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THE BEHAVIOR OF AIR BUBBLES
IN ACOUSTIC FIELDS
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William A. White

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IN ACOUSTIC FIELDS

by

William A. White

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

Gaseous cavitation poses a severe limitation on sonar performance. Simple vacuum experiments, a search of the literature and observations of the behavior of air bubbles in standing wave fields were made in order to gain information useful to the design and fabrication of sonar transducers and domes. Subjects discussed include bubble resonance and damping, radiation force, microstreaming and rectified diffusion. A set of simple rules is set down to help guide the sonar designer in order to minimize the effects of gaseous cavitation.

The writer wishes to express his appreciation to the Advanced Technology Laboratory of the General Electric Company for the opportunity and help given him in this study. Mr. L. H. Bernd, Fluids Engineer, and Roland Otten, Laboratory Technician, deserve special thanks.

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1. Introduction.

Gaseous cavitation poses severe limitations on sonar performance. It causes excessive absorption, scattering and dispersion of sound waves. It alters the radiation impedance of the medium and as a consequence causes driving circuit failures. It limits the amount of acoustic energy which can be placed into the water.

The highest acoustic energy levels from sonar systems occur at and near the face of transducers. Often these transducers are surrounded by fairings which protect the transducer and streamline it for minimum hydrodynamic resistance. Modern sonar dome and transducer fabrication techniques produce a variety of sizes and shapes of cracks capable of entrapping air. These air-water systems (the air filled holes and cracks) may promote gaseous cavitation.

The purpose of this study is to gain an understanding of the effects of cracks and holes on gaseous cavitation.

2. Initial Experiments.

Initial experiments were conducted in a vacuum chamber. The chamber consisted of a thick plexiglas cylinder about 12 inches in diameter and about eight inches high resting on a brass base through which connections were made to a laboratory vacuum pump. The cover was a thick plexiglas sheet through which connections were made to a mercury manometer. The pump was capable of producing a vacuum of $27\frac{1}{2}$ inches of mercury.

The first variable considered in the growth of air bubbles in water was the degree of saturation of the water. Samples cut from an artgum eraser were scrubbed in a detergent solution to reduce the number of the already abundant nucleation ¹ sites. The samples were then placed in three evaporating dishes containing tap water, water saturated at one atmosphere and de-gassed water (saturation were 1.6, 1.0 and 0.1 atmospheres, respectively). The dishes were placed under a vacuum.

At 15 inches of mercury the sample in the supersaturated water contained 25 bubbles per square centimeter, in saturated water 10 bubbles per square centimeter and the sample in degassed water contained no bubbles, as expected. After 10 minutes the vacuum was increased to 24 inches of mercury. The bubble concentrations in the three dishes increased to 100, 50 and 1 respectively. After ten minutes under this condition each nucleation site was producing bubbles at the rates 20, 10 and one bubble per minute.

Assuming the three rubber samples contained the same amount of air

¹Nucleation sites refer to the points from which bubbles grow. In cavitation and boiling they are believed to be micro-gas bubbles which are kept from dissolving in the water by some stabilizing factor, such as a hydrophobic crack in a dust particle, or some sort of skin around the bubble /30/. Numbers between slashes refer to the bibliography.

to begin with at one atmosphere pressure we can conclude that the dissolved gas in the water contributed strongly to the formation of bubbles. Gas diffusion is a significant factor in bubble production in water.

Since the first bubble appeared on the sample of artgum in the degassed water at 24 inches of mercury, we may estimate the size of the largest pore by considering surface tension effects. The pressure due to surface tension must be equal to the difference between a vacuum of 24 inches of mercury and atmospheric pressure,

$$\Delta P = \frac{2\sigma}{R}$$
$$R = \frac{2\sigma}{\Delta P} = 1.82 \times 10^{-4} \text{ cm.}$$

where σ is the surface tension and R the radius of curvature. The pore sizes are then on the order of 10^{-4} cm., one micron.

The next vacuum experiment attempted to limit nucleation to a single site. A fine hypodermic needle was plugged at the syringe end in order to provide a known gas volume. Under vacuum this produced uniform bubbles of constant size at the needle tip. These bubbles were counted and the pressure at which they broke away was recorded. Computations using the ideal gas law showed that over the period of observation the number of bubbles could be attributed entirely to simple expansion of the original gas in the needle. The period of observation had to be extended.

However, attempts to extend the period of observation failed for several reasons. Most often the hole became wetted (filled with water). When the hole remained dry, a point was reached with increasing vacuum where so many nucleation sites became active that the water became violently agitated. As a result the bubbles produced at the tip broke

off at different sizes and the value of the observations was lost. Several interesting phenomena were observed, however, despite the frustrated aim of the experiment.

The first occurred when the hole became wetted at a relatively high pressure, before many other nucleation sites became active. Bubbles continued to form at the tip of the needle, but they were not emerging from the hole. Rather they were growing from a scratch, just visible, on the surface around the hole. As each bubble grew and detached itself a very tiny one would be left behind at the scratch which in turn grew, and so the process continued until the small bubble left was mechanically dislodged. This action lasted from a few cycles to as long as 50 or so cycles at almost constant pressure. Obviously diffusion was the mechanism contributing most of the gas for these bubbles.

Secondly, the bubbles forming near the base of the hypodermic needle grew much larger than those at the tip before breaking away. The needle had been plugged with paraffin wax, and a wax coating covered the base of the needle. This led to a consideration of bubble size versus wetting angle.

3. Wetting Angle and Pore Size.

Consider a bubble growing at a hole in a plane surface. A cross section is indicated in Figure 1.

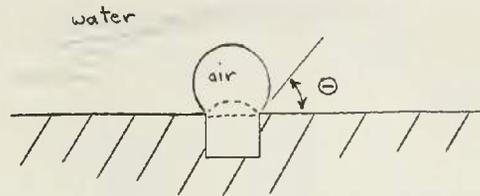


Figure 1. Bubble growing at a pore in a surface.

The cylindrical holes have a radius r . The bubble's radius is R . The density of the water is ρ and the density of the air is negligible ². The surface tension of the air-water interface is σ . The force tending to anchor the bubble is $2\pi r \sigma \sin \Theta$ /2/. The buoyant force is $4\pi R^3 \rho g / 3$ for a spherical bubble. The volume must be corrected in this case for the spherical segment within the hole.

Wetting angle may limit the Θ produced at a site such as the hole of Figure 1. Wetting angle is a measure of the adhesion of a liquid to a solid, and is a function of the surface energies of the two substances /1/. Place a drop of liquid on the solid and let it travel slowly downhill as indicated in Figure 2. The advancing wetting angle, Θ_a , and the receding wetting angle, Θ_r , are defined as indicated. Wetting angle is measured through the liquid phase at the point of contact /1/.

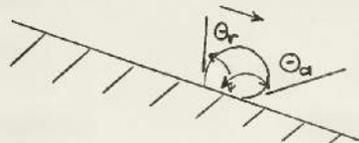


Figure 2. Wetting angle.

²The density of air is 3 orders of magnitude less than that of water. The adhesion of the gas to the solid is neglected.

As a bubble grows on a surface, the angle θ will equal θ_r . Therefore if a bubble growing at a hole reaches θ_r prior to becoming buoyant enough to break away, the size of the hole will have no effect on the bubble size. Figure 3 illustrates this case.

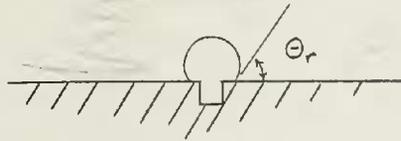


Figure 3. Bubble growing away from pore.

Define the critical radius, R_c , by equating mooring force due to surface tension to buoyant force and solving for R_c .

$$R_c = \left(\frac{6\sigma}{\rho g} \frac{\sin^2 \theta}{[4 - (1 - \cos \theta)^2 (2 + \cos \theta)]} \right)^{1/2} \quad \text{for } \theta \leq 90^\circ$$

$$R_c = \left(\frac{6\sigma}{\rho g} \frac{\sin^2 \phi}{(1 - \cos \phi)^2 (2 + \cos \phi)} \right)^{1/2} \quad \begin{array}{l} \text{for } \theta \geq 90^\circ \\ \text{where } \phi = \pi - \theta \end{array}$$

A plot of R_c versus θ is shown in Figure 4. By simple trigonometric relationship we find r_c , the radius of the intersection of the sphere and the plane. A plot of r_c versus θ is shown in Figure 5. The volume of gas which breaks away is shown in Figure 6. This is the volume which breaks away after θ_r has been reached. This will be the case if the pore in the surface is equal to or smaller than r_c .

Consider a hole of radius a in a material of wetting angle θ_r . If on Figure 5 the point (a, θ_r) falls below the critical curve the bubble will grow away from the edge of the hole before detachment and will be of radius r found directly above the point (a, θ_r) . If the point lies above the curve the bubble will detach itself before θ_r is reached at an angle θ found directly to the right of the point (a, θ_r) .

In the above discussion it has been assumed that the bubbles are spherical and that the only force on them is buoyant force acting at right angles to the surface. The bubbles will be approximately spherical if the diameter is less than five millimeters.

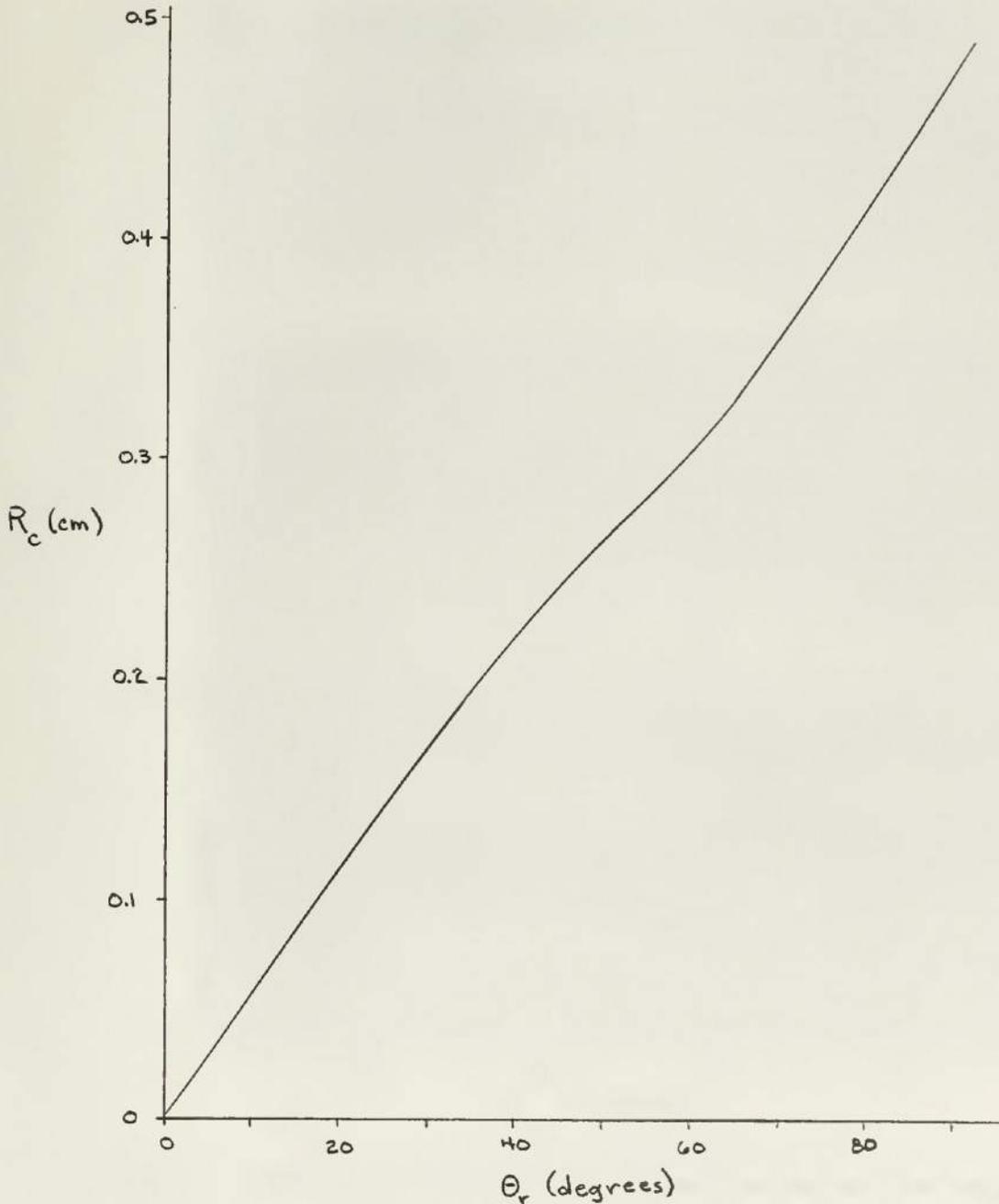


Figure 4. Critical radius of a bubble as a function of wetting angle.

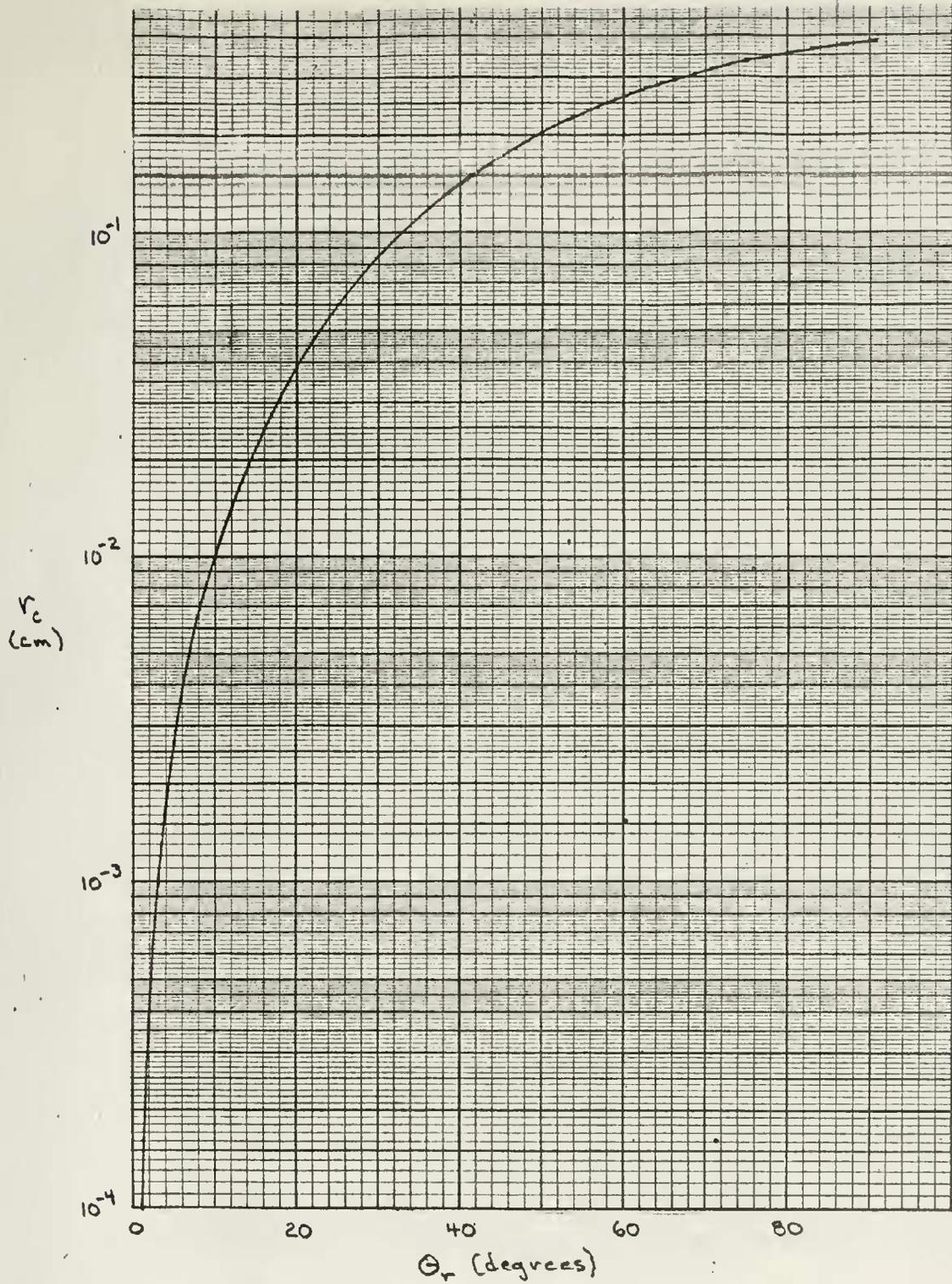


Figure 5. Radius of contact area as a function of wetting angle.

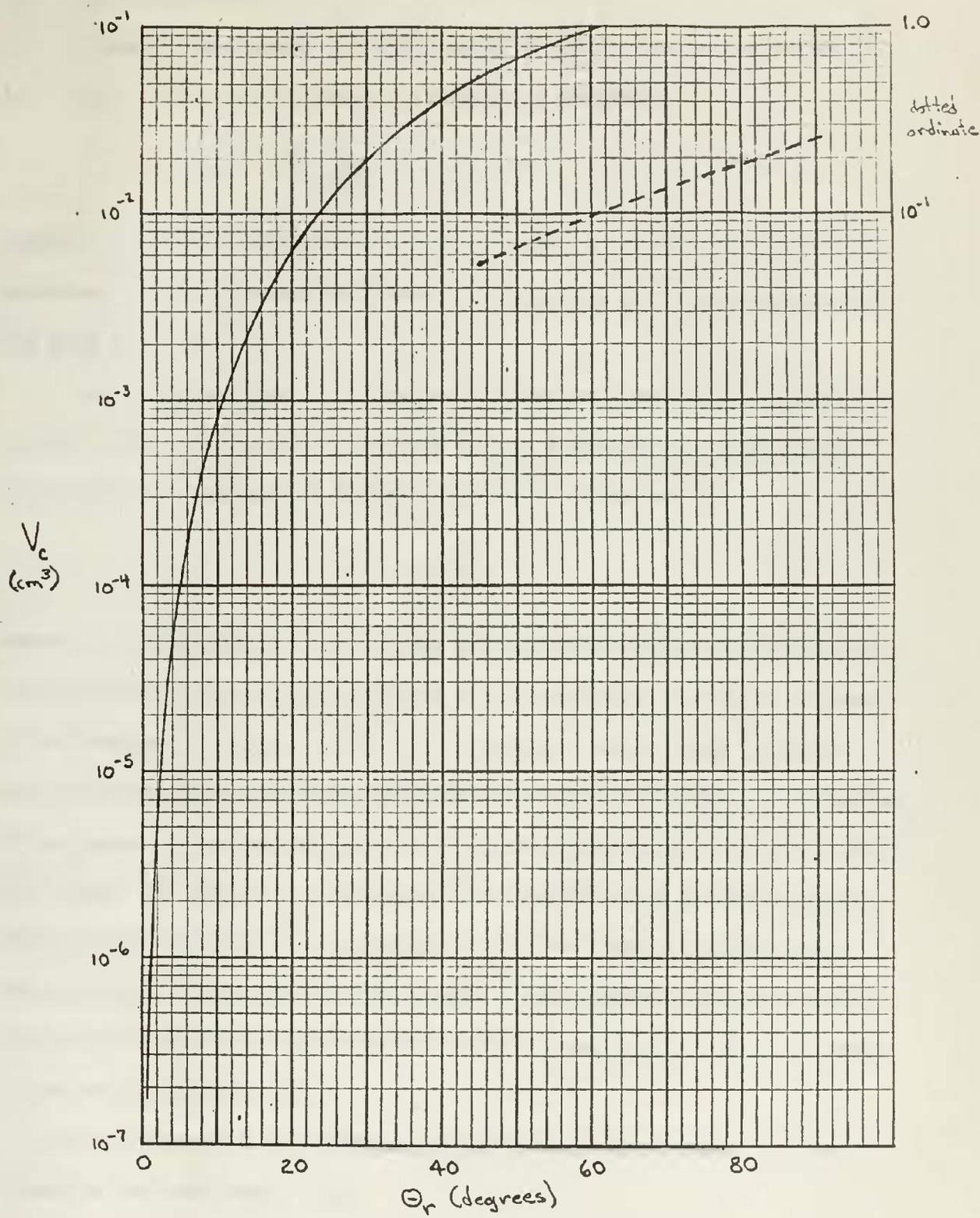


Figure 6. Critical volume as a function of wetting angle.

4. Bubble Resonance.

If small, the volume oscillations of a bubble can be described by the linear second order equation in units of pressure,

$$m \frac{d^2v}{dt^2} + R_m \frac{dv}{dt} + sv = 0$$

where m is the generalized mass of the system, R_m is the mechanical resistance, s is the volume stiffness of the system and the change in volume from V_0 is v .

The effective mass of the system, m , may be found by evaluating the kinetic energy of the fluid produced by any incremental volume change.

The result for a spherical bubble in an infinite medium is:

$$m = \frac{\rho}{4\pi R_0}$$

where ρ is the density of the fluid and R_0 is the radius at equilibrium. If the bubble is very small compared to the wavelength of sound in water at the resonant frequency (which is always the case for air bubbles in water at normally encountered pressures) the effective mass is independent of the shape of the bubble /18/. R_0 is then interpreted to be the radius of a sphere of volume V_0 . The effect of boundaries in the fluid may be understood by considering the change in kinetic energy resulting from the boundary. For a semi-infinite fluid (for example a bubble on an infinite rigid plane boundary) the effect is to double the effective mass of the resonant system /15/.

The stiffness, s , of a volume of air of any shape under adiabatic expansion and contraction is,

$$s = \frac{\gamma P_0}{V_0}$$

where γ is the ratio of specific heats of the gas, P_0 is the equilibrium pressure inside the bubble and V_0 is, as before, the equilibrium volume. PLESSET and HSIEH have shown by allowing the gas to vary in space as well as time inside the bubble that isothermal behavior should be expected of a bubble at all frequencies /27/. Under this condition,

$$s = \frac{P_0}{V_0}$$

The equilibrium pressure inside the bubble is the sum of the ambient pressure in the fluid, P_a , and the pressure due to surface tension, $2\sigma/R$, where R is the radius of curvature of the air-water interface.

If one considers an air void in a crack, P_0 can be either above or below ambient depending upon whether the solid is hydrophyllic or hydrophobic respectively (wetting angle less than or greater than 90°). Figure 7 illustrates the two cases. In cases where the radius of curvature



Figure 7. The pressure inside a pore depends on wetting angle. of the interface is small, surface tension effects may dominate in determining P_0 . For large bubbles ($R_0 > 100$ microns) in water at atmospheric pressure the surface tension effect is negligible.

The mechanical resistance, R_m , is a measure of the damping of the volume oscillations of the void. It is due to the following three physical processes.

1. Acoustic radiation of sound energy (scattering).
2. Net loss of energy due to heat conduction from the air to the water.

3. Viscous losses in the fluid near the boundary.

DEVIN presents a theoretical discussion of these processes and compares them with the results of various experimenters /7/. Agreement with the data is good. A plot of logarithmic decrement due to each process is given in Figure 8. These are Devin's results and are valid for bubbles ranging in size from 3 microns to 3 millimeters radius.

The resonant frequency of an undamped bubble is given by,

$$f_0 = \frac{1}{2\pi} \left(\frac{s}{m} \right)^{1/2} = \frac{1}{2\pi R_0} \left(\frac{3\gamma P_0}{\rho} \right)^{1/2}$$
$$= \frac{1}{2\pi R_0} \left(\frac{3\gamma (P_0 + \frac{2\sigma}{R})}{\rho} \right)^{1/2},$$

where all terms are as previously defined.

Using DEVIN's definition of δ , namely $\delta = \frac{1}{Q}$, the total damping constant, the resonant frequency of the damped bubble is given by,

$$f_{0d} = f_0 \left(1 - \frac{\delta^2}{4} \right)^{1/2}$$

From Figure 8 and the above equation it is seen that the maximum difference in resonant frequency between the damped and undamped case is less than two percent for spherical bubbles.

The resonant frequency of a void of volume V_0 at one atmosphere pressure is plotted in Figure 9. Surface tension and boundary effects are not included, but corrections may be applied in any given situation from principles covered in the above discussion.

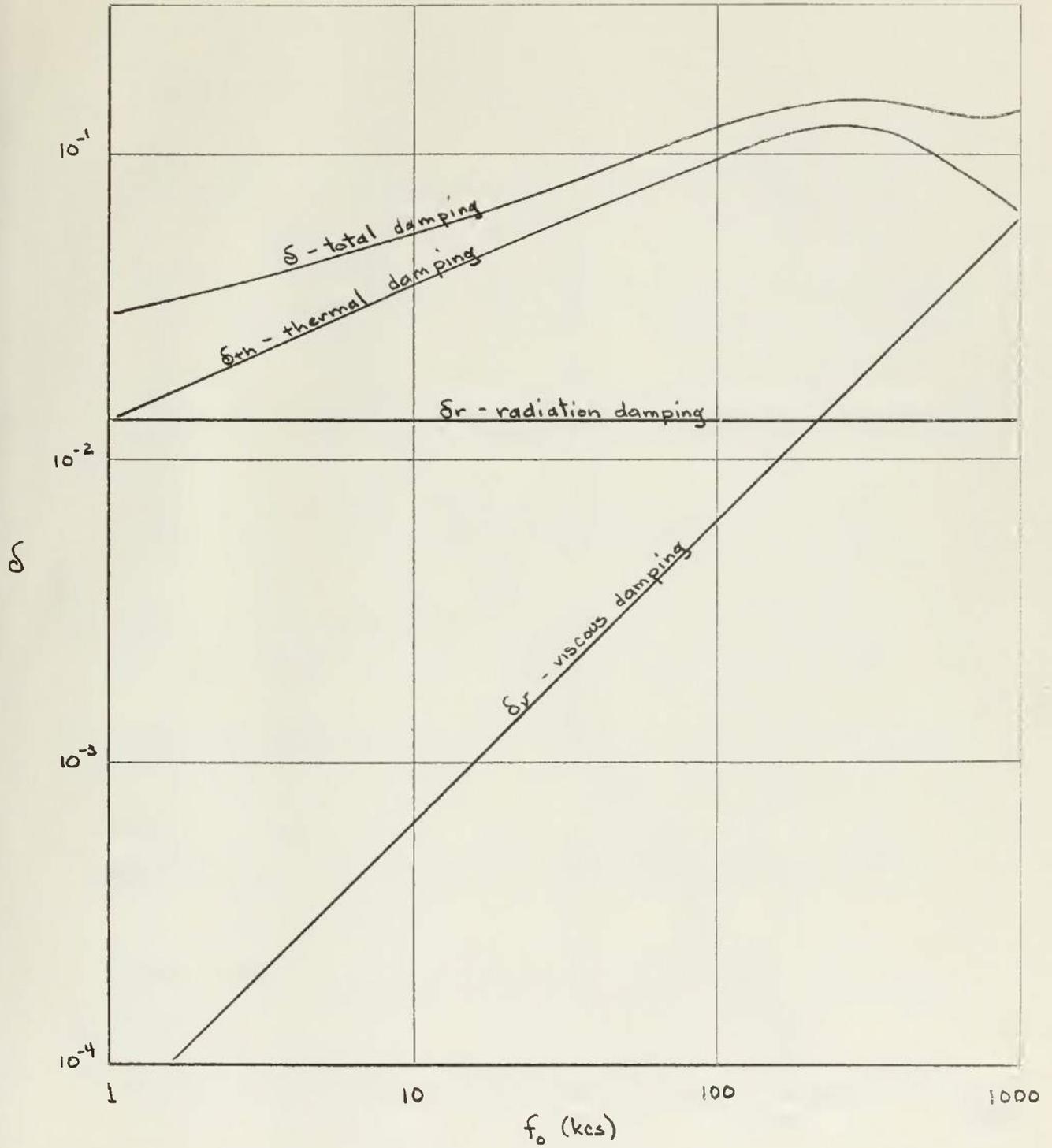


Figure 8. Theoretical damping constants for resonant air bubbles in water (after DEVIN).

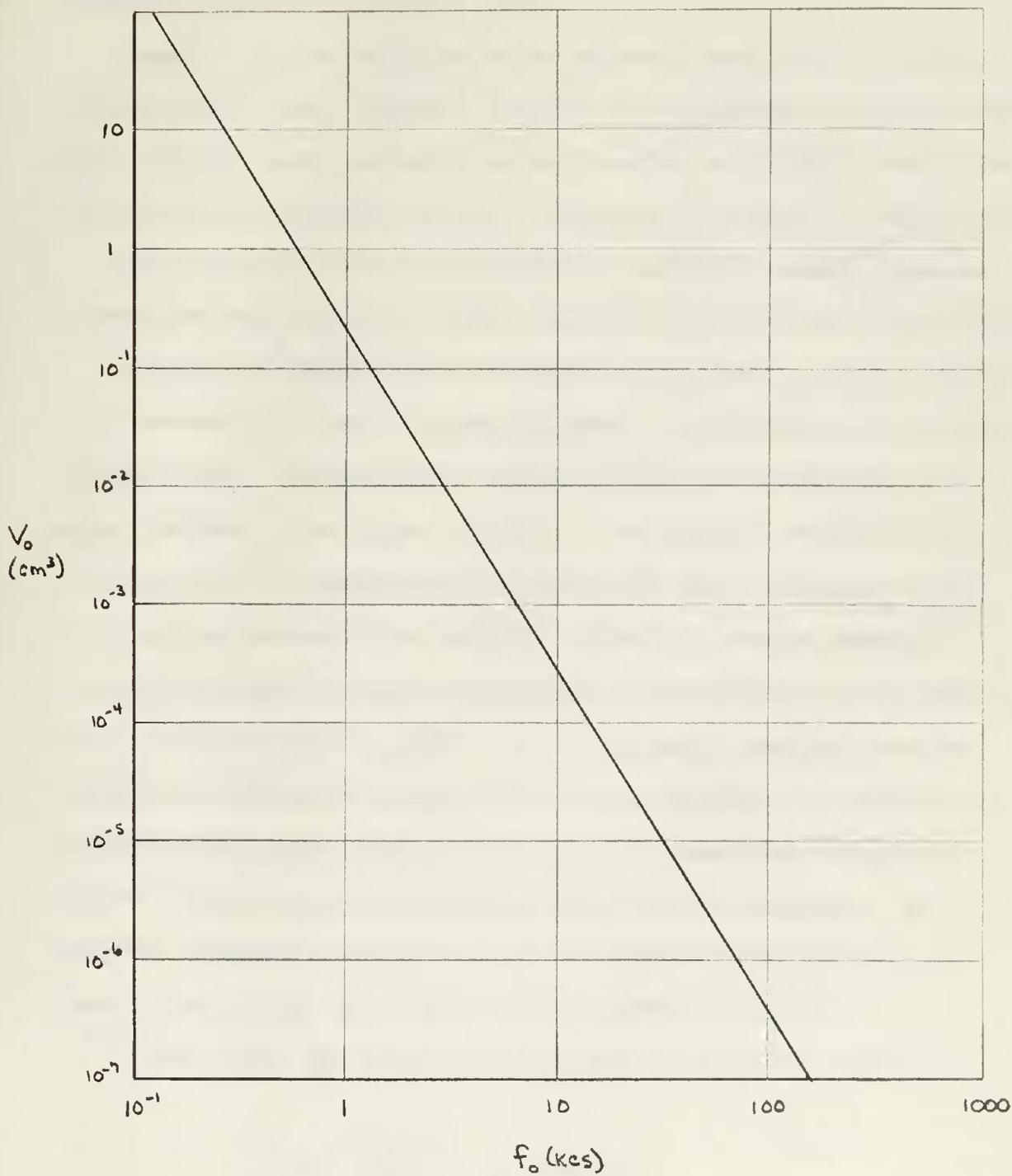


Figure 9. The volume of a void versus its resonant frequency.

5. Radiation Force.

The buoyant force on bubbles and the sizes of bubbles which break away from solid surfaces was considered in Section 3. Another force bubbles experience is radiation force.

When a bubble is subjected to an incident sound field it pulsates at the incident sound frequency, just as any mechanically resonant system will oscillate when a harmonic forcing function is applied. These pulsations re-radiate acoustic energy. This behavior is known as scattering.

The superposition of the incident and scattered acoustic pressures distributed over the bubble cause a net force to be exerted on the bubble.

YOSIOKA and KAWASIMA have calculated the radiation pressure acting on a compressible sphere in plane progressive and standing wave acoustic fields /38,39/. Good agreement with the theory was demonstrated for oxygen bubbles in both types of fields. The radiation pressure is in the direction of propagation for a progressive wave, and shows a prominent peak for resonant sized bubbles. Radiation pressure normalized to its maximum value is plotted as a function of normalized size in Figure 10 to illustrate their results. For a stationary (standing) wave the direction depends upon the size of the bubble relative to resonant size. Bubbles smaller than resonance will be forced toward the nodes, and bubbles larger than resonance will be forced to the antinodes. The radiation pressure is shown to vanish on resonant sized bubbles in a standing wave field. This last case is plotted in Figure 11.

YOSIOKA gives the peak radiation pressure acting on a bubble as,

$$P_{MAX} = \frac{4\pi I}{k^2 c} \frac{\delta_r}{\delta_r + \delta_{th} + \epsilon_y}$$

where I is the acoustic intensity, k is the wave number in water, c is the velocity of sound in water and the δ 's are the damping constants as plotted in Figure 8.

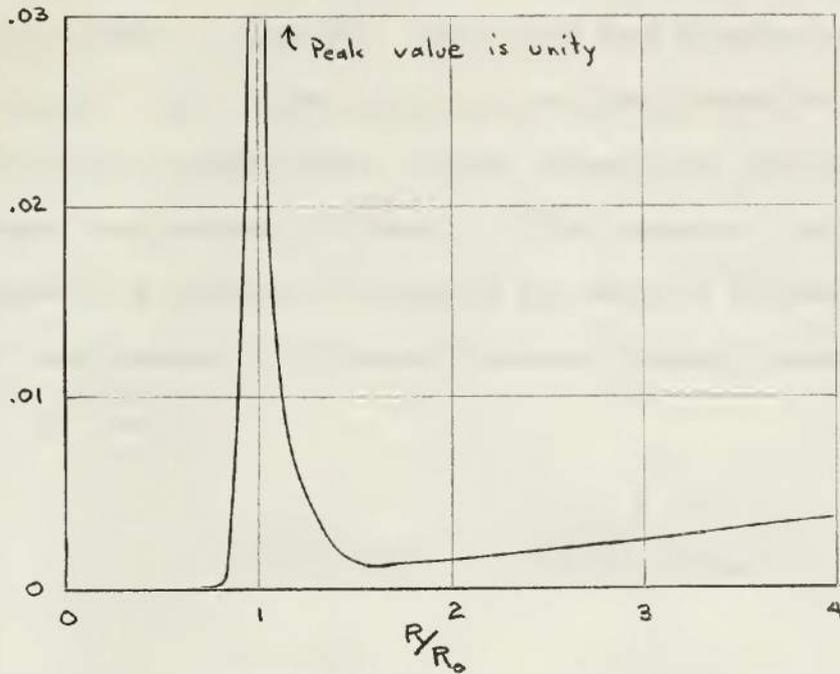


Figure 10. Radiation pressure in a progressive field.

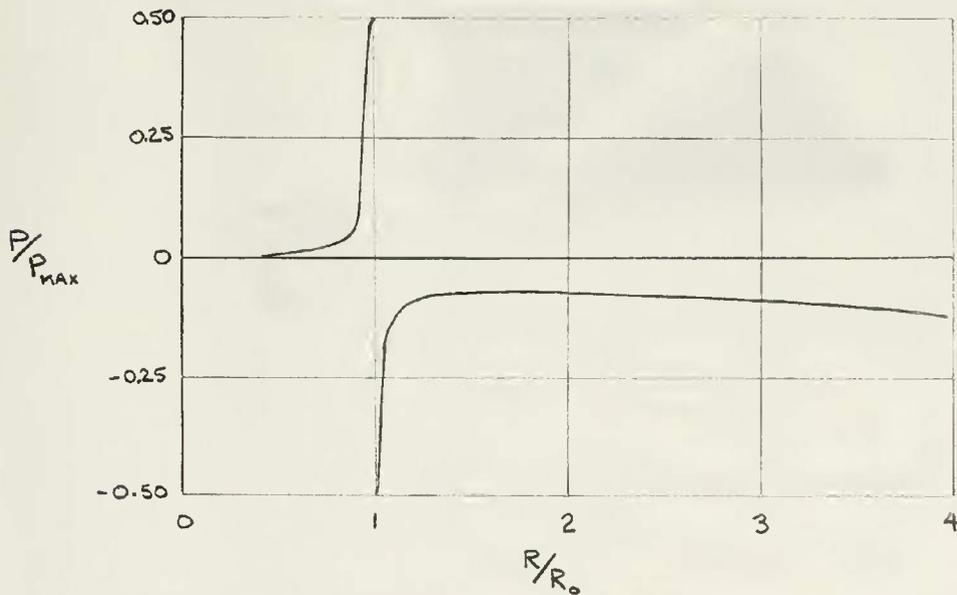


Figure 11. Radiation pressure in a standing field.

6. Microstreaming.

Microstreaming refers to the motion set up in the water near an oscillating bubble. A systematic investigation of this phenomenon was made by ELDER in 1958 /8/. Elder found four distinct regimes of stable streaming. Which regime exists in any given situation is a function of the acoustic pressure level and the viscosity of the liquid. The four regimes are sketched in Figure 12. The thresholds for the various regimes as a function of viscosity are shown in Figure 13. Notice that for water regime II is virtually absent. (kinematic shear viscosity $0.01 \text{ cm}^2/\text{sec}$).

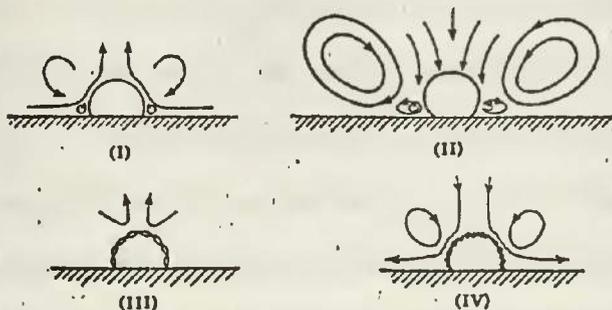


Figure 12. The four regimes of streaming.

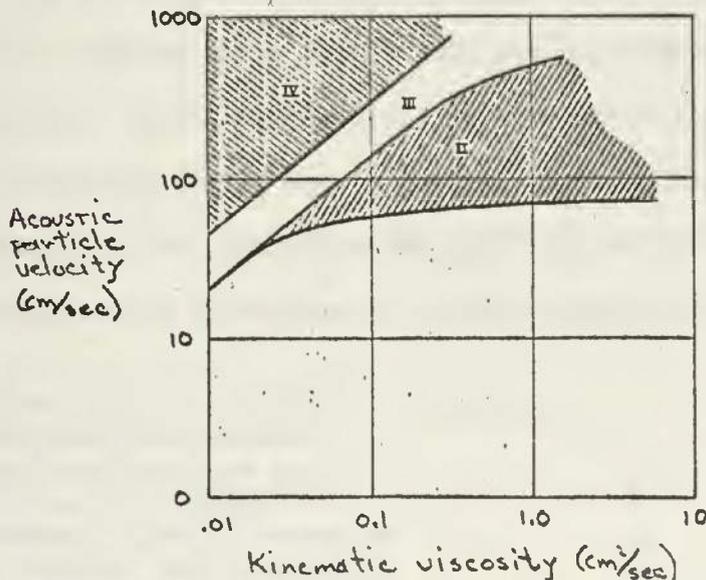


Figure 13. Threshold lines for regimes II, III and IV.

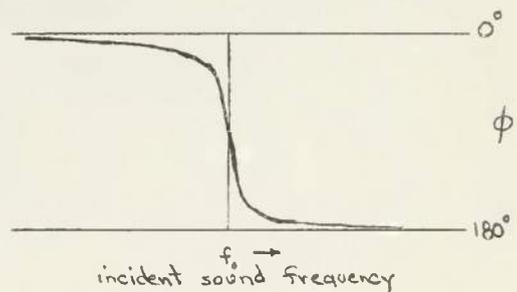
7. Rectified Diffusion.

Rectified diffusion describes a process whereby an air bubble oscillating in a sound field in water grows by a net inward diffusion of air into the bubble. This phenomenon has been extensively analyzed in the literature /12,17,27,28,29/.

Consider a bubble oscillating in a sound field such that the pressure inside the bubble is in phase with the incident acoustic pressure ³. The water is assumed to be saturated with air at one atmosphere pressure. When a rarefaction occurs the bubble has a surface area $4\pi(R_0 + R_1)^2$ and the water at the surface is now supersaturated with air due to the reduction in pressure. Under this condition air will diffuse into the bubble. When the bubble and water are under compression the bubble has a surface area $4\pi(R_0 - R_2)^2$ and the water at the surface is undersaturated. Air will then diffuse into the water. But the amount of air which diffuses is proportional to the surface area through which it diffuses. Therefore more gas will diffuse into the bubble than out of it, and a net growth of the bubble will be observed.

There are two reasons why a bubble will not grow indefinitely by rectified diffusion. First, as resonance is approached the phase relationship of the pressure inside the bubble and in the fluid is changed producing conditions unfavorable to a net influx of air into the bubble. Secondly, as resonance is approached the radial oscillations of the

³The pressure inside the bubble will be in phase with the acoustic pressure for bubbles which are smaller than resonant size. For bubbles larger than resonant size the pressures are 180° out of phase. The transition takes place at resonance and is very sharp /8/.



bubbles become unstable due to the increasing amplitude of vibrations /17/.

Both STRASBERG and PLESSET give formulae for the maximum size a bubble will grow by rectified diffusion /30,17/. Strasberg's equation is,

$$R_{\max} = \frac{0.4}{f} \left(\frac{\Delta P}{\rho} \right)^{1/2}$$

where ΔP is the peak pressure change from P_a , f is the incident sound frequency, and ρ is the density of the water. Plesset's equation is based upon the stability of radial oscillations, and is,

$$R_{\text{crit}} = \frac{1}{2\pi f} \left(\frac{24\sigma}{5\rho\Delta P} \right)^{1/3}$$

where σ is the surface tension, and the other terms are as before.

Since surface tension increases the pressure inside a bubble, and rectified diffusion depends upon the water adjacent to the bubble becoming supersaturