Proceedings of the 8th International Symposium on Cavitation
CAV2012 – Submission No. 148
August 14-16, 2012, Singapore

Hydrodynamic Mechanisms in Cavitation Erosion

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SUMMARY

A refined description of the hydrodynamic mechanisms involved in determining the erosiveness of a collapsing cavity is presented. It highlights the impact of the possible presence of a partially glassy sheet and that collapse symmetry/asymmetry needs to be considered when analyzing the flow. Also, the impact of these processes on experimental or numerical procedures to assess cavitation erosion is discussed.

BACKGROUND

Present development towards higher demands on emission control in shipping increases the demands on efficiency of the propulsion system. This often means that the propeller needs to be designed to run in cavitating conditions and that the risk of cavitation erosion needs to be controlled rather than avoided. However, the mechanisms controlling whether cavitation becomes erosive or not are elusive, and despite many years of research not fully known. Thus, the knowledge and tools to create an erosion free propeller design are inadequate, and a success of a design relies on the experience of the designer. When it comes to assessing the risk of erosion, a paint test in a cavitation tunnel is reasonably accurate to approve a design or not, but does still not give sufficient feedback on how to change a rejected design. With a good understanding of the mechanisms controlling cavitation erosion, the use of high-speed video of the cavitation events in combination with the paint test may greatly improve the situation if the resolution is high enough to correctly trace and interpret the cavitation dynamics. The use of high-end simulation techniques is also becoming a promising alternative. In this paper, we will share our latest insights of some details of these hydrodynamic mechanisms that seem to have a great impact on the erosiveness of cavitation on hydraulic equipment.

The starting point of the discussion is the EroCav handbook of Bark *et al.* [1] which forms a framework for an analysis approach based on the kinematic energy focusing of cavitation, starting with the build up of the potential work of the global cavity, through the focusing mechanisms of, possibly disintegrated, collapsing cavities; by tracing the history of a cavity an improved assessment of its erosiveness can be achieved. This process was primarily described for the analysis of experimental studies, but allowing for application in future advanced numerical approaches. At CAV2009, Bark *et al.* [2] introduced a concept of secondary cavitation, vapour generated in the decomposition process of a focusing cavity, that in itself might contribute significantly to erosion problems. It was thus argued that not only the primary process, as described in the EroCav focusing model, needs to be captured in numerical simulation, or experimental recordings, but also these secondary cavities and consequently the physics that generates them, mainly shear between the external flow and cavity induced flow features. In later work, [3][4], further ideas on mechanisms believed to have a major control on cavitation erosion, was presented, including generation of vortices at the end of an asymmetric collapse of a cavity, the internal flow in a cavity and mechanisms for generation of cloud cavitation.

This paper will further present a refinement and reformulation of the details discussed in [3][4] and we will highlight some phenomena observed in cavitation experiments that are believed to have a large impact on the erosiveness of certain cavitation collapses: the focusing and synchronization by a glassy cavity, the collapse symmetry or asymmetry, and the generation of vortex cavitation at the rebound.

EROSION FROM MIXED GLASSY AND BUBBLY CAVITATION

It is generally considered that cloud cavitation is a necessary component in serious erosion problems. There are several reasonable explanations for this argument, e.g. by the amplification of pressure levels by synchronised and accelerated collapses of more than one cavitation bubble and the expected lower fractions of incondensable gas captured in the bubbles compared with a larger glassy sheet. It has however been noted several cases where collapses of mainly glassy cavities have lead to considerable erosion damage, even worse than nearby cloud collapses, see e.g. Figure 1; by mainly glassy we consider a glassy cavity with some cloud cavitation being generated on the edges of the cavity. The mechanisms for this have not previously been clearly articulated. From recent renewed studies of experimental data, we now believe we have a plausible model for this behaviour.

We first remark that in the final collapse of the micro cavity, it is probably still cloudy cavitation that causes the erosion damage, but the glassy part of the cavity may greatly enhances the erosiveness. The process is believed to be that a, travelling or fixed, sheet is generated at the surface and throughout the collapse of this sheet, by shear imposed by the external flow, secondary cloud cavitation is continuously being generated at the edge of the sheet.

The mechanisms for the enhancement are mainly three. First, the glassy cavity can reduce scattering of collapse location, focusing the collapse to an area of the surface that will remain the same for most collapse cycles. One example is shown in Figure 1: The collapse of the primary glassy sheet is restricted to a small area while the area for the collapse of the rebounding cloud is much larger, and thus also weaker.

