CAVITATION AND HYDRAULIC MACHINERY

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Some New Approaches to the Study of Cavitation

by

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Some New Approaches to the Study of Cavitation

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Abstract

The design of some experiments to check the assumptions of and to extend existing transient cavitation bubble theory is described. New developments in instrumentation are discussed and preliminary examples of their application to the problem are given.

Résumé

Voici l'étude de quelques expériences qui ont pour but de vérifier les hypothèses de la théorie actuelle concernant les bulles transitoires de cavitation et de la développer. On mentionnera aussi de nouveaux progrès de l'instrumentation et on donnera des exemples de leur application au problème en question.

Introduction

The literature on cavitation has grown to great proportions since studies began in the late nineteenth century. This is due to the great number of variables involved and to the wide range of the aspects of cavitation any one of which may happen to be of prime interest to investigators in different fields.

In such a situation it seems logical to attempt to simplify the problem as much as possible and to attack one aspect at a time. It is also quite apparent that the basic mechanisms involved should be treated from a mathematical point of view. However, there is a definite threshold of direct observational understanding which must first be attained in order to permit the establishment of the basic assumptions which must provide a foundation for any analytical treatment. Many other hydrodynamic phenomena are so accessible to observation that the required assumptions are made without conscious effort. In the case of small bubble cavitation, as distinct from supercavitating flow, the situation is quite different. Bubble lifetimes are measured in milliseconds, or even microseconds, and wall velócities may reach thousands of feet per second when bubble dimensions are so small as to require a high power microscope even if they were stationary. This combined behaviour makes direct observations extremely diffiuclt, since velocities as well as displacements are magnified as far as any photographic recording is concerned. However, it is essential that direct observations be made, since such basic assumptions as whether or not the bubble remains spherical are involved.

One of the first significant attacks on the problem was that of Knapp and Hollander [1] in 1948, who took pictures of cavitation in flow at 20,000 frames per second, using strobe light techniques developed at the Hydrodynamics Laboratory of the California Institute of Technology by Dr. Haskell Shapiro and the author. These photographs revealed such things as bubble "rebound" and the rough, non-spherical appearance of the bubble surface after rebound.

In 1952 a multiple frame Kerr cell shutter camera was developed [2] which increased the picture rate by an order of magnitude and cut exposure times by an order of magnitude to about one tenth microsecond. This equipment was applied to the study of single bubbles formed by boiling and showed that vapor bubbles with sufficiently small gas content would collapse without "rebound".

In 1955 [3] the picture rate was raised to one million per second and exposure time reduced to about thirty billionths of a second. Movies were taken of acoustically generated cavitation near a photoelastically sensitive solid. It was found that only bubbles collapsing directly on the boundary, produced observable fringes in the solid. This was felt to reduce the probability of shock waves being of great importance in cavitation damage and to increase the importance of direct impact, or what has sometimes been called "water hammer".

Research Program

These points have been mentioned primarily to illustrate the value of direct observation. The purpose of this paper is to show how observations may be extended in the future.

The starting point of the work to be discussed here, is contained in the paper "On the Mechanism of Cavitation Damage by Nonhemispherical Cavities Collapsing in Contact with a Solid Boundary" by Naudé and Ellis [4]. In this case the cavities were generated by an electrical discharge in water. The underwater spark occurred between two tungsten wires which would be placed at varying distances from an aluminum plate. The shape of the collapsing cavity as a function of time was calculated using a Legendre Polynominal expansion. The theory made the simplest assumptions of a perfect fluid, neglecting compressibility and viscosity and yet very good agreement was obtained with experimental shapes observed in photographs taken with an improved version of the Kerr cell camera. Perhaps the most

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(1) Numbers in brackets refer to reference list at end of text.

important finding in this study was that a jet could form on the side of the bubble opposite the solid wall and could strike the wall at high enough velocity to cause damage. Fig. 1 shows a series of photographs showing the formation of the jet. It is visible in this case, because the walls of the bubble were parallel enough so that the back lighting used could enter the bubble and silhouette the jet. Other indications of the jet may be seen in the photoelastic response of solids and the small hole left in a plate of aluminum after one collapse.

The above mentioned experiment, while agreeing very well with theory, is admittedly somewhat specialized. Objections to such things as excessive gas content due to the spark could be disregarded because the jet was shown to strike before the volume of the bubble was much less than a third of its initial volume. The analysis was not carried beyond this phase because of increasing errors in the calculations. Another objection was heat generation by the spark, but this affected the collapse a negligible amount because of the relatively long lifetime of the bubble. Of course, it was the governing feature during the growth phase.

