ABSTRACT

The concept of focusing of the collapse energy is well established for the case of collective collapse of cloud cavitation. It has been indicated however that erosion can also be generated by cavities that stay glassy until a very late stage of the collapse, a circumstance implying that focusing of energy should be analyzed also for this type of cavities.

In this study, the concept of focusing of the collapse energy has been applied in practical observations as a procedure for analysis of erosive cavities.

From some experiments, it was found that glassy cavities can, as focusing cavities, be closely related to the generation of severe erosion. A simplified cascading process of the focusing of collapse energy is also assumed for the glassy cavity. Furthermore, erosion tests results showed that any type of fluctuations in the focusing of the collapse energy lead to a decrease of the collapse pressure and thus a decrease of the erosion.

INTRODUCTION

Concentration or, as it is called below, focusing of the collapse energy on very small domain of the solid surface is an obvious requirement for generation of cavitation erosion. This in fact can happen at a collapse of a cavity can be understood already from the solution of the Rayleigh-Plesset equation for the collapse of a single cavity. The highest values of the kinetic energy density occur in a small volume around the collapse centre and when the minimum radius is reached the energy has been transformed into potential energy felt as pressure by the surrounding matter. In the case of cloud cavitation this focusing is in particular pointed out and described by Mørch [2]. The focusing of energy is obvious in his model. First it predicts the collapse in the cloud to proceed from the cloud boundary towards the centre and secondly the energy is cascaded towards the innermost bubble(s) by the mainly acoustic interaction between the successively collapsing bubbles. The innermost bubble(s) will by this process collapse be forced by a pressure significantly higher than the environmental one and thus generate amplified pressure pulses and micro-jets of increased speed. The erosion damage is assumed to be caused by the collapses of these small innermost bubbles close the solid surface.

Further, according to the ideas put forward by Shima et al. [11] both the micro jet and pressure pulse generated by the collapse of the innermost cavities may transfer the energy to the solid that finally generates the erosion.

It is also noted that the individual pits forming the cavitation erosion are of fairly small scale, typically from a few µm up to mm-size. This observation also part of the classic erosion model summarized above. Large-scale deformations, as bents trailing edges etc., certainly can be generated by collapsing cavitation but that is not classified as erosion.

It is finally mentioned that the mechanics of collective collapses of bubble clouds was first considered by Van Wijngaarden [1] and further developed by Mørch [2], Chahine [3], Wang and Brennen [4] and others. Although inherent in the theory and sometimes pointed out the concept of focusing is not much discussed in the classical studies.

Bark [5] and Schöön and Bark [6] have reported that not only cloud cavitation but also cavities that stay mainly glassy during most of the collapse can collapse very violently and contribute to the erosion, possibly in an indirect but nevertheless very effective way. In earlier experiments on propeller model made by Bark [5], erosion occurred in the region where the traveling glassy sheet cavity collapsed. In later experiments with different foils (Schöön and Bark [6]), pitting have been
observed in the region of violent collapses of a glassy sheet cavity.

The ideas and conclusions presented below are preliminary results of ongoing work in the European project EROCA V (www.ero cav.de). The aim of Chalmers’ sub-project is to investigate in the way which the collapses of cavities become violent and erosive and to develop principles for analysis and identification of eroding cavitation. This work includes also the possible contribution to erosion due to the behavior of almost and partly glassy cavities as indicated in the paragraph above.

As a first step in this work the focusing concept has been extended as will be briefly described below. Experiments have been used for verification of fundamental ideas. Below will for example be shown results supporting the idea that the development towards erosive collapses often can be traced back to early behaviors of glassy or partly glassy cavities and that this is a useful information. The work was originally described in the contract reports by Bark et al. [9] and [10].

In this study, the concept of focusing of the collapse energy has been developed for application in practical observations, as a procedure for analysis and to a limited extent also detection of erosive cavitation. Engineering application requires some definitions as introduced below. The analysis procedure is aimed to be applicable to observations of cavitation at model or full scale and to some extent also numerically simulated cavitation.