Secondly, the glassy cavity also prevents scattering in time. By being attached to the sheet, the cloudy structures are prevented from disparate collapses through the creation of secondary cavitation by shear; this holds also regarding disintegration of the cavity into smaller, less erosive, cavities. The synchronisation of the collapse of the bubbles is an important mechanisms in creating highly erosive cavitation, and can be realised in other ways, e.g. by a vertical horseshoe vortex.

Lastly, the transfer of collapse energy from the collapsing sheet to the cloudy edges appears to be very efficient, leading to a strong focusing mechanisms from global to micro cavity, following the principles of the EroCav handbook [1]. This is significant considering that while the energy being made available for the collapse pulse can be assumed to be higher for a pure glassy sheet of the same volume as a pure cloudy cavity, although the comparison is problematic, the cloud seems to be more efficient in focusing its available energy, leading to higher energy densities at the surface. For the mixed case considered here, it appears we may get the worst of both.

CONSEQUENCES OF AN ASYMMETRIC COLLAPSE

In reference [3], an idea of a practical measure of erosiveness was presented by measuring the size of the cavity as a function of time during the collapse. The rationale was based on the notion that a fast, or an accelerated, collapse is more erosive than a slow or decelerating one. Later, it was found that this was not sufficient and that also the development of the rebound needed to be trapped [4]; the idea is illustrated by Figure 2, where then the conclusion was that a sharp ‘spike’ in the tracking of the collapse identifies an erosive event.

Assymmetry in collapses was first analysed by Benjamin and Ellis [5], and has been followed by more papers; the focus in our analysis of the impact is however different. From our observations, the erosiveness is often reduced if the collapse is asymmetric, and the reason seems to be the generation of a vortex directly after, or even during, the collapse; the process will be explained based on numerical simulation results below.

Based on this, we introduce the separate notation of the compression rebound and the vortex rebound. The former is, in its idealised form, the rebound due to compressibility of the content of a spherical bubble collapsing symmetrically due to external pressure forcing. The vortex rebound on the other hand, is a form of secondary cavitation expanding following the formation of a vortex in the shear following an asymmetric collapse.

We remark that in practical situations, both are almost always present but the balance between them differs. One example is given in Figure 2 where also the impact of a late vortex rebound, occurring after the fast mainly compression rebound, on the temporal evolution of the cavity is clear from the plot. One further example is presented in Figure 3, where the size and the resolution of the image makes is possible to follow the process in some detail. Here, also the generation of cloud cavitation from the glassy cavity by shear, discussed in the previous section, is visible.

The mechanisms behind the formation of the vortex rebound is presented in Figure 4, based on a detailed LES simulation of an upstream collapsing sheet [6]. The three dimensional simulation is performed for a 2D NACA0015 foil at angle of attack using incompressible LES, see [7] for details. The fact that the simulation technique does not allow a compression rebound makes it possible to study a pure vortex rebound, which will never be the case in reality. Summarising the development, as detailed discussion is out of the scope of this paper format, we see the remaining sheet in the first frames of Figure 40, and vortices being generated and starting to cavitate in the shear between the upstream moving fluid behind the sheet and the external flow. In the later frames, the shear, and thus the vortex rebound, is generated by the asymmetry of the collapse.

The reasons for the observed reduced erosiveness if a strong vortex rebound is generated are still to be verified. It is however believed that the vortex takes energy from and disperses the collapse in time and over a larger area. It is also probable that the vortex can lift the cavity slightly from the surface thereby decreasing the pressure pulse level on the surface. Note also that this mechanisms increases the requirement on resolution in both experimental and numerical assessment of risk of erosion. If the frame rate is not high enough, nor the awareness of the mechanisms in the analysis, a strong vortex rebound may be misinterpreted for a strong compression rebound; the latter being an indicator of high risk of erosion while the former is not.

THE GENERALIZED COLLAPSE AND REBOUND

As more and more details of the cavity collapse process are being revealed, we have found it appropriate to introduce a decomposition of the mechanisms summarized by what we call generalized collapse and rebound; a terminology introduced to facilitate discussion on these phenomena. Some details are left out, in order to better align the discussion with the material in this paper, but a more complete description is in review for publishing.

Starting with the rebound process, as already discussed in the previous paragraph, the *generalized rebound* of a collapsed cavity is the composite of the main mechanisms of the

- *Compression rebound,* due the expansion of cavity content compressed during the collapse, and
- *Vortex rebound,* due to shear generated during the collapse by re-entrant flow or collapse asymmetries.

This decomposition is valid, with some differences in the details, for both primary and secondary cavities.

The main mechanisms responsible for the *generalized collapse* of a cavity are the

- *Simple collapse,* forced by the global pressure,
- *Filling by re-entrant jets,* where a thin layer of liquid between the cavity and the surface fills the cavity internally,
- *Filling by reversed jet-like flow,* due to the collapse forcing pressure field, separation, stall or shed vortices, and
- *Collective cloud collapse,* of possibly existing cloud cavitation.

When it concerns secondary cavitation, there is additionally the

- *Collapse pulse,* created by the collapse and rebound of the primary cavity, and
- *Global pressure,* possible both before the collapse of the primary cavity as well as in the recovering flow following the collapse.

These concepts are not uniquely or strictly defined, but highlights, to our present best knowledge, the main mechanisms of the hydrodynamic processes involved in cavitation collapses and controlling it erosiveness.

CONCLUSIONS

This paper presents some details of the hydrodynamic phenomena involved in cavitation erosion, which is in our experience not well known or sufficiently considered. The final events causing erosion damage, e.g. the material stress and the pressure pulses or micro jets hitting the material surface, are of course vital, although out of scope in this paper. Instead we focus on the cavity dynamics leading up to the final collapse, enabling or not the energy concentration that may yield damage.

Awareness of the development from a global cavity, through the micro cavity, to the generalized collapses and rebounds, is of course beneficial when analysing cavitation, but the description presented here also, or perhaps mainly, have an impact on requirements on resolution in experiments or simulations. To achieve a reliable analysis of the risk of erosion, the collapse history needs to be traced as detailed as possible, and as far back as possible, as well as the dynamics of the rebound.

The presented hypotheses are primarily based on analysis of high-speed video recordings of cavitation events, using a frame rate of in some cases 90,000 fps, in some cases supported by numerical results of incompressible LES. It is believed that in order to verify the ideas, as well as developing the insights further, highly resolved numerical simulations, including e.g. gas content and compressibility, will play an important role.

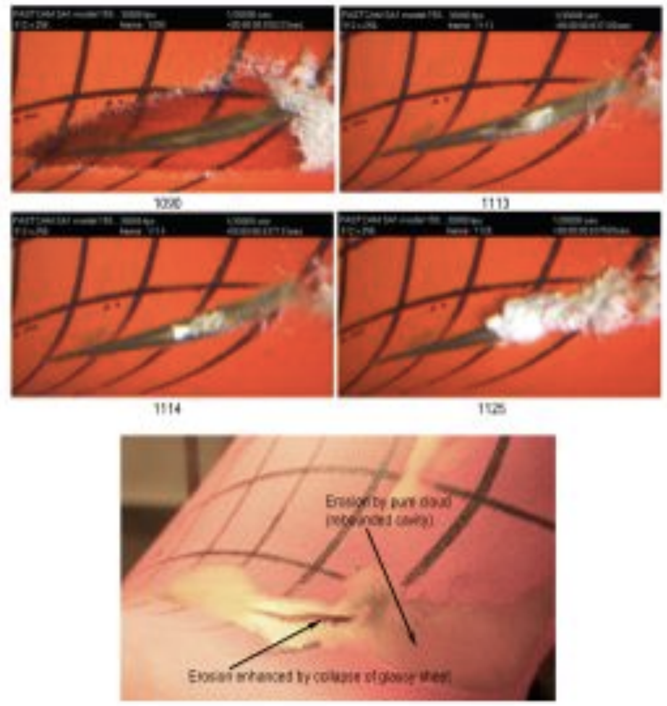

Figure 1. Sheet cavitation in the root region of a propeller operating in inclined flow. Leading edge to the left. Above: Frames from high-speed video. 1090: All parts of the cavity interface are accelerating towards the collapse point. The cloud to the right is generated by the shear between the filling flow and the flow outside the sheet. 1113: Less than 1/30000 s before minimum cavity. 1114: The captured smallest cavity size. 1125: The fast part of the rebound is over. Lower photo: Erosion at model test of a propeller, 8-9 m/s. Extreme erosion (removal of bronze) by symmetrically collapsing, almost glassy sheet cavity, and moderate erosion (paint removal only) by pure cloud cavitation after some hours of operation. SSPA cavitation tunnel.

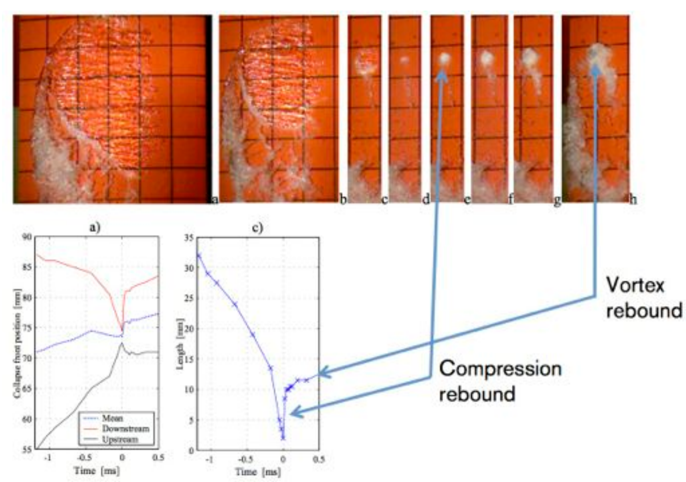

Figure 2. Rather symmetric collapse of a sheet on a foil in unsteady inflow from right. Plots of upstream and downstream collapse fronts and streamwise length of cavity. Experiment in the SSPA cavitation tunnel.

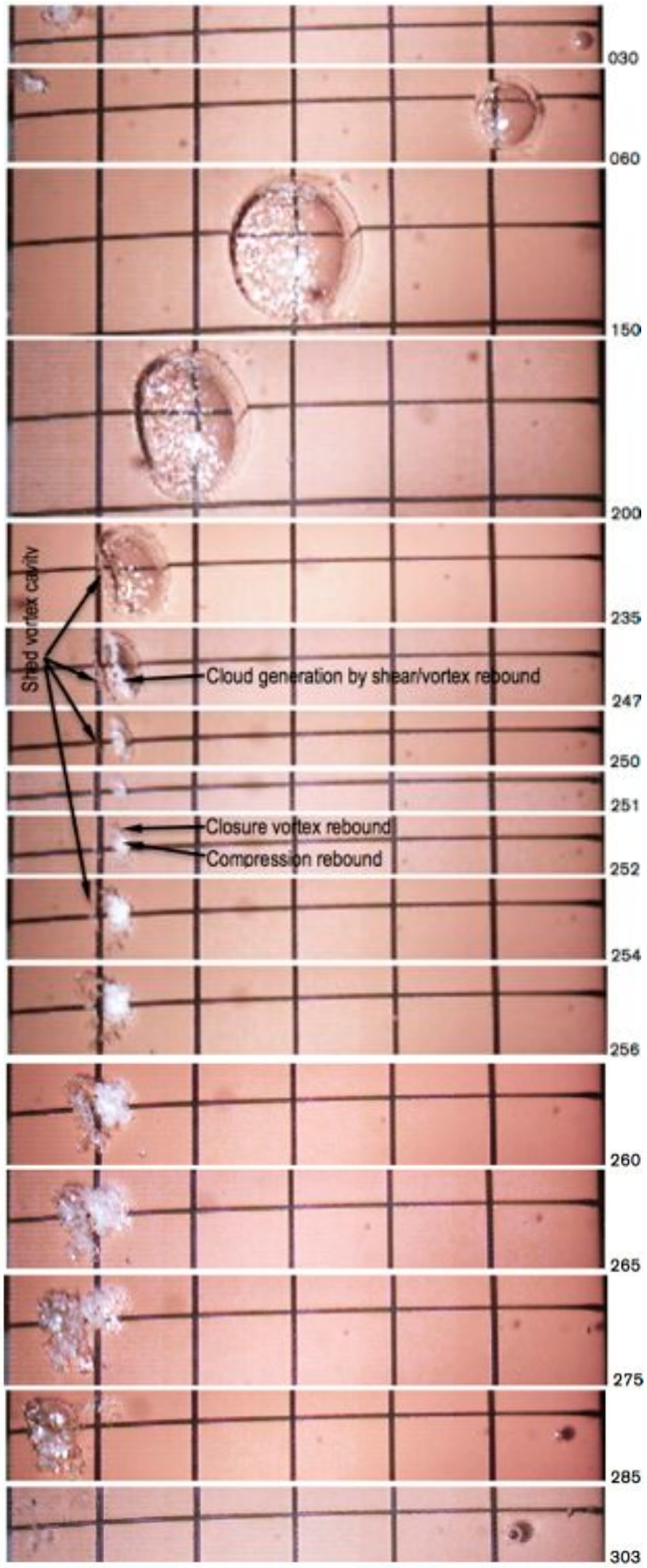

Figure 3. Asymmetric collapse of travelling bubble and generation of a vortex rebound. Flow from right, oscillating foil, 12 000 f/s, frame number to the right, chord length of foil is 120 mm. SSPA cavitation tunnel.

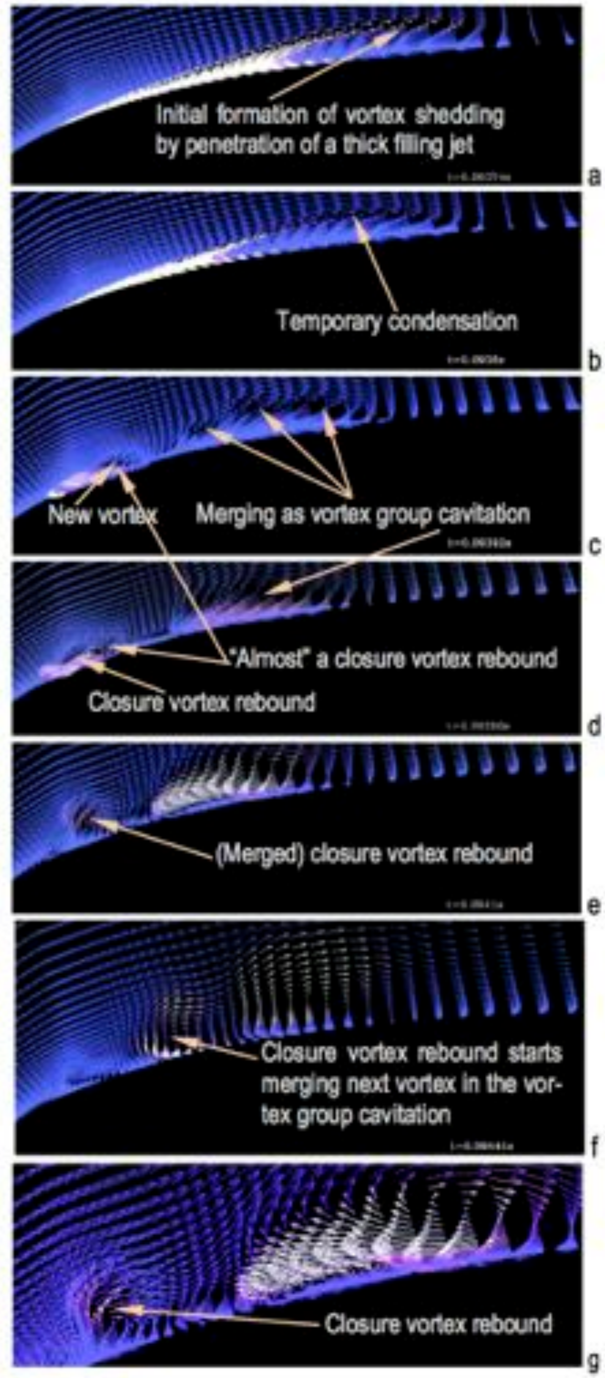

Figure 4. Implicit 3-D, LES simulation of the upstream moving collapse of an attached sheet on a 2-D NACA 0015 foil at stationary inflow from left, Lu (2010). Frames a-c: Formation of cavitating vortices in the downstream region. Frames d-f: Formation of a vortex rebound close to the sheet detachment point. White velocity vector is pure vapour. Frame g: Enlarged part of frame e demonstrating the vortex rebound following the final collapse of the sheet, arrowhead far left.

ACKNOWLEDGEMENTS

Financial support is provided by Rolls Royce AB through the University Technology Centre at the department of Shipping and Marine Technology, Chalmers. Part of the work has also been supported by the European Union project "Hydro Testing Alliance" (HTA), JRP6, with input from the earlier European projects EROCAV and VIRTUE.

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