UNIVERSITY OF MICHIGAN
DEPARTMENT OF MECHANICAL ENGINEERING
CAVITATION AND MULTIPHASE FLOW LABORATORY

UMICH-014456-1-PR

Progress Report No. 1

Period: 1 March - 1 June, 1976

by

Frederick G. Hammitt

Supported by Office of Naval Research

Contract No. NOO14-77-C067

Ann Arbor, Michigan

May 18, 1976

The initial 3-month project period has been to some extent a transition from our related work on sodium cavitation in our vibratory system (supported by an ERDA contract) which is terminating shortly, to more basic studies in water, as required by our new ONR contract. For both the sodium and the water work, we are attempting as a first step to develop a mechanical damage "predicting-capability" by counting and quantifying as to impulse delivered (to a microhydrophone in vicinity of damaged specimens) the bubble collapse pressure pulses in the cavitating field.

The results initially obtained in water under the ERDA contract resulted in a statistically good correlation ($\lesssim$ 25% standard error) of the type:

$$MDPR = C_1 \text{ (Area)} - C_2$$

where Area = area under curve of integrated pulse-count energy-spectrum, ie,

$$\text{Area} = \int_{E=0}^{E=\infty} N(E)dE \ .$$

N(E) is number of pulses of energy E per unit energy interval (as measured by electronic pulse counter), and dE is energy interval.

C_1 is an amplitude constant directly relating "Area" and MDPR, and C_2 represents a threshold damage energy. It is encouraging to note that a relatively good correlation was obtained for these relatively crude and preliminary results, for energy integral to first power, as would be expected from

the simplest possible damage model. These tests covered a relatively large range of liquid temperature and static pressure, with all data being correlated by the same equation.

The sodium data, also over a large range of pressure and temperature, is still being reduced. However, a similar correlation appears again to exist for sodium.

Under the ONR contract we have constructed a bench-type facility for correlating the microhydrophones and electronic "chain" used, so that a direct relation between cavitation bubble collapse pulse delivered impulse, and electronic counter output will be available. Known impulse is delivered to the probes by a small "hammer" arrangement. No final data is yet available from this bench correlation facility, but hopefully will be obtained during the next report period.

While high-temperature of sodium required "wave-guide" probes which are certainly not ideal, we plan to use direct probes in the ONR work in water. We also plan to improve the electronic components in the near future. We will then calibrate all probes, as well as original and improved "electronic chain", in the bench calibration facility.

For the ONR contract, we plan very soon to also commence similar pulse-count energy spectrum damage tests in our "high-speed water tunnel" (venturi facility with $\sim$ 65 m/s maximum velocity capability). While work accomplished in our vibratory facility used only 304 SS, we plan to continue with this material, but also soft aluminum in the water tunnel. Individual pit counts will be correlated with pulse-count energy spectra, as will MDPR (mean depth of penetration rates).

Eventually other materials will be introduced into the program for both vibratory and venturi system to investigate the relative-intensities of corrosion and mechanical attack under different flow and material parameter combinations. For these tests it is planned that the effects of anodic and cathodic currents can be studied to try to understand more clearly the inter-relations between chemical and mechanical attack in different types of laboratory facilities, so that eventual realistic prediction of anticipated field results from laboratory tests will be possible.

University of Michigan
Department of Mechanical Engineering
Cavitation and Multiphase Flow Laboratory

Progress Report No. 2

Period: 1 June - 1 September, 1976

UMICH-014456-2-PR

by

Frederick G. Hammitt

Supported by: Office of Naval Research
Contract No. N00014-76-C-0697

Ann Arbor, Michigan

August 25, 1976

I. INTRODUCTION

This document (Progress Report No. 2) covers our work under ONR Contract No. N0014-77-C067 for the period from June 1 through September 1, 1976.

The major activity during this period was included in the preparation and submission of an "Internal Report", ERI Report 014456-1-I to ONR covering our calibration of pressure transducer microprobes for the counting and quantifying of cavitation bubble collapse pulses in damaging cavitation regimes to provide cavitation bubble collapse spectra for eventual generation of erosion rate predicting relations of the general form

$$MDPR = f(\text{Spectrum Area}) \qquad (1)$$

where Spectrum Area is the area under a bubble collapse pulse spectrum of pulse number vs. energy, as described in our previous reports (1, eg) and proposal. Spectrum Area is here proportional to total bubble collapse pulse area in the cavitating region where damage is to be produced. In addition to erosion rate predicting equations of the form of Eq. (1), this measurement will allow also a computation of the "efficiency" of the delivery of energy to the damaged surface from the region of bubble collapse as compared with the energy operative in the erosion process. This latter, according to most previous work, can best be expressed in the form of an Ultimate Resilience, i.e., "strain energy to failure", if failures are of brittle (rather than ductile) nature. Such a relation would then be of the form:

$$\text{Spectrum Area} = C \cdot \eta \cdot UR \qquad (2)$$

where C is a constant involving the calibration constant for the probe, η is the "efficiency" sought, and UR is ultimate resilience (or other selected material parameter. If η were known for a class of cavitation regimes, then MDPR could be calculated from the pulse count measurement. The long-sought damage predicting ability from an easily done external measurement would then be in hand, and one of the major objectives of our present work accomplished.

