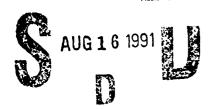**AD-A239 722**

<u>Final Report</u>

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BUBBLY CAVITATION FLOWS

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1. INTRODUCTION

This constitutes the final report on the research accomplished under ONR Contract No. N00014-85-K-0397 entitled "Bubbly Cavitation Flows" executed during the period <u>June 1, 1985</u> to <u>March 31, 1991</u>. A substantial number of publications and conference presentations were generated during this time and it would be superfluous to repeat that material in this report. However we will give a brief summary of the principal technical achievements of the research. Since the research had both experimental and analytical components it is convenient to report on each separately. The objective of the program as a whole was to gain a better fundamental understanding of bubbly cavitation flows. To do so it was necessary to understand the interactions between the dynamics of an individual bubble and the flow field in which it is evolving <u>and</u> the interactions between bubbles when they are sufficiently numerous to have such interactions. Both interactions were explored as a part of this research.

2. EXPERIMENTAL PROGRAM

During the last few years we have conducted a detailed experimental investigation of the dynamics and acoustics of travelling bubble cavitation. Work reported in publications 7, 9, 11, 12, 13 examined travelling bubble cavitation on two classic axisymmetric headforms (a Schiebe body and the ITTC headform) and, with the help of some novel instrumentation, revealed a number of previously unrecognized features in the dynamics and acoustics of cavitation bubbles. Novel features of the experiment were the use of lucite bodies with the hydrophone installed in a water filled cavity within the headform. Since lucite has an acoustic impedance not too different from that of water, the internal hydrophone records the noise from the collapsing bubbles in a way which is relatively

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free of the distortion and reverberation of the facility. Secondly, we utilized various forms of surface mounted electrodes to measure the local electrical impedance of the fluid and thereby achieve various ends. Local patch electrodes were used to detect the passage of a bubble and therefore to trigger a photographic flash unit so that a detailed photogaphic record could be made of the bubble as it grows and collapses during its passage through the low pressure region. These detailed observations revealed complicated bubble dynamics, beginning with the growth of hemispherical bubbles separated from the body by a thin liquid film and evolving through a process of bubble distortion, possible bubble fission and collapse, all of which indicated strong interaction with the details of the flow close to the headform (boundary layer shear, separation, transition). The later stages of bubble evolution were somewhat different on the two headforms, primarily because of the presence of laminar separation on the ITTC body and its absence on the Schiebe body. The measurements of the acoustic pulses generated by bubble collapses on the two headforms clearly showed that these interactions between the bubble dynamics and the flow had a major effect upon the cavitation noise. For example, the collapse would produce one, two or more acoustic pulses, depending on whether or not fission occurred prior to collapse; as might be expected, the probability of multiple pulses increased with the maximum size of the bubble. These and other features of single bubble dynamics and acoustics are described in publications 7, 9, 11, and 12. Comparison is also made with analytical predictions based on the Rayleigh-Plesset equations.

In addition to the single bubble studies, the statistics of cavitation events were also studied (publications 12, 13). The ability of the surface electrodes to detect all cavitation events, as well as the maximum size of the bubbles, allowed accumulation of a great deal of statistical information with relative ease. In addition, simultaneous measurements were made of the nuclei number distribution in the flow upstream of the body. An existing holograph camera was used for this purpose and nuclei number distributions were obtained by manually surveying the reconstructed holographic images. Comparison was made between the measured cavitation bubble maximum size distributions and those predicted using the measured nuclei number distribution and the Rayleigh-Plesset model for the bubble dynamics. Because the process of obtaining the nuclei number distribution was quite laborious

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during the early phase of the program, we were only able to make four such comparisons. While the overall event rates were quite well predicted, the statistical quality of the nuclei number distributions was not good enough to allow detailed comparison of the measured and predicted bubble size distributions.

The lack of an instrument capable of making nuclei number distribution measurements without the intensive labor associated with the holographic method and with on-line capability so hindered the later experiments that it was decided to proceed to purchase one of the two commercially available light-scattering instruments in order to enhance our capabilities for the present and future contract work. A fairly careful screening process was undertaken during which both Aerometrics and Dantec (the two manufacturers) conducted demonstrations in our own Low Turbulence Water Tunnel (LTWT). In both instances comparison was made with nuclei distributions measured by our holographic system. We recognized even before these tests that there were some inherent difficulties with the light-scattering method which would require the calibration of these devices against the holographic system. The demonstrations confirmed the need for such calibrations. As a result of these comparative tests of the Aerometrics and Dantec instruments, we decided that the Dantec instrument was better suited for our purposes and proceeded with that purchase. Present and future research on the relationship between the nuclei distributions and the observed cavitation (including the noise) will benefit from this enhanced capability.