From some experiments, carried out with a propeller model in inclined flow in a SSPA cavitation tunnel, it has been found that not only cloud cavitation is effective in focusing of the collapse energy and generating erosion, a mainly glassy cavity can also collapse violently and contribute significantly to erosion by focusing of the collapse energy.

The erosion tests showed that the maximum erosion occurs for the case in which the same amount of the collapse energy is focused to the same region in every cavitation cycle. Any type of fluctuations in the focusing of the collapse energy will lead to a decrease of the collapse pressure and thus a decrease of the erosion. Analysis of such behaviors can for example be used for reduction of scale effects at erosion tests at model scale.

The most important result at present is however that the experimental observations seem to support the analysis procedure being under development.

FOCUSING OF COLLAPSE ENERGY - THE EXTENDED CONCEPT

From earlier studies it was concluded that:

- Focusing of collapse energy is the common effect of single bubble and cloud collapses.
- This effect is crucial for erosion.
- Generation of erosion could be related also to collapses of mainly glassy and large-scale cavities.

Based on this conclusion it is assumed that an extended concept of hydrodynamic focusing of collapse energy would be a proper concept to study in order to trace the cavitation development towards an eroding collapse. Particularly it was assumed that this is a way to trace the small-scale part of the erosion process back to the large-scale hydrodynamics of relevance for design and engineering applications.

In this section some definitions and a simplified model for cascading of collapse energy to the innermost bubbles generating the pitting will be introduced. Together they will constitute the extended concept of focusing of collapse energy.

We start with a single innermost bubble, close to a body surface, in an ideal bubble cloud. We assume further that the collapse of this innermost bubble, forced by the pressure pulse generated by the collective collapse of the surrounding bubbles, generates a pit on the body surface. This innermost bubble is here called a “micro cavity”. The collapse of this micro cavity can be complex, for example include formation of a micro-jet and disintegration into still another cluster of still smaller bubbles according to Shima et al. [11]. What happens during the collapse of the micro cavity is however left outside the present discussion and simplified model. We just notice that collapse energy is, by the last cascading step in the original cloud, transferred to the micro cavity.

For the present purpose we may also say that we are not interested in the details of the successive collapses and energy cascading proceeding from the cloud periphery and inwards among the bubbles surrounding the innermost bubble, i.e. the micro cavity. We only take account of the pressure pulse forcing the micro cavity. In such a global view we can call the surrounding bubbles a “focusing cavity”.

In studies of two acoustically interacting bubbles it is pointed out by Fujikawa and Takahira [7] and later by Hallander [8], that the pressure radiated by a larger bubble can significantly intensify the collapse pulse generated by a smaller bubble. The larger bubble becomes thus a forcing bubble in the interaction process, similar to the bubbles surrounding the micro cavity in the case of a cloud collapse.

The extension to a collapse of two neighboring cavities of any shape, for example a part of a sheet and a small bubble close to this sheet is obvious. In this case it is, in analogy with the cloud collapse, realistic to assume that it is the small bubble that generates the pitting after it has gained collapse energy from the collapse of the sheet. A problem in this analogy may be that the small bubble can be expected to collapse before the sheet. This problem can at this stage be circumvented by assuming that the small bubble is by some process generated so that it is present at the moment when the collapse energy related to the sheet is focused and can be transferred to the small bubble.

In obvious analogy with the cloud case above the collapsing part of the sheet is called a “focusing cavity”, and this term is thus used to characterize a cavity of any configuration, the behavior of which results in focusing of collapse energy that is further transferred to the smaller cavities responsible for the pitting.

It is noted that also the collapse of a micro cavity means a focusing of collapse energy. The point with discriminating this from the focusing by the focusing cavity is that the focusing made by the focusing cavity is more global and observable by the naked eye. It can be observed on a high-speed video recording or similar of an engineering cavitation process while the observation of the focusing motion of a micro cavity can usually be made only at idealized conditions.

The discrimination between a focusing cavity and a micro cavity is however not very critical. It is set by observation
conditions and by the observer’s estimate of what part of the collapse process that is relevant to trace. To the definition is also added a comment of a limiting case allowing that a focusing cavity can continuously transform into a micro cavity in the case of an idealized behavior. An example of this are the cavities studied by Shima et al. [11] having initial diameters of some mm and classified above as micro cavities.

As pointed out in the introduction different mechanisms can be associated with the focusing. We pointed out the successive cascading of energy in a cloud. The one simplest to observe is the geometrical focusing related to the symmetry of collapse motion being described by the solution of the Rayleigh-Plesset equation. A very important parameter related to this solution is also the history of the pressure forcing the collapse, a problem further discussed in [9]. The effect of the pressure history on the amount of energy that is finally focused is the final acceleration of the collapse. The acceleration is not that simply measured but a good indicator of it is the violence of the rebound.

Summarizing so far we have thus replaced the physically more complete models by the simplified model comprising only two types of cavities, a focusing cavity and at least one micro cavity. To this model is also added the hypothesis that the model is valid and useful for engineering analysis of eroding cavitation, particularly for analysis of the early and global signs of development towards erosive collapses.

In addition to the basic definitions above, two supplementary and important aspects of the focusing are mentioned. A substantial part of the collapse energy will at the end of the collapse be concentrated to a small “focus volume”. The concentration of the collapse energy to this focus volume is called a “focusing in space”.

The collapse energy in the focus volume can also be distributed over time in different ways, and consequently it can be relevant to define a “focusing in time”.

- In case of a single collapsing cavity, a perfect focusing is reached when the energy is well focused in space and in time, which means a maximum amount of the collapse energy is concentrated in a small volume, the focus volume during a short interval of time.
- In practice most cavities disintegrate into larger and smaller parts during the collapse. A sheet cavity can for example, due to break off or detachment from the leading edge, generate more than one focusing cavities that later on will disintegrate into smaller groups. Such a group or group individuals (sub-cavities) do not usually collapse simultaneously or at the same spot. As is discussed more in detail in [9] and [10] the concept of focusing can however also be applied to such conditions.

A particular configuration of a group is a sequence of cavities created continuously or successively in time. Shedding from a sheet cavity can for example generate such a sequence of sub-cavities. The concept of focusing can also be applied to the collapse of a group or sequence of cavities: The maximum focus is reached when all the cavities in the group or a sequence collapse towards the same point. Each sub-cavity in the group or sequence is in this process a focusing cavity.

For a sequence, a perfect focusing is obtained when all the cavities are convected to the same collapsing point. For a group of general configuration, the focusing is usually more dispersed, especially if the sub-cavities in the group disintegrate further into a group of new sub-cavities.

The concept of focusing extended in this way is used to make systematic observations and analysis of cavitation particularly in experimental studies at model scale. Once a collapse supposed to generate erosion has been detected the most important step in the analysis of the behavior is the identification of the focusing cavities, their development, the possibilities to cure the problem etc. In numerical simulation, where the final collapse cannot be observed, the identification of the focusing motion can perhaps be detected at an early stage and be an indicator of erosion risk.

For a propeller it is noted that the propeller rotation constitutes a large-scale sequence being maximally focused when the collapse points are the same at each revolution.

**EXPERIMENTAL PROCEDURES AND SETUP**

Cavitation tests were made in the high-speed test section of SSPA cavitation tunnel with a propeller model mounted on an inclined shaft. With this arrangement it was possible to isolate different eroding cavitation patterns as pure cloud cavitation, mixed cloud and glassy cavitation and finally also almost glassy sheet without significant amount of bubble formations.

