat sheet cavity, which remains attached to the blade. In view of the sound production, we are in particular interested in cloud cavitation, which is a special sub-type of sheet cavitation.

In steady flow conditions a sheet cavity is often considered to be steady. However, in reality, it rarely is. The interface is most times not smooth, and there is entrainment of cavities into the main flow. These cavities implode at the rear part of the blade. When observing sheet cavitation experimentally, several researchers found that under certain conditions large bubble clouds break off regularly. These break-offs occur even at steady uniform inflow conditions. One of the first describing the break-off process was Knapp (1955). He described the break-off to be caused by a filling of the cavity volume by a re-entrant jet. After him several others have also described the break-off process, some confirming the existence and

Fig. 1. Schematic noise spectrum of a ship propeller

importance of a re-entrant jet Lush *et al.* (1986), and more recent Le *et al.* (1993). Avellan *et al.* (1988), however, claim that growth of instabilities on the cavity interface and transition to turbulence is the major cause of break-off. Also Kubota *et al.* (1989) state that the re-entrant jet is not of major importance, though their measurements can also be used to confirm the existence of a re-entrant jet.

As the collapse of these clouds is important for the noise generation, it is necessary to study the mechanism of cloud cavitation. Therefore, in our study, we simplify the situation to a cavitating 2D profile in a steady uniform flow. For the time being, we have mainly concentrated on observing and analysing the flow qualitatively, as we are not fully equipped to obtain reliable quantitative data.

2 Experiments

When performing cavitation experiments it is important to have a flow similarity. Especially the cavitation number σ must be kept equal to the full scale value, with σ defined as: $\sigma = (p_\infty - p_v) / \frac{1}{2} \rho U^2$.

In general design practice, model propellers are tested and their noise spectrum is measured. However, it appears to be very difficult to predict the spectrum and noise levels on the full scale version accurately. For this prediction, good scaling rules are needed. One of the reasons that scaling of the spectrum is difficult, is that the other dimensionless numbers (e.g. Reynolds number, Froude number, Weber number) as well as parameters like nuclei number and size distribution, are generally not kept similar to full scale situation. Especially the Reynolds number seems to be important in our case, since a change of this number can alter the type and structure of cavitation that is found on the blades.

As velocities tend to be lower in experiments, we need to lower the pressure. Therefore our observation experiments have been done in a cavitation tunnel in which the static pressure can be reduced down to 0.2 atm . The observation section measures 30 cm square and 50 cm in length. Experiments are performed with a Naca 16009 profile, chord 20 cm . The profile is made of plexiglass, in order to be able to observe the flow inside the cavity. Velocities range from 3 to 8 ms^{-1} .

Observations are mainly done by means of a *High Speed Video* (HSV) set, with a frame rate of 500 frames or 1000 half frames per second. For illumination, the set includes two stroboscopic light heads.

3 Observations and Discussion

Analysing the video registrations, we divide the cavity shedding into two types: regular, periodic shedding and irregular shedding. In our observations, we always found some entrainment of cavities into the wake of the sheet cavity. We will first describe the regular, periodic process of break-off of most times large cloud cavities. Next, the irregular shedding will be discussed. It is thought that the process of shedding is caused by the same effects.

3.1 BREAK-OFF CYCLE

When the cavity length is rather large (about 30 to 50% of the chord length), and when the angle of attack is not too small (here 4 to 6 degrees), i.e. when the cavity is not too thin, then a cyclic behaviour is revealed, in which break-off of large cavity structures is seen. From the HSV observations the structure of the cloud cavitation and the break-off mechanism became clear: The cause of the break-off was the formation of a re-entrant jet, and the subsequent collision of the jet with the cavity interface. The break-off cycle is drawn schematically in figure 2. In figure 3 a sequence of HSV frames is shown. In the top right edge of each frame, the time is given in *msec*. The break-off cycle can be described as follows:

1. A sheet cavity, smaller than some equilibrium length, starts to grow.
2. At a certain length the growth will cease, and a re-entrant jet is formed at the closure of the cavity.
3. This jet is directed towards the leading edge of the profile/cavity. The velocity of the (front of the) jet is of the same order of magnitude as the main velocity.
4. The re-entrant jet reaches the cavity near the leading edge and collides with the cavity interface. (See also first photograph in figure 3).
5. The rear part of the cavitation sheet forms a more or less spanwise cylindrical bubble cloud. The cloud contains a large amount of circulation, originating from the momentum of the jet, being opposite to the main flow.

Fig. 2. Schematic cloud break-off cycle

6. The front part of the original cavity is reduced to a tiny sheet cavity, which will again grow and start over the cycle from point 1. The cloud will be transported downstream.

The described, large structure, break-off process occurs quite regular, with a frequency f that gives rise to a constant Strouhal number:

$$Str = \frac{f L_{cav}}{U} \approx 0.3$$

Here, L_{cav} is the maximum cavity length. Although this result is based on limited observations so far, it is in agreement with the results of Le *et al.* (1993). In case of regular periodic cloud shedding, the cloud is shaped like a cylinder, containing a large amount of vorticity. The cavitation is quite violent.

In some cases (especially at lower angle of attack, for this profile 4 degrees) only a part of the span shows series of periodic shedding. Thus the flow is not completely two dimensional, and the cloud is U-shaped, due to its circulation. Also, the re-entrant jet shows spanwise velocity components. However, at the spanwise center of the cloud, the flow is again similar to that described before.

Fig. 3. High speed video observations of the break-off cycle

The three dimensional effects on the re-entrant jet are to be investigated further in next series of experiments.

3.2 IRREGULAR CLOUD SHEDDING

At low angle of attack, or low Reynolds numbers (for this profile below 4 degrees or below 5 ms^{-1}), the re-entrant jet does not have enough momentum to rule out viscosity, so that it can not reach the leading edge of the cavity. In that case there still is a re-entrant jet present, which creates a layer of stagnant liquid on the profile, inside the cavity. This layer is the cause of a more irregular pattern of shedding of small cloud/vortex structures, that again have the U-shape. Here the

shedding is caused by collision of the tops of wave disturbances on the re-entrant jet layer inside the cavity and disturbances on the outer sheet cavity interface. Thus, break-off takes place at an irregular chord position and not at the leading edge of the cavity, like in the case of regular shedding. Also the shedding frequency is less regular. Still, regular sequences can be found locally.

4 Numerical Modelling

The mechanism of cloud formation will be analysed by numerical modelling. For this, the flow is assumed to be a potential flow, and the numerical method is based on the panel method. Several researchers have approached the problem by using a Taylor expansion to transform the boundary conditions from the cavity interface to conditions on the profile surface or its camber line. Though we used this method for the calculation of a steady sheet cavity, we decided to abandon this approach for the calculation of unsteady sheet and cloud cavitation. The major drawback of this method is that the local cavity thickness is a single valued function, which excludes modelling of a re-entrant jet. Therefore, we are presently working on a numerical method in which the boundary conditions are imposed on the moving cavity interface, involving re-paneling of the boundary in each time step.

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