II. WORK ITEMS PERFORMED

A. Preparation and Submission of Probe Calibration Report and Related Experiments

Microprobes of two distinct types for the measurement and counting of cavitation bubble collapse pulses are to be used in this ONR project, which will benefit from related previous work accomplished in high-temperature sodium for Argonne National Laboratory (2, eg). While a "direct submergence" acoustic microprobe, i.e., sensitive element submerged in fluid, is no doubt ideal for this work, such probes suitable for high-temperature sodium are not generally available. For this reason, a "wave-guide" type of probe where the active element is not in the hostile environment, but rather at the opposite end of a stainless steel rod (12-inch length in our case) was necessary for the sodium tests. However, future water tests for our ONR contract will preferably use direct submergence probes, such as the Kistler probe, or a special design which we have developed here under our ONR contract. Thus it was necessary to develop a method of calibrating, against measured input energy, probes of both of these types.

For this purpose we have used a pendulum-hammer device from which the input potential energy can be easily computed. We have then utilized the same electronic chain for measuring pulse count spectra that was used in the sodium cavitation experiments, and can also be used for the coming water tests. The results of this correlation of several probes (Kistler, U-M direct submergence, U-M wave guide) is detailed in our "internal report" (3). The calibration of thes probes, reduction and analysis of the data, and the preparation and submission of the "internal report" (3) has been accomplished during the present report period.

B. Design, Fabrication, Calibration of U-M Direct Submergence Pressure Pulse Microprobe

A direct submergence pressure micro-transducer, suitable for temperatures to ~500°C, and hence suitable for high temperature tests in almost any fluid, has been designed, fabricated, and calibrated with pendulum-hammer device previously discussed, during the present report period. The performance of this "U-M Direct Submergence" probe appears to be good, so that it can be used along with a standard Kistler probe in our forthcoming water experiments.

C. Component Design and Fabrication for ONR Venturi Tests

Our previous pulse-count spectrum cavitation damage tests in both sodium and in water for Argonne were all performed in our vibratory facility, over a relatively extensive temperature and suppression pressure range for both fluids. It is now our intension for the ONR contract to emphasize similar tests in a flowing venturi facility with water as the basic test fluid. Some tests, where it appears particularly desirable, will continue to be of the vibratory type. However, for added realism and applicability to field systems, it is planned to conduct the next series of tests in our venturi tunnel system suitable for up to ~200 f/s, (U-M High-Speed Water Tunnel (4)). While this has been used extensively in past years, it has not been utilized recently, so that some preparatory work was necessary for its reactivation. This has been accomplished to a large extent during the present report period.

In addition, some design and fabrication of test components to allow installation of suitable damage test specimens and microprobes (previously discussed) has been necessary. This was accomplished during the present report period. Venturi damage tests are to be made using damage specimens with geometry and location entirely symmetrical to the acoustic probes, in the diffuser portion of the venturi. Initial damage tests will be made with soft aluminum and for very

short durations, so that bubble collapse pulse counts and crater formation can be correlated. Later tests will include stronger materials and longer durations. Test parameters to be studied include velocity and degree of cavitation. Only slight temperature variation is possible in this facility.

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UNIVERSITY OF MICHIGAN
DEPARTMENT OF MECHANICAL ENGINEERING
CAVITATION AND MULTIPHASE FLOW LABORATORY

Progress Report No. 3

Period: 1 September - 1 December, 1976

UMICH-014456-3-PR

by

Frederick G. Hammitt

Supported by: Office of Naval Research

Contract No. N0001 4-76-C-0697

Ann Arbor, Michigan

November 20, 1976

I. INTRODUCTION

This document (Progress Report No. 3) covers our work under ONR Contract No. N00014-76-C-0697 for the period from September 1 through December 1, 1976.

Project activity during the present report period involved operations both in our vibratory damage facility and in our High-Speed Water Tunnel (1). In addition, an "internal report" for submission to the coming I.Mech.E. Conference on "Scaling for Performance Prediction in Rotodynamic Machines", 6-8 September, 1977, at the University of Stirling, U.K., was prepared and submitted (2). This document includes portions of our work during the present report period, as well as related previous work. It advances particularly the concept of "cavitation erosion efficiency", η_{cav} (3) relating measured bubble collapse spectrum acoustic power to measured "erosion power", i.e., the product of volume loss rate and material volumetric failure energy, as described, eg., by "ultimate resilience", UR. We believe that this is an essentially new concept from the viewpoint of à priori prediction of eventual cavitation erosion rates in laboratory and field devices from instantaneous essentially acoustic measurements.

II. WORK ITEMS PERFORMED

A. Corrosive and Mechanical Damage Effects

One of the primary objectives of the present project is to further elucidate the relation between corrosive and mechanical cavitation damage effects in laboratory and field devices. It is the present lack of knowledge in this area primarily, which prevents the reliable prediction of field damage rates from conventional

"accelerated" laboratory cavitation damage tests, in which the mechanical aspect is normally substantially emphasized. Our development of the bubble collapse pulse-count spectrum technique will hopefully allow reliable measurement of the mechanical portion of the overall cavitation damage attack, which is not at present possible. To verify these pulse count results, it is, however, necessary to provide damage data where the relation between corrosive and mechanical intensities is varied for a range of materials. We are attempting to provide this information from our vibratory facility tests next described.

The mechanical intensity can be varied in a vibratory facility by varying either horn amplitude or suppression pressure, and we intend to investigate both effects in the near future. The corrosive intensity can be varied by utilizing different fluids, or perhaps by applying anodic or cathodic potentials. We intend to apply this latter effect in the future, but for the moment we are investigating the effect of a substitution of "synthetic sea water" (2.4 %NaCl addition by mass to tap water), chosen for maximum interest to ONR, for ordinary tap water for 3 test materials: aluminum 1100-0, 304 stainless steel, and 1018 carbon steel (cold-rolled). We presume that the carbon steel will show maximum sensitivity to corrosive attack, the stainless steel minimum, and soft aluminum intermediate. The results to date (Fig. 1) confirm this expectation.

Two atmospheres compressed air were used for cover gas for these tests* which were conducted at ~26 °C, so that the gas content is approximately saturation for these conditions. We later intend

*1.5 mil (38 μm) double amplitude.

to investigate the effect of an inert cover gas such as argon, thus eliminating to a large extent the dissolved and entrained oxygen.

The pulse-count data for the above condition was obtained earlier, but will be verified in more detail at a later date, once the pulse count technique and instrumentation have been further refined in our venturi tests described next.

B. Tunnel Venturi Tests

Additional work has been necessary during the present report period to complete water tunnel "shake-down" for the purposes of the present program so that operation over the full range of velocity, pressure, and gas content would be possible. In addition the instrumentation for bubble collapse pulse counting has been further refined to include a "pulse-shaper", necessary to suppress pressure fluctuations after an initial bubble collapse impulse so that a meaningful count of such pulses can be made. Figure 2 shows oscilloscope photos of typical probe output from the U-M micro-probe pressure transducer described before (3), comparing results with and without pulse-shaper.

Figures 2 and 3 show typical probe output from the venturi cavitating field. The duration of a single pulse from this data is 1-4 μs, as would be expected theoretically, and from earlier high-speed bubble collapse photos (4). Thus the time response of the U-M probe is adequate for the present purpose.

Figures 2 and 3 also show the variation of pulse strengths for these random samplings. The high narrow peaks shown represent

presumably the more energetic bubble collapse pulses primarily responsible for cavitation damage. Figure 4 shows a pulse-count spectrum obtained earlier (5) in the present venturi, using a Kistler probe, pulse-shaper, and multichannel analyzer. However, absolute calibrations for this data are not available. It is the immediate objective of the present program to obtain new similar data, which can be reduced to terms of absolute energies, and correlated with measured damage data obtained under the same flow conditions. This will allow calculation and evaluation of a "cavitation erosion efficiency" as previously explained (2,3), and the eventual à priori prediction of eventual damage rates from these "acoustic" measurements.

II. CONCLUSIONS

Cavitation damage vibratory facility tests upon three materials of varying degrees of susceptibility to corrosive tacck (alum., C/S, SS) have been completed in both synthetic sea water and conventional tap water, at a particular suppression pressure and temperature. Thus two degrees of corrosivity (fresh water and salt water) have been investigated upon 3 materials using one mechanical intensity. The pulse count spectrum for this condition was also measured, but new more refined measurements of this type will be made later. In addition, different mechanical effects will be investigated by varying horn amplitude, suppression pressure, temperature, and cover gas, i.e., the effect of an inert cover gas such as argon will be compared with results from the present tests with air.

The characteristics of the bubble collapse pulse as encountered in a flowing system (venturi) have been investigated with our new (U-M) microprobe, developed under this project (3). Their duration has been found to be $\sim$ 1-4 μs, as expected on theoretical grounds and also previous bubble photographic results. This verifies the suitability of the U-M probe, which is suitable for high temperature $\sim$ 1000°F, for the present research. Thus later direct comparison with liquids such as high-temperature sodium will be possible. The probe output, combined with suitable presently available electronic components, including a high-pass frequency filter and pulse shaper, can then be counted and measured as to amplitude to provide the desired bubble collapse pulse spectrum for calibration with measured damage rates in the same system. Our previous results of this type did not employ the new U-M probe, but rather a "wave-guide" probe for high temperatures, and a commercial Kistler probe, not suited to high temperature operation, for low temperature water tests.

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5. O. Ahmed and F. G. Hammitt, "Pressure Pulse Distribution from Cavitation Collapse", ORA Rept. No. UMICH 013503-2-I, March 1975.

FIGURES

1.(a) Weight Loss vs. Time for Aluminum 1100-0, C/S 1018, and SS 304 in Tap Water and Artificial Sea Water, and (b) SS 304 alene.

2. Oscilloscope Output from U-M Probe in Venturi (a) with and (b) without Pulse-Shap

3. Oscilloscope Output from U-M Probe in Venturi; (no Pulse-Shaper).

4. Spectrum of Pressure Pulses from Venturi.

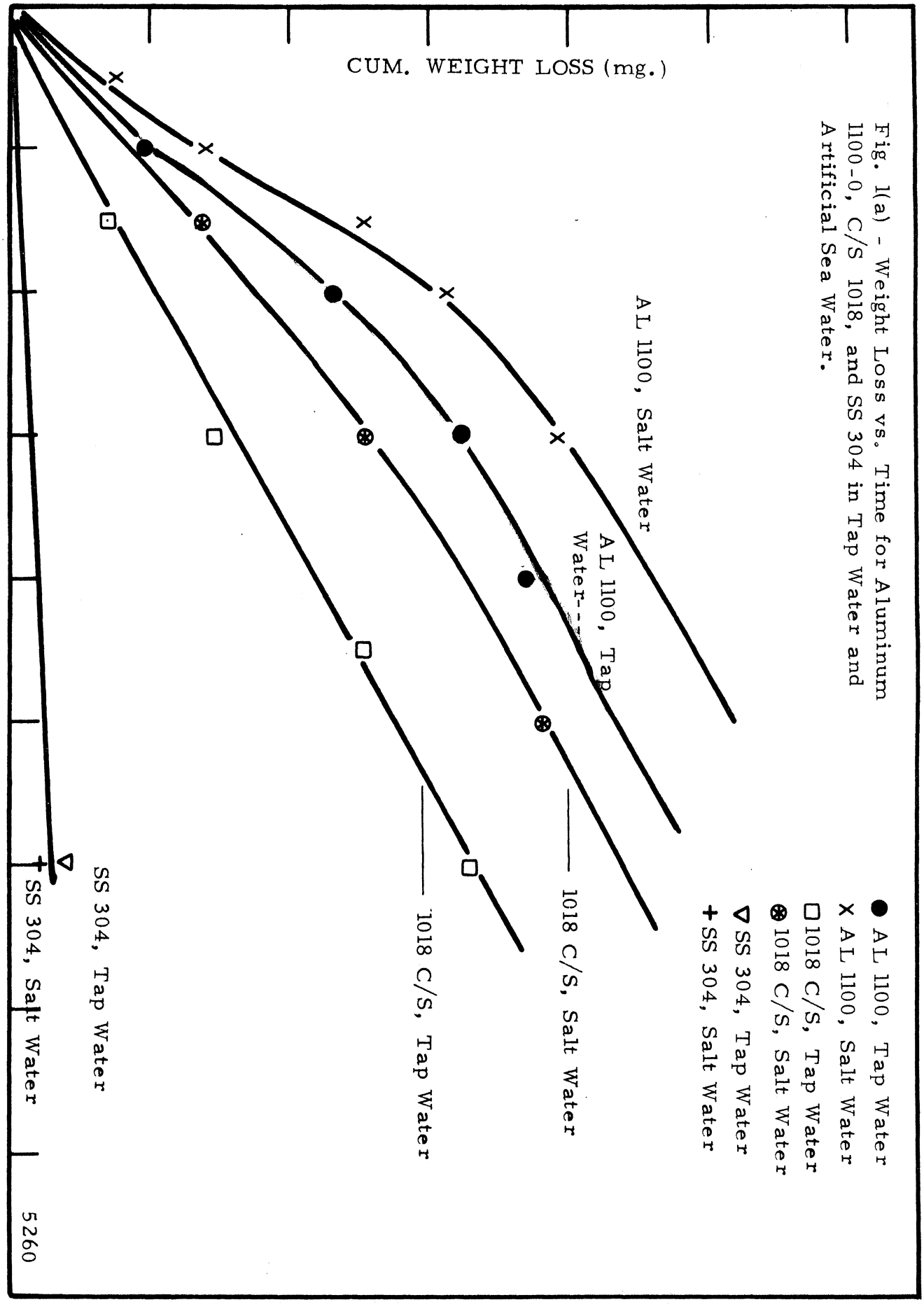
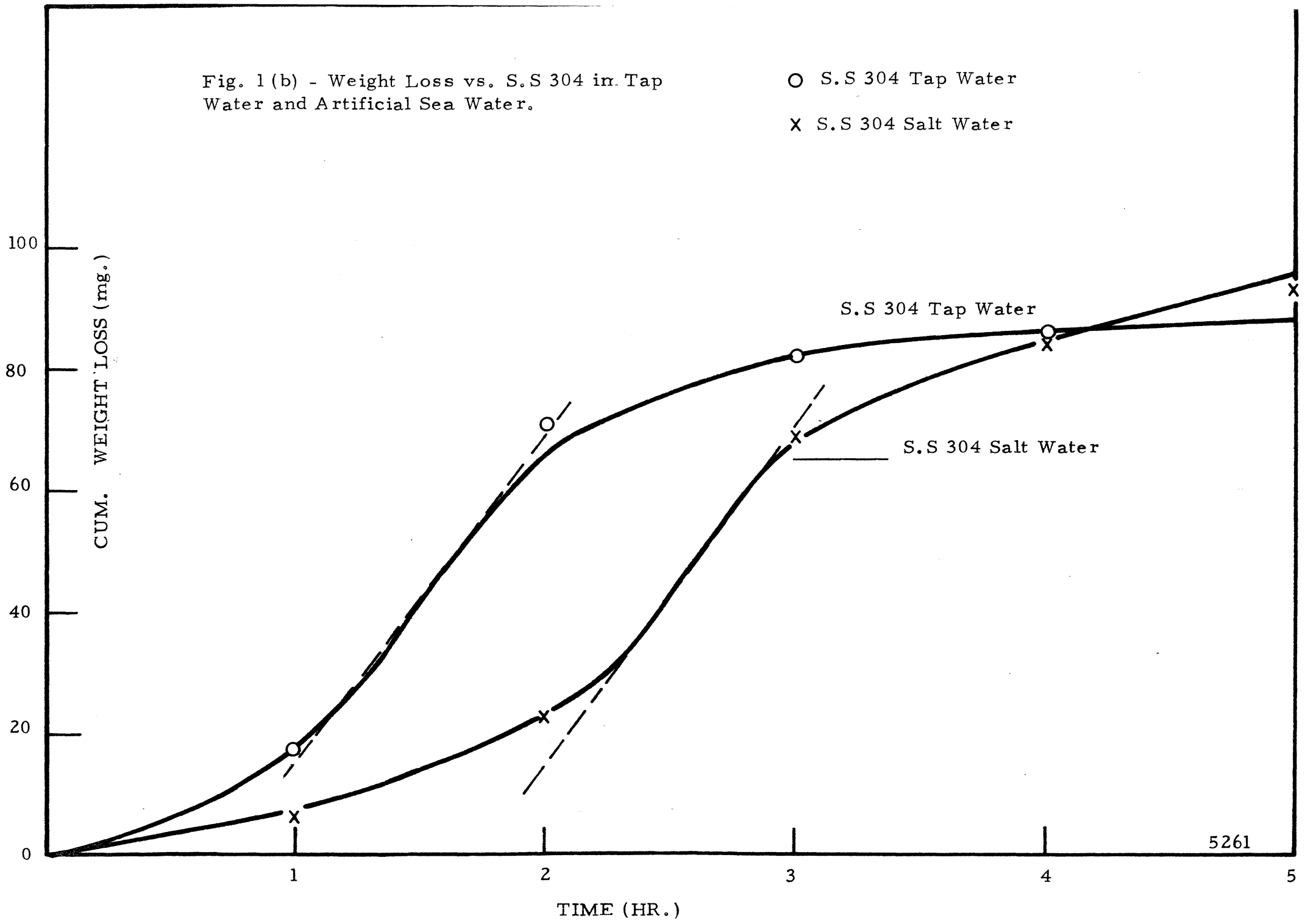


Fig. 1(a) - Weight Loss vs. Time for Aluminum 1100-0, C/S 1018, and SS 304 in Tap Water and Artificial Sea Water.

Fig. 1 (b) - Weight Loss vs. S.S 304 in Tap Water and Artificial Sea Water.



"Errata for Progress Report No. 3"

(Univ. of Michigan)

"Legends for Figures 2 and 3 are interchanged"

Contract No. N00014-76-C-0697

F. G. Hammitt, Principal Investigator

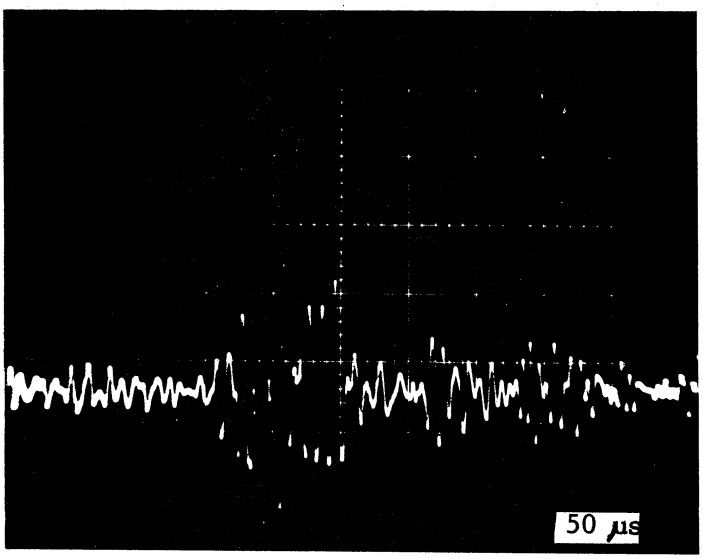


Fig. 2 - Oscilloscope Output from U-M Probe in Venturi (a) with and (b) without Pulse-Shaper.

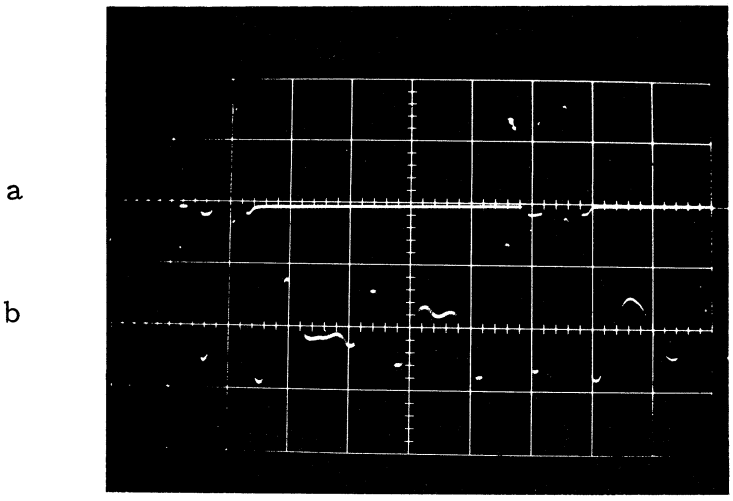


Fig. 3 - Oscilloscope Output from U-M Probe in Venturi, (no Pulse-Shaper).

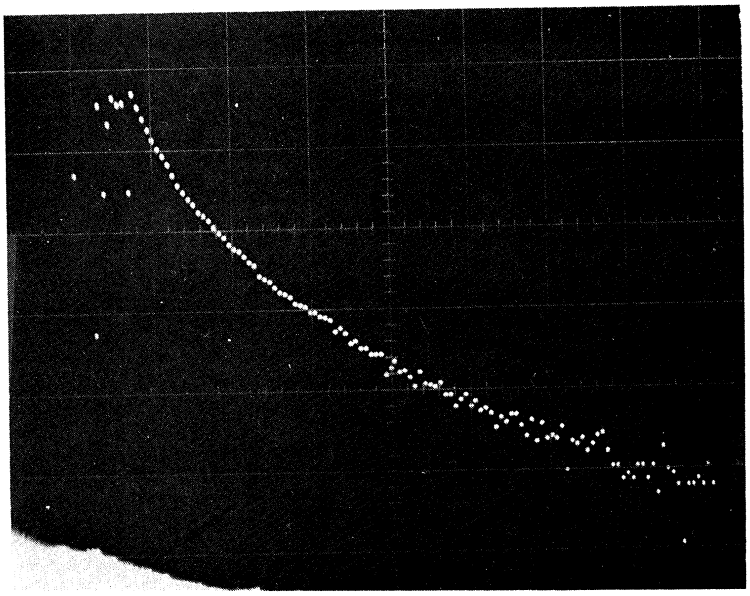


Fig. 4 - Spectrum of Pressure Pulses from Venturi.

Progress Report No. 4

Period: 1 December, 1976 to 1 March, 1977

UMICH 014456-4-PR

by Frederick G. Hammitt

Supported by: Office of Naval Research
Contract No. N00014-76-C-0697

Ann Arbor, Michigan
February 22, 1977

I. INTRODUCTION

This document (Progress Report No. 4) covers our work under ONR Contract No. N00014-76-C-0697 for the period December 1, 1976 through March 1, 1977.

Progress was made during the present report period in three areas:

(1) Cavitation erosion tests in vibratory facility over a range of mechanical intensities (amplitudes and suppression pressures) in both synthetic sea water and tap water over a range of test temperatures, designed to separate mechanical from corrosion erosion effects.

(2) Bubble collapse pulse spectrum measurements in venturi facility

(3) Calibration of microprobes in terms of pressure vs emf. Both direct submergence and wave guide probes are involved.

Further details are given in the following.

II. WORK ITEMS PERFORMED

A. Vibratory Facility Damage Tests

As indicated in our previous progress reports, it is our overall plan for the vibratory facilty to measure cavitation damage resistence of three materials in terms of maximum damage rate (MDPR) and incubation period, at varying degrees of cavitation mechanical intensity (horn amplitude and/or suppression pressure) in both tap water and synthetic sea water as a function of liquid temperature. The materials, chosen for varying degrees of corrodibility, are 304 stainless steel, 1020 carbon steel, and 1100-0 aluminum. Tests for these three materials over the temperature range $\sim$80-220°F at 2 and 3 bar suppression pressure and at horn double amplitude of 1.5 mil, are now about one-half complete. These tests will continue during the coming report period. It is planned also to conduct similar tests at 1.0 mil double amplitude. Thus four distinct mechanical amplitudes will be eventually available for the 3 materials over the pertinent temperature range in both synthetic sea water and tap water.

The mechanical amplitudes will be eventually "measured" by measuring the bubble collapse pulse count spectra for the vibratory facility cavitation conditions used. A direct-submergence probe will be used for this purpose. It will then, we hope, be possible to separate the mechanical from corrosive components of the overall erosion for these tests, and to correlate the mechanical damage rate with the measured pulse count spectra.

B. Tunnel Venturi Tests

A series of bubble collapse pulse spectra have been made in our water tunnel venturi facility for various velocities and cavitation conditions. Total gas content for these tests was approximately constant and was measured by Van Slyke.

It is planned to continue this pulse count survey over approximately the full range of flow velocities and cavitation conditions obtainable with this facility. At this time the survey is approximately one-half complete. After completion of the pulse count survey, damage tests will be made with selected materials, so that a correlation between damage rate and pulse count spectra can be obtained for this flowing facility. This correlation will then be compared with those obtained from the vibratory facility to attempt to develop more generalized correlations with wider demonstrated applicability.

The present venturi pulse count spectra have been obtained with two direct submergence microprobes symmetrically positioned at the point where cavitation damage rate will later be measured. These pulse count spectra have been obtained "manually" to guarantee the greatest degree of precision in the measurment of the characteristics of the individual bubble collapse pulses, i.e., the data has been obtained by direct oscilloscope pictures of probe emf output without "pulse-shaping". Counts of amplitude vs. number of pulses is then obtained by direct examination and tabulation of the data from the scope photos. This very careful processing of the probe output data results also in the ability of recognizing those components of the output which result from the probe characteristics rather than those of the collapsing bubbles, such as probe "ringing" behavior, etc. It is hoped eventually to automate the techniques, and then obtain the required pulse counts by multi-channel analyser However, before designing suitable pulse-shaping circuitry it is first necessar to know closely the pulse characteristics involved, and that is the secondary purpose of our present procedure.

C. Probe Calibration

A facility for comparing probe outputs in the oscillating pressure field induced by our vibratory horn has been developed and used to "calibrate" our U-M direct submergence probe against a commercial direct-submergence Kistler probe, for which output in emf vs. fluid pressure oscillation is known. It is also planned to so calibrate our wave-guide probes against these direct submergence probes, so that studies previously completed in our vibratory facility in liquid sodium, using wave-guide probes, can be directly compared with the present water results.

Progress Report No. 5

Period: 1 March, 1977 to 1 June, 1977

UMICH 014456-5-PR

by Frederick G. Hammitt

Supported by: Office of Naval Research

Contract No. N00014-76-C-0697

Ann Arbor, Michigan

February 22, 1977

I. INTRODUCTION

This document (Progress Report No. 5) covers our work under ONR Contract No. N00014-76-C-0697 for the period March 1, 1977 through June 1, 1977.

Progress was made during the present report period in three areas:

(1) Cavitation erosion tests in vibratory facility over a range of mechanical intensities (amplitudes, temperatures, and suppression pressures) in both synthetic sea water and tap water over a range of test temperatures, designed to separate mechanical from corrosion erosion effects.

(2) Bubble collapse pressure pulse height spectrum and damage rate measurements in venturi facilities.

(3) Calibration of microprobes in terms of pressure vs. emf. Both direct submergence and wave guide probes are involved.

Details are given in the following.

II. WORK ITEMS PERFORMED

A. Vibratory Facility Damage Tests

As previously indicated, it is our overall plan for the vibratory facility to measure cavitation damage resistence of three materials in terms of maximum damage rate (MDPR) and incubation period, at varying degrees of cavitation mechanical intensity (horn amplitude, temperature and/or suppression pressure) in both tap water and synthetic sea water as a function of liquid temperature. The materials, chosen for varying degrees of corrodibility, are 304 stainless steel, 1018 (cold-rolled) carbon steel, and 1100-0 aluminum. A test matrix for these three materials over the temperature range 27°C-104°F ($\sim$80-220°F) at 2 and 3 bar suppression pressure, and at horn double amplitude of 1.5 mil, and has been completed.

This data has been reduced (1) to show the dependence of maximum MDPR ratios between fresh and salt water results upon temperature and maximum MDPR itself. A substantial dependence of these ratios upon these parameters was found. In addition, the relation between incubation period and maximum MDPR was investigated. For the entire scope of the tests, a generally inverse

relationship between these parameters was found, as would be intuitively expected. However, for the individual material sets, the relationship appears to be in the opposite sense to that expected intuitively. Of course, this may be due to the influence of changing corrosive effects in these tests. Much further evaluation and testing are apparently necessary before any definitive conclusions be drawn in these regards.

Additional tests will continue at reduced amplitude to further investigate effects of reduced intensity. Thus four distinct mechanical amplitudes will be eventually available for the 3 materials over the pertinent temperature range in both synthetic sea water and tap water.

The mechanical amplitudes will be eventually "measured" by measuring the bubble collapse pulse count spectra for the vibratory facility cavitation conditions used. A direct-submergence probe will be used for this purpose. It will then, we hope, be possible to separate the mechanical from corrosive components of the overall erosion for these tests, and to correlate the mechanical damage rate with the measured pulse count spectra.

B. Tunnel Venturi Tests

Bubble collapse pressure pulse height spectra tests have been continued in our water tunnel venturi facility for various velocities and cavitation conditions. Total gas content for these tests was approximately constant and measured by Van Slyke. A report (2) describing the operation of this instrument was written.

As previously indicated it is planned to continue this pulse height spec analysis over approximately the full range of flow velocities and cavitation conditions obtainable with our facility. The initial survey is now nearly complete, and damage tests on soft aluminum have been started. The use of other mater is also planned, so that an eventual correlation between damage rate and pul count spectra can be obtained for this flowing facility. This correlation will then be compared with those obtained from the vibratory facility to attempt to develop more generalized correlations with wider demonstrated applicability.

The present venturi pulse count spectra have been obtained with two dire submergence microprobes symmetrically positioned at the same axial position, where cavitation damage rate is also measured. These pulse count spectra ha been obtained "manually" to guarantee the greatest degree of precision in th measurement of the characteristics of the individual bubble collapse pulses, i.e., the data has been obtained by direct oscilloscope pictures of probe en

output without "pulse-shaping". Counts of amplitude vs. number of pulses are then obtained by direct examination and tabulation of the data from the scope photos. It is hoped eventually to automate the techniques, and then obtain the required pulse height spectrum using a multichannel analyzer. However, before designing suitable pulse-shaping circuitry, it is first necessary to know closely the pulse characteristics involved, and that is the secondary purpose of our present procedure. Much progress toward attainment of this secondary objective has been made during the present report period. This is summarized in refs. 3 and 4, which, along with ref. 2, were prepared as "term papers" in partial fulfillment of the course ME 490, and also used as "internal reports" for this project. Direct supervision of the work was by M. K. De*. It is planned to summarize the most significant portions of these results in an article for the coming ASTM symposium on "Erosion: Prevention and Useful Applications", Vail, Colorado, Oct. 24-26, 1977.

Measurements to date (3,4) show the detailed characteristics of the bubble collapse pulses obtained in the venturi for a typical cavitation condition. These results were obtained by both our own (U-M probe) and a commercial (Kistler) probe, with very similar results. Calibration between these probes, along with "wave-guide" probes, is being obtained in another facility. The results have shown that the natural frequency of each probe is $\sim$ 0.1 MHz, and that the duration of a typical pulse group is $\sim$ 30 μs. Hence, the time response of the probes is reasonably adequate to the purpose.

C. Probe Calibration

A facility for comparing probe outputs in the oscillating pressure field induced by our vibratory horn has been developed and is available to "calibrate" our U-M direct submergence probe against a commercial direct-submergence Kistler probe, for which output in emf vs. fluid pressure oscillation is known. These calibrations, including our wave-guide probes used in our previous vibratory tests with liquid sodium, are now nearing completion.

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*Mr. De will continue to supervise this work in fulfillment of his Ph.D. dissertation requirements.

The University of Michigan
Department of Mechanical Engineering
Cavitation and Multiphase Flow Laboratory

Progress Report No. 6
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by Frederick G. Hammitt
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I. INTRODUCTION

This document (Progress Report No. 6) covers our work under ONR contract No. N00014-76-C-0697 for the period June 1, 1977 through September 1, 1977.

Progress was made during the present report period in three areas: (1) Cavitation erosion tests in our sealed vibratory facility over a range of "mechanical" intensities generated by variation of the experimental independent variables of horn amplitude, liquid temperature, and suppression pressure. Horn frequency is fixed at 20 kHz. To vary relative corrosive effects, tests were conducted in both Ann Arbor tap water and in synthetic sea water, with composition approximately following ASTM Standard No. D1141-52. These tests are designed to produce data separating mechanical from corrosive erosion effects. It is hoped that the mechanical component of this damage can be measured (and predicted) by bubble collapse pressure pulse height spectra. The further development of this technique is the objective of the two following project sub-areas. (2) Bubble collapse pressure pulse height spectrum and damage measurements in U-M high-speed water-tunnel facility in cavitating venturi geometry. (3) Calibration in cavitating field of several direct submergence and wave-guide pressure microprobes in terms of applied pressure vs. output emf. Most of the required work of this type has been completed.

II. WORK ITEMS PERFORMED

A. Vibratory Facility Damage Tests

As indicated in our last Progress Report (No. 5), it is our overall plan for the vibratory facility to measure cavitation damage resistance, in terms of maximum MDPR and incubation period, of three materials: 304 stainless steel, 1018 (cold-rolled) carbon steel, and 1100-0 aluminum, in tap water and synthetic sea water. Sufficient bar stock of each material has been obtained to allow continuation of the ONR test program to completion without recourse to additional bars of material so that no question of minor material variations will be involved. A test matrix for these materials over the temperature range 27-104°C at 2 and 3 bar suppression pressure, and at horn peak-to-peak amplitude of 1.5 mil ($\sim$38 μm) was completed during the previous report period (1). These results have now been incorporated

into an ASTM conference paper (2) to be presented at the Symposium on Erosion: Prevention and Useful Applications, ASTM Committee G-2, Vail, Colorado, October 24-26, 1977, along with our venturi pulse height pressure spectrum results, to be discussed later. We hope that the Vail paper will eventually be incorporated as an article in a hard-cover ASTM STP to be eventually published as a result of this conference.

In the near future we expect to continue additional vibratory tests of this sort, investigating the effects of varying horn amplitude upon the results. The results are presented (1,2) in terms of the effect upon the ratio between maximum MDPR in salt and fresh water of the variation of the other test parameters, including the dependence of this ratio upon maximum MDPR itself. In addition, the relation between incubation period and maximum MDPR was investigated. It was found to be heavily dependent upon the test material itself.

B. Tunnel Venturi Pulse-Height Spectrum and Erosion Tests

Numerous bubble collapse pulse height pressure spectra have been measured in the diffuser portion of a cavitating cold-water plexiglass venturi, at two different cavitation conditions (extent of cavitating region), over a substantial range of throat velocity, and total gas (primarily air) content, as measured by a standard Van Slyke meter.

An approximately complete set of such pressure pulse height readings has now been obtained, using two direct submergence pressure microprobes (our own "U-M probe", and a commercial Kistler), installed flush with the venturi-diffuser wall, in axially symmetric positions. These microprobes, along with a geometrically-similar 1100-0 aluminum damage specimen, also mounted flush with the venturi wall, are located in the plane, normal to the venturi axis, which coincides with the fullest extension of the cavitation region used ("cavitation condition II" "Cavitation condition I" is a condition somewhat closer to inception.

The pulse height spectra have been obtained "manually", with the probe outputs fed through charge amplifier, high-pass frequency filter (to reduce non-cavitation background noise), into an oscilloscope. The "scope photos" were then examined to obtain the data necessary to form the spectra. This somewhat laborious procedur was used rather than a pulse-shaper, multichannel-analyzer (MCA) circuit for automatic output, since it provided much more information on actual pulse characteristics. The present procedure was a necessary first step to the development of an automatized circuit for an eventual damage predicting instrument.

Initial damage runs on the 1100-0 aluminum specimens have been made simultaneous with the gathering of pulse height data. Substantial damage occurred during the 15 min. exposures used. No detailed pit counts or weight loss measurements were made for these initial runs, but a qualitative positive correlation between pulse height spectra area and quantity of erosion was obtained.

The most significant features of all of the above are to be presented at the aforementioned Vail Conference (2). Fuller detail are found in the project report by M. K. De (3).

C. Probe Calibration

As mentioned in our last progress report, we have developed a facility for the cross-calibration of any two of our various pressure microprobes in the cavitating field of our 20 kHz vibrating horn. The 20 kHz signal alone could be used if horn amplitude were reduced or the facility pressurized. However, it is desirable to use the actual cavitation signal for added realism for the cross-calibration between pairs of microprobes, and for the most part this was done. Incidentally, another form of cross-calibration between probes in an actual cavitation field is obtained in the venturi tests, where two probe positions are available which are entirely symmetric to the flow field. The venturi probe cross-calibration is not as precise as that provided by the vibratory horn fixture, since in general individual collapsing bubbles in the venturi are not equidistant from the probes, unless their position of collapse is the venturi axis. Scope photos show that sometimes, but not usually, this is the case.

Using both the special calibrating facility and/or the venturi itself, we have now cross-calibrated all our available microprobes (4). This includes a standard Kistler, our U-M probe (both of ~ 0.1 MHZ resonant frequency), and two "wave-guide" probes used in our earlier vibratory sodium damage tests (5,6).

III. BIBLIOGRAPHY

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