The cavitation behavior on the propeller was recorded by a HYCAM high speed camera which is able to reach 8000 frames per seconds when loaded with 30 m film. We also used high-speed video at 1000 frames per second and ordinary video recording at stroboscopic light. The propeller was coated with a red matt paint for better observation of the cavitation pattern. The roughness of the paint also stabilizes the cavitation slightly.

Erosion tests were made with the propeller painted with black stencil ink according to the SSPA standard procedure.

**EXAMPLES OF CAVITATION OBSERVATIONS ON PROPELLER MODEL**

In this section observations and analyses of cavitation behaviors in three model experiments are described according to the focusing concept introduced in the preceding sections.

**Highly focused collapses - Severe erosion**

Figure 1 shows an example of a symmetric collapse performed by a root cavity on the propeller operated at the cavitation number 0.8. The root cavity consists of a large mainly glassy sheet with a thick cloud formation in the downstream part and a few bubbles around the edges. In frame a, the root cavity has already detached from the leading edge and transformed into a traveling cavity moving downstream where it collapses and rebounds close to the trailing edge. This traveling cavity, including the cloudy part, is identified as a focusing cavity since it performs an accelerated and symmetric collapse, as a single cavity without significant disintegration, towards a very small volume. A very violent and intensely white rebound of the focusing cavity can be observed in frame f. A second and quite violent collapse is performed by the rebounded cloudy cavity close to the trailing edge. Notice that, as far as can be resolved,
there is a glassy part and a bubble formation attached to the glassy cavity during the whole collapse process, (Figure 1.d and Figure 2). However, due to the moderate frame rate it cannot be judged if the transformation of the glassy part to a cloud starts before the minimum size is reached.

The erosion of the stencil ink, and even of the bronze, is shown in Figure 4. There is a strong impression that the erosion is generated below the collapse of the glassy as well as the cloudy part of the cavity. The eroded area close to the trailing edge is a result of the collapse of the rebounded cavity looking as a very homogeneous cloud of small bubbles. The narrow erosion patches further out on the blade are due to the collapse of a slender and mainly glassy “streak cavity” also performing a highly focused collapse as an almost glassy cavity towards a line, Figure 3.

Figure 5 illustrates a final collapse of a slender root cavity on propeller operated at the cavitation number 0.9. In frame c, the mainly glassy cavity has already detached from the leading edge, and transformed into a traveling cavity that performs a rather fast and violent collapse towards a line, between frame c and frame d, and followed by a very white and violent rebound in frames e and f. As can be seen in the frames, the red paint has been removed along a thin line in the region where the collapse of the glassy cavity has occurred.

Figure 6 shows an example from an earlier test with a propeller in a wake. In frame a, the small mainly glassy cavity is a part of a sheet cavity that has detached from the leading edge region. In the next three frames, it performs an accelerated and rather symmetrical collapse focusing the collapse energy towards a small area on the blade. Very white cloudy structures can be seen during the rebound phase (frame f). The shown collapse happens just upstream the dark patch where the red paint is eroded away, a fact indicating the random variation of the cavitation behavior one blade passage to another (The blade rate sequence is not well focused).

Notice that all the focusing glassy cavities presented in the three examples have transformed, during their collapse, into traveling cavities detached from the leading edge. In all cases there were observed small bubble formations that might behave as micro cavities. This was true also at cavitation number 0.9 sometimes generating cavities that were significantly more free from bubble formations than the example shown in Figure 6.

The observations made at these conditions all support the idea that a glassy cavity can be very effective, at least as a focusing cavity in generation of erosion.

well focused cloud collapse

Figure 7 shows an example of moderate root cavitation that finally after a complex process develops into a main cloud shown in frame d. This cloud is identified as a focusing cavity. It collapses in frames e and f and results in the larger erosion patch shown in Figure 8.a. The smaller erosion patch seen upstream the large one (to the left) is created by the collapse of a mainly glassy part of the cavity.

The cloud in frame d performs a rather well focused collapse although more than one focus points usually can be seen. The mean position of the collapse points differ also slightly between different blade passages, a fact that disperse the focusing and reduce the erosion. On blade No.2, Figure 8.b, the cavitation is also significantly more intermittent, a process that can be interpreted as dispersion of the focusing in time and thus expected to result in still more reduction of the erosion.

This example shows how a random or unsteady distribution of the collapse energy in time and/or space will decrease the cavitation damage.

Well focused but non-erosive cloud collapses

Figure 9 shows an example of cloud cavitation being on the limit to generate erosion. In an earlier test, the red standard paint was slightly polished, but not removed, during the observations. Again, after a complex generation process, a cloud has formed a focusing cavity, frame e. It performs a fairly well focused accelerating collapse towards a small area, frame f. The rebound that followed was only moderately fast, a first indication of that the erosion would be weak. The overall behavior of the single collapses was however violent enough to start an erosion alarm.

As in the case above the focus was at most blade passages also dispersed by disintegration of the cloud into a few separate collapse points that also were scattered around over a rather large area at during successive blade passages. Still more support for the weak erosion tendency came from the video recording showing that the collapses occur at some distance from the blade surface (Shadows are visible below the cavities in frame f in Figure 10), a fact that of course significantly reduces the erosion.

DISCUSSION AND CONCLUSIONS

The concept of focusing cavity has been extended and applied to observations of more or less erosive propeller cavitation. The extended concept of focusing is the core of an ongoing work with a procedure for analysis of eroding cavitation, [10]. The main point of the paper is the confirmation of the hypothesis that the simplified model for energy focusing can be used for engineering analysis of eroding cavitation. This means that it is in many cases sufficient to consider only one energy cascading step, the step from the focusing cavity to the micro cavity. The model is the basis for the introduction of the focusing cavity and the extended focusing concept.

- The first examples, Figures 1-6, illustrates a perfect focusing in time and space of the collapse energy performed by an almost glassy or mixed glassy-cloudy cavity cavity causing severe erosion. The observations made in these examples show that a glassy or almost glassy cavity can, as a focusing cavity, contribute at least indirectly to erosion by transferring the collapse energy to the “micro-cavities”, that are supposed to directly generate the pitting. These observations can be added to those on still more glassy cavities reported in [6] and the conclusion is then that focusing cavities could in all these cases be traced back to early formations of traveling cavities.

The dominating generation process of the traveling cavities was in all cases the detachment of a sheet or sheet-like cavity from the leading edge region and there is little doubt that a significant part of the accelerating collapses of these rather large scale glassy or mixed cavities can be
related to the erosion observed in some cases at very well defined spots.

The examples shown above may give the impression that the glassy cavities are the most effective in focusing and thus result most erosion. Although glassy cavities are very effective it is however too early to make that conclusion. A main problem at comparison of erosion by different cavity types is the normalization of data.

- The pure cloud cavitation in Figure 7, is less eroding than the previous examples. One reason is supposed to be the fragmentation of the cloud into a group of cloudy focusing cavities collapsing at different time and points, demonstrating the effect of unsteady distribution of the collapse energy on erosion damage. It has been indicated that fluctuations in space and fluctuations in time in the focusing of the collapse energy will both lead to a decrease of the collapse pressure and thus a decrease of the erosion.

- The condition shown in Figures 9 and 10, is an example of non-eroding cloud cavitation, which performed a symmetric rather well focused collapse towards a small region, not close enough to the blade surface however. Focusing is thus not sufficient, it has to be also on the body surface.

- The examples with cloud cavitation show that the focusing concept works for them as well. Single clouds can be well focused towards a single point or they can disintegrate and collapse towards a few points, often slightly different for different cavitation cycles. The latter means that energy focusing is dispersed and that the erosion damage is reduced. Due to complex creation processes, including vortex shedding, it also happens that clouds collapse at some distance from the body surface, also that a fact reducing the erosion damage.