The success of the above work has led us to initiate the present program. This program requires the development of instrumentation to provide very high optical resolutions of transient phenomena and to permit flow visualization which will become important as the analysis is extended to include the case of gross flow. This case is one step closer to the eventual application of theoretical results confirmed by experiment, to the cases of practical interest for the hydraulics designer. The program involves further study of the no-flow case in which a single bubble is held stationary by a very weak spherical sound field. This enables a single bubble to be held stationary in the volume of the liquid and permits arbitrary positioning with respect to the solid boundarv. The work done with the spark bubble would thus be repeated, without the objection of excessive gas content or high temperatures. It is necessary to hold the bubble stationary in the fluid, not only for photographic purposes, but also to avoid an excessive distortion of the bubble during collapse, due to the upward momentum caused by buoyancy which would ordinarily act. Fig. 2 shows the equipment involved in this experiment. At the center is the black bubble chamber which houses a barium titanate spherical shell transducer. Windows may be seen at the bottom of the chamber. The one on the left allows light to silhouette the bubble, and the one on the right is for the camera which is a long box using a special plate emulsion. A small amount of gas is injected into the chamber and rises to center of the sound field where it is trapped. The amount of gas may be accurately controlled and the chamber is kept at a low initial pressure, so that a small volume of gas is necessary to provide a relatively large nucleus. A diaphragm is then broken and the pressure from the vertical pipe accumulator shown in the photograph is allowed to collapse the bubble. While not necessary for this experiment, it was

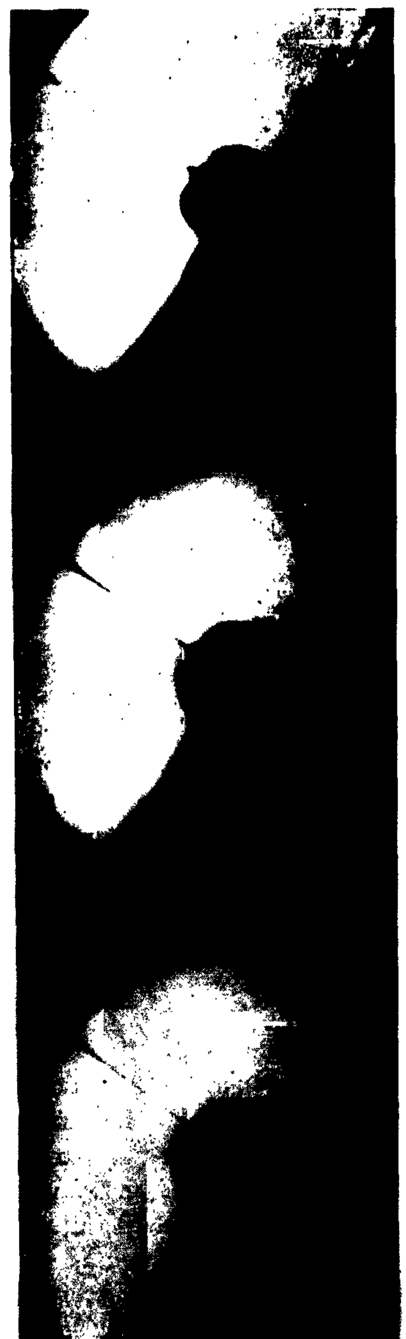

Fig. 1. Formation of a Jet during Collapse on a Rigid Wall

Largest bubble diameter shown is 0.67 centimeter and time between pictures is ten microseconds.

Fig. 2. Acoustical Apparatus for Holding and Collapsing a Stationary Bubble

anticipated a very high intensity light source would be necessary for proper flow visualization in the later phase of the study. Development has therefore been started on equipment using a ruby laser. Fig. 3 shows a 0.13 centimeter diameter air bubble photographed in silhouette with light from such a ruby laser. This bubble is being held stationary by the spherical sound field. The extreme sharpness of the bubble boundary is very gratifying. This is due to the fact that the light is extremely monochromatic. Also to be seen in this photograph are many interference patterns of circular shape. These are caused by small particles of dust in the water. This suggests the possibility of using very small particles as flow visualization tracers, and this will be done in the phase dealing with cavitation in gross flow. The tracers will be polystyrene spheres 2650 angstroms (2.65 $\times 10^{-5}$ cm) in diameter. They are small enough so that they will remain permanently suspended in water, and not settle out as larger particles might. The ratio of surface to volume is also so high that the particle should follow streamlines in the flow.