Finally, we should mention that the new instrumentation developed during the present program has value not only in studies of bubble cavitation but also in studies of attached cavitation. Publication 14 reported on such measurements which revealed some oscillations of attached cavities which had not been reported previously.

3. ANALYTICAL PROGRAM

Analytical approaches developed as a part of the present program have provided significant insights into the interactions between cavitation bubbles in various contexts. This body of work was presented in publications 1 to 6, 8, 10, and 15 and may be summarized as follows. In any of these flows there exists a parameter $\beta = \alpha L^2 / R^2$ where α is the void fraction of the bubble mixture, L is the typical dimension of the bubbly cloud and R the

typical radius of the bubbles. If β is much smaller than unity, then the bubbles essentially behave as though they were alone in an infinite liquid and the dominant natural frequency in the system is the natural frequency, ω_B, of a single bubble in an infinite liquid. If, however, β is of order unity or larger, then there exist significant modes of oscillation of the system ("cloud" modes) with natural frequencies substantially smaller than ω_B. This is the domain of significant bubble interactions. Indeed, we have shown (publications 4, 5, 6) that when typical damping is introduced, the cloud modes will dominate because, being at lower frequencies, they are more lightly damped than the individual bubble oscillations at ω_B.

The early analytical work (publications 1 to 6) was all concerned with small amplitude, linear oscillations of bubbly clouds having identical bubbles and therefore a single individual bubble natural frequency. Later we developed a methodology to examine some non-linear effects in the dynamics and acoustics of bubbly clouds. Specifically, this analytical approach retains only the non-linear terms which involve quadratic combinations. Publications and, 10 and 15 describe the implementation of this methodology to the case of a bubble fluid bounded by an infinite flat wall oscillating normal to its own plane. Several significant non-linear effects emerge in this example. In particular the oscillations in the wall pressure may be dominated by second and high harmonics of the bubble natural frequency while the bubble volume oscillations continue to be dominated by a response at the fundamental. Not only do the non-linear effects increase with increasing wall motion amplitude, but they also increase with decreasing void fraction, a feature which may be important in the context of low void fraction cavitating flows.

While these non-linear solutions provide instructive initial progress there are a number of ways in which the methodology can be used to shed further light on some of the frequency-dispersion effects which may occur in cavitating flows. For example, the flat wall solution (publications 8 and 10) was obtained for a bubbly mixture in which all the bubbles are identical and therefore there is only one bubble natural frequency. However we have also obtained a solution for the case in which there is a distribution of bubble sizes with, therefore, a spectrum of bubble natural frequencies (publication 15). The non-linear frequency dispersion in this case reveals a phenomenon called "harmonic cascading" in

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which the higher harmonics of oscillation of a few larger bubbles can excite oscillations of a much larger number of smaller bubbles at their fundamental. Secondly, the aforementioned flat wall solution has no cloud natural frequencies as would be the case if the bubble mixture had a finite dimension. Therefore we obtained a solution of the case of a flat wall with a layer of bubbly mixture of finite thickness and examined the non-linear effects in that case (publication 15).

4. PUBLICATIONS

1. d'Agostino, L. and Brennen, C.E. 1983. On the Acoustical Dynamics of Bubble Clouds. Presented at the ASME Cavitation & Multiphase Flow Forum, Houston, TX, June 1983, pp. 72-75.

2. d'Agostino, L., Brennen, C.E. and Acosta, A.J. 1984. On the Linearized Dynamics of Two-Dimensional Bubble Flows over Wave-Shaped Surfaces. ASME Cavitation & Multiphase Flow Forum, p. 8.

3. d'Agostino, L., Brennen, C.E. and Acosta, A.J. 1988. Linearized Dynamics of Two-Dimensional Bubbly and Cavitating Flows over Slender Surfaces. J. Fluid Mechanics, Vol. 192, pp. 485-509.

4. d'Agostino, L. and Brennen, C.E. 1989. Linearized Dynamics of Spherical Bubble Clouds. J. Fluid Mechanics, Vol. 199, pp. 155-176.

5. d'Agostino, L. and Brennen, C.E. 1988. Acoustical Cross-sections of Spherical Bubble Clouds. ASME Cavitation and Multiphase Flow Forum Booklet, pp. 50-53b.

6. d'Agostino, L. and Brennen, C.E. 1988. Acoustical Absorption and Scattering Cross-sections of Spherical Bubble Clouds. J. Acoust. Soc. of Amer., Vol. 84, No. 6, pp. 2126-2134.

7. Brennen, C.E. and Ceccio, S.L. 1989. Recent Observations on Cavitation and Cavitation Noise. Proc. Third ASME Int. Symp. on Cavitation Noise and Erosion in Fluid Systems, F.E.D. Vol. 88, pp. 67-78.

8. Kumar, S. and Brennen, C.E. 1990. Non-linear Effects in Cavitation Cloud Dynamics. ASME Cavitation and Multiphase Flow Forum, Toronto, Canada, June 1990, F.E.D. Vol. 98, pp. 107-113.

9. Ceccio, S.L. and Brennen, C.E. 1990. Observations of the Dynamics and Acoustics of Attached Cavities. ASME Cavitation and Multiphase Flow Forum, Toronto, Canada, June 1990, F.E.D. Vol. 98, pp. 79-84.

10. Kumar, S. and Brennen, C.E. 1991. Non-linear Effects in the Dynamics of Clouds of Bubbles. J. Acoust. Soc. of America, Vol. 89, No. 2, pp. 707-714.

11. Ceccio, S.L. and Brennen, *C.E. 1990*. The Dynamics and Acoustics of Travelling Bubble Cavitation. Proc. Eighteenth Symp. on Naval Hydrodynamics, Ann Arbor, MI, Aug. 1990, pp. 87-104.

12. Ceccio, S.L. and Brennen, C.E. 1991. Observations of the Dynamics and Acoustics of Travelling Bubble Cavitation. J. Fluid Mech. (submitted).

13. Kumar, S. and Brennen, C.E. 1991. Statistics of Noise Generated by Travelling Bubble Cavitation. ASME Cavitation and Multiphase Flow Forum, Portland, OR, FED Vol. 109, pp. 55-62.

14. Ceccio, S.L. and Brennen, C.E. 1991. Dynamics of Attached Cavities on Bodies of Revolution. ASME J. Fluids Eng. (submitted).

15. Kumar, S. and Brennen, C.E. 1991. An Acoustical Study of Travelling Bubble Cavitation (to be submitted for publication).

16. Kumar, S. and Brennen, C.E. 1991. Some Non-linear Interactive Effects in Bubble Cloud Cavitation (to be submitted for publication).

5. PERSONNEL

Professors C. E. Brennen and A. J. Acosta were co-Principal Investigators on this contract which also supported and helped educate a number of graduate students. Luca d'Agostino is now a professor at the University of Pisa in Italy. Steven L. Ceccio is an assistant professor at the University of Michigan. Sanjay Kumar is about to receive his Ph.D. degree and will be spending a year as a postdoc with Professor Fruman in Paris. Yan Kuhn de Chizelle is still a graduate student who will be participating in the tests which Professors Ceccio and Brennen will be conducting in the Large Cavitation Channel in Memphis in the near future.

6. LIST OF PRESENTATIONS OF RESULTS

List of Papers Published in Refereed Journals:

1. d'Agostino, L., Brennen, C.E. and Acosta, A.J. 1988. Linearized Dynamics of Two-Dimensional Bubbly and Cavitating Flows over Slender Surfaces. J. Fluid Mechanics, Vol. 192, pp. 485-509.

2. d'Agostino, L. and Brennen, C.E. 1989. Linearized Dynamics of Spherical Bubble Clouds. J. Fluid Mechanics, Vol. 199, pp. 155-176.

3. d'Agostino, L., Brennen, C.E. and Acosta, A.J. 1988. Linearized Dynamics of Two-Dimensional Bubbly and Cavitating Flows over Slender Surfaces. J. Fluid Mechanics, Vol. 192, pp. 485-509.

4. d'Agostino, L. and Brennen, C.E. 1989. Linearized Dynamics of Spherical Bubble Clouds. J. Fluid Mechanics, Vol. 199, pp. 155-176.

5. Kumar, S. and Brennen, C.E. 1991. Non-linear Effects in the Dynamics of Clouds of Bubbles. J. Acoust. Soc. of America, Vol. 89, No. 2, pp. 707-714.

6. Ceccio, S.L. and Brennen, C.E. 1991. Observations of the Dynamics and Acoustics of Travelling Bubble Cavitation. To appear in J. Fluid Mech.

List of Non-Refereed Publications:

1. d'Agostino, L. and Brennen, C.E. 1983. On the Acoustical Dynamics of Bubble Clouds. Presented at the ASME Cavitation and Multiphase Flow Forum, Houston, TX, June 1983, pp. 72-75.

2. d'Agostino, L, Brennen, C.E, and Acosta, A.J. 1984. On the Linearized Dynamics of Two-Dimensional Bubble Flows over Wave-Shaped Surfaces. ASME Cavitation and Multiphase Flow Forum, pp. 8   .

3. d'Agostino, L. and Brennen, C.E. 1988. Acoustical Cross-sections of Spherical Bubble Clouds. ASME Cavitation and Multiphase Flow Forum Booklet, pp. 50-53b.

4. Brennen, C.E. and Ceccio, S.L. 1989. Recent Observations on Cavitation and Cavitation Noise. Third ASME Int. Symp. on Cavitation Noise and Erosion in Fluid Systems, F.E.D. Vol. 88, pp. 67-78. (Invited paper)

5. Kumar, S. and Brennen, C.E. 1990. Non-linear Effects in Cavitation Cloud Dynamics. ASME Cavitation and Multiphase Flow Forum, Toronto, Canada, June 1990, F E.D. Vol. 98, pp. 107-113.

6. Ceccio, S.L. and Brennen, C.E. 1990. Observations of the Dynamics and Acoustics of Attached Cavities. ASME Cavitation and Multiphase Flow Forum, Toronto, Canada, June 1990, F.E.D. Vol. 98, pp. 79-84.

7. Ceccio, S.L. and Brennen, C.E. 1990. The Dynamics and Acoustics of Travelling Bubble Cavitation. Proc. Eighteenth Symp. on Naval Hydrodynamics, Ann Arbor, MI, Aug. 1990, pp. 87-104. (Invited paper)

8. Kumar, S. and Brennen, C.E. 1991. Statistics of Noise Generated by Travelling Bubble Cavitation. ASME Cavitation and Multiphase Flow Forum, Portland, OR, June 1991, F.E.D. Vol. 109, pp. 55-62.

List of Invited Presentations:

1. Brennen, C.E. and Ceccio, S.L. 1989. Recent Observations on Cavitation and Cavitation Noise. Invited Keynote Paper at Third ASME Int. Symp. on Cavitation Noise and Erosion in Fluid Systems.

2. Ceccio, S.L. and Brennen, C.E. 1990. The Dynamics and Acoustics of Travelling Bubble Cavitation. Invited paper at Eighteenth Symp. on Naval Hydrodynamics, Ann Arbor, MI, Aug. 1990, pp. 87-104.

List of Conference Presentations:

1. d'Agostino, L. and Brennen, C.E. 1983. On the Acoustical Dynamics of Bubble Clouds. Presented at the ASME Cavitation and Multiphase Flow Forum, Houston, TX, June 1983.

2. d'Agostino, L., Brennen, C.E. and Acosta, A.J. 1984. On the Linearized Dynamics of Two-Dimensional Bubble Flows over Wave-Shaped Surfaces. Presented at ASME Cavitation and Multiphase Flow Forum.

3. d'Agostino, L. and Brennen, C.E. 1988. Acoustical Cross-sections of Spherical Bubble Clouds. Presented at ASME Cavitation and Multiphase Forum Booklet.

4. Brennen, C.E. and Ceccio, S.L. 1989. Recent Observations on Cavitation and Cavitation Noise. Invited keynote paper at Third ASME Int. Symp. on Cavitation Noise and Erosion in Fluid Systems.

5. Kumar, S. and Brennen, C.E. 1990. Non-linear Effects in Cavitation Cloud Dynamics. Presented at ASME Cavitation and Multiphase Flow Forum, Toronto, Canada, June 1990.

6. Ceccio, S.L. and Brennen, C.E. 1990. Observations of the Dynamics and Acoustics of Attached Cavities. Presented at ASME Cavitation and Multiphase Flow Forum, Toronto, Canada, June 1990.

7. Ceccio, S.L. and Brennen, C.E. 1990. The Dynamics and Acoustics of Travelling Bubble Cavitation. Invited paper, Eighteenth Symp. on Naval Hydrodynamics, Ann Arbor, MI, Aug. 1990.