The simplified model for focusing of collapse energy by cascading hypothesis about its relevance can be summarized as:

- The erosive collapse process, characterized as a focusing of collapse energy, can for the purpose of analysis of erosive collapses, be simplified into an approximate process including a focusing cavity and micro cavities only. The focusing cavity can have any structure, glassy, cloudy or mixed. In the limit of an “ideal” focusing cavity it can towards the end of the collapse continuously transform into a micro cavity.

This core of the model is supplemented by the following two statements:

- The continued collapse of the micro cavity results in further focusing, for example by formation of the micro-jet etc. This final process generates the pitting.
- The focusing cavity is typically developed from the global body cavity, typically a sheet, by break-off, leading edge detachment, shedding, etc. and the micro cavities are generated late enough to be there and to absorb the energy for the last focusing and cascading step to the body surface.

There is little doubt that the cavities considered in the first examples are very erosive and that much of the collapses of the large connected cavities contribute to the erosion. Still better support for more idealized and almost glassy cavities is found in [6]. Together these data are stated to be a good support for the simplified model and the use of the focusing concept to find the early indications and analyze the development towards eroding cavitation.

Examples of problems that need further consideration are:

- Exact mechanisms for cascading of collapse energy to the micro cavities from a glassy focusing cavity is not demonstrated yet but that energy transfer seems quite plausible and is not considered as a large problem.
- The generation of micro cavities at the right place and time may seem to be a weak part of the model. As a temporary support for that slightly drastic assumption is used the fact that it so far has been impossible to generate a focusing cavity without any attached micro cavities during the end of the collapse. Among speculations on mechanisms during the late part of the collapse may be mentioned instabilities as discussed by Brennen [12] p. 71. As a possibility in some cases is also added the ideal limiting case supported by the observations by Shima et al. [11].
- A main simplification is the reduction of the cascading steps to one step only. For a cloud collapse this may at first seem to be a significant simplification but when the focusing cavity is glassy the model can be supposed to approach the physics. Because the model is not aimed for any quantitative prediction but for detection and qualitative analysis only the simplification is however acceptable.

Concerning the applicability of the present approach it is noted that the described behavior can be found in real cavitation. The shown examples, selected to support the hypothesis, are however slightly extreme or idealized. In many cases the focusing cavities are smaller, exist during a shorter time and are therefore less easily detected. Large focusing cavities can for example be generated by detachment from the leading edge region while small ones can originate from small-scale shedding.

Although much remains about the practical implementation the experience so far indicates that the approach puts the focus on tracking early developments towards eroding collapses and thus also bring a link to the global flow, engineering parameters and the design process (Iterative design by analysis). The concept was primarily developed for application to experimental observations but it may also be a basis for detection of early developments towards erosive behaviors in numerically simulated cavitation.

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Figure 1. Collapse of a mixed glassy-cloudy cavity at the root of a propeller blade, condition of highly focused collapse. (σ = 0.8, pictures taken from high-speed film).

Figure 2. Final collapse of a mixed glassy-cloudy cavity at the root of a propeller blade. (Pictures taken from video recording).

Figure 3. Collapse of streak cavitation on the propeller blade.
Figure 4. Picture of an eroded blade, condition of severe erosion, \((\sigma = 0.8)\).

Figure 5. Final collapse of a slender cavity at the root of a propeller blade, \((\sigma = 0.9)\).

Figure 6. Examples of a violent collapse of a glassy cavity. (Pictures taken from high-speed film).

Figure 7. Collapse of cloud cavitation at the root of a propeller blade, condition of well-focused cloud collapse. (Pictures taken from high-speed film).
Figure 8. Pictures of eroded blades, condition of weak Erosion.

Figure 9. Collapse of cloud cavitation at the root of a propeller blade, condition of well focused but not erosive cloud collapses. (Pictures taken from high-speed film).

Figure 10. Collapse of cavitation at the root of a propeller blade, condition of well focused but not erosive cloud collapses. (pictures taken from video recording).