The wave length of the ruby laser light is 6943 angstroms, and hence the tracer particles cannot be observed directly. However, it is only necessary to observe the scattered light from these particles in order to trace the flow direction and velocity, if the duration of the light pulse is known. This will permit a study of the interactions of the boundary layer and the cavitation bubble collapse, as both tracer particle path and bubble collapse will be visible in the same photograph.

This technique resembles that used by Fage and Townend [5] in the early thirties. However, lack of sufficient light intensity limited their studies to very low flow velocities. For comparison, a modern high pressure mercury point source can be expected to give about 10 watts of radiant power. A pulsed ruby laser will provide about fifty million watts at peak power. For a microsecond exposure time, 50 watt seconds would thus be available for exposing the photographic plate. It is felt that exposure times as short as a billionth of a second may be approached. One of the greatest technical problems is presented by the necessity of pulsing the ruby for short durations. This has been accomplished by Dr. Hellwarth of the Hughes Corporation using a Kerr cell, but the pulsing has not been repetitive [6].

The bubble photograph of Fig. 3 was not a short-duration laser picture. The exposure time was about 200 microseconds. However, by the time this paper is presented, it is felt that the short pulse problem will have been solved.

Fig. 4 shows the details of the present ruby laser light source. A Xenon flash tube is located at one focus of the elliptical reflector and the ruby rod is located at the other focus. It may be seen in the upper part of the photograph. In addition to the ruby light source, a more efficient optical arrangement for re-

Fig. 3. A 0.13 Centimeter Diameter Air Bubble Photographed in Silhouette with Light from a Ruby LASER

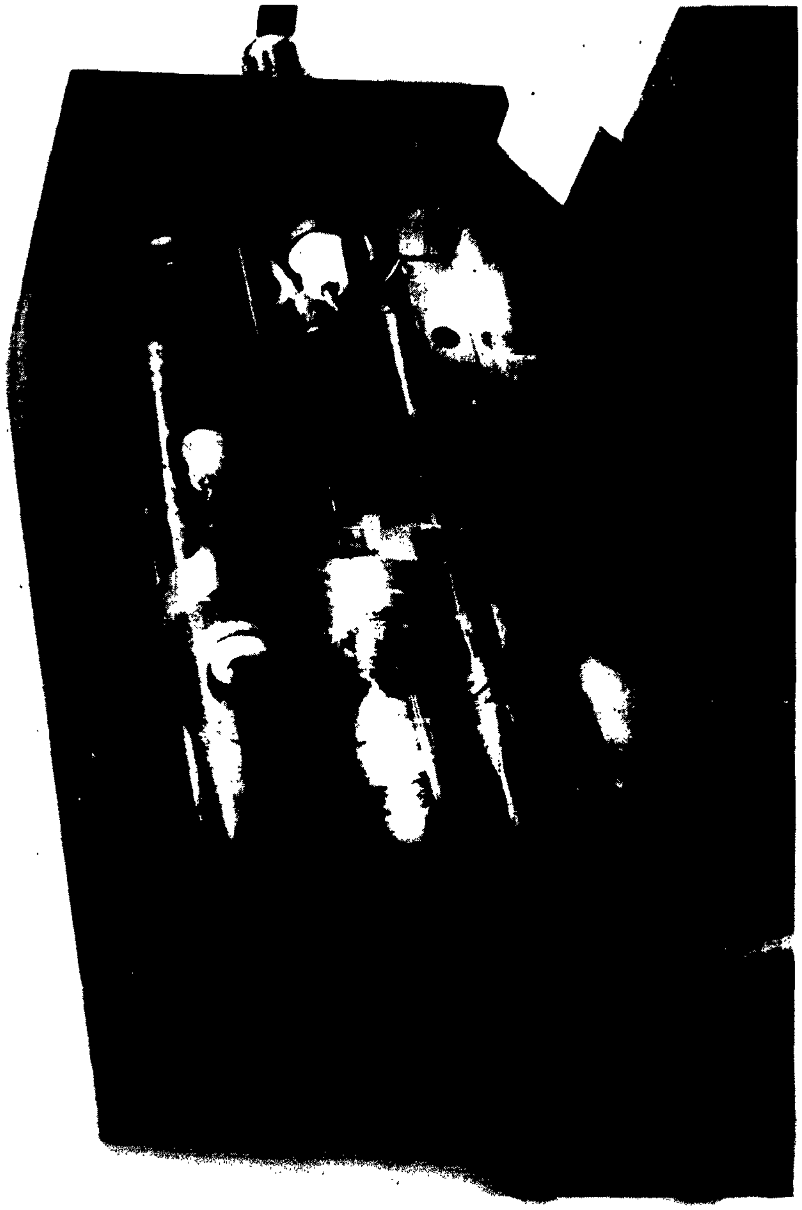

Fig. 4. Ruby LASER Light Source Showing Xenon Flashlamp and 3 × 1/4-Inch Ruby Cylinder (top) in Elliptical Reflector

Fig. 5. Dark Field Photograph by Forward Light Scattering from Polystyrene Spheres
The smallest is 2.86×10^{-4} centimetres.

ceiving scattered light from tracer particles has been devised. Fig. 5 is a photograph using this technique. The smallest bright spots are three micron particles. Only about twice the exposure time is required for this scattered light photograph as is required for direct silhouette illumination.

With the ruby light source and this more efficient optical system, visualization of flow at 50 fps, and with magnifications of 50 times should be possible. Interaction between the bubble collapse and the boundary layer should be observable.

It is usually difficult to observe single bubbles under high velocity flow conditions. The probability of finding a single bubble in the field of observation for such a short time is negligible. Also, there are usually large numbers of bubbles present and interaction effects would make the analysis extremely difficult.

These are some of the reasons which have lead to the design of a new flow facility for this study. This is a blow-down type of water tunnel in which there is no pump, and gas pressure is used to force the water from one tank, through the working section, and into the receiving tank in which the pressure may be as low as vapor pressure. The entire flow system is completely closed, so that the water may be kept at vapor pressure between runs. This will permit a thorough job of degassing of the liquid. Together with a proper filtering system, this should result in a minimum of nuclei being present. Under these conditions it should be possible to form a bubble by injecting a small gas nucleus just behind the stagnation point in flow over a two-dimensional body. The problem, not only of timing and location of the bubble, but also of bubble interaction will be solved in this manner. In addition, the fact that the liquid is initially at rest, and there is no pump in the system, should result in a very low turbulence level. Thus the transition from the study of single bubbles with no flow can be made to the case of single bubbles in high velocity flow.

After the behavior is compared with theory, it is intended to introduce more than one bubble so that bubble interactions may also be studied. Statistical methods can then be used to correlate this more idealized experiment with actual flow situations around a submerged body. An elliptical body will be used for the blow-down tunnel phase. In this case the ideal fluid pressure field is readily calculable, and varying the direction of flow with respect to the ellipse will provide a variation of pressure distribution when desired.

This paper is intended to be merely a discussion of the method of attack on the cavitation problem. It is hoped that there will be substantial results available by the time this symposium takes place. At this time the newness of the program prevents any substantial conclusions from being drawn.

Acknowledgement

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DISCUSSION

Danos H. Kallas[1]

We at the U. S. Naval Applied Science Laboratory are greatly interested in the mechanisms of cavitation damage. As a consequence of this interest we have built a rotating-disk machine which has been successful in causing reproducible damage to a variety of materials. Although we are still not able to explain the collapse of bubbles to our complete satisfaction, we see in Dr. Ellis' very original work an opportunity to better understand this mechanism. The investigations presently being conducted by the author provide us with a clear picture of a manner of bubble collapse in which the energy of collapse is transferred, by means of a jet, to the proximately located material causing the material to deform.

Several outstanding facts are evident from the work of Dr. Ellis. To mention but one, it shows that the early mathematical theory of Lord Rayleigh, which stated that damage resulted from shock waves produced by the bubble collapse, is not the complete answer. It appears that the collapse of the bubble must take place on the surface of the material in order for any damage to occur. The most important contribution of this work is that for the first time we are able to see both mathematically and visually the actual jet which is believed to be the cause of damage.

As is the case in all presentations of original work, points of interest have arisen which invite clarification. Objections to the excessive gas content and heat generation caused by the spark have been considered in the course of the investigation. However, the effects of surface tension at the interface of the solid spark producing probe, the liquid test medium and the bubble vapor have not been considered in this work. It would be useful to know how these effects contribute

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to the formation of the jet shown, since the interface surface could be either concave or convex in form, depending on the surface tension of the liquid and the material of the probe.

It is gratifying to note that the work described in the paper is being extended to cover investigations of bubble collapse in actual flow conditions in addition to studies of bubbles in non flow conditions. The greater similarity between experimental parameters in these prospective tests and the parameters in water tunnel and rotating-disk machine tests will give added scope to this work and to any conclusions obtained therefrom.

Authors' Closure

It is true that effects of surface tension on perturbations of bubble shape have not been considered theoretically. An experiment was done, however, in which the spark gap wires came into the bubble parallel to the solid boundary rather than normal to it. In this case the general shape appeared to be the same as before although the actual jet was not visible. Mr. Kallas' criticism is well taken, and we plan to do the experiment again with a bubble which is not spark generated and would not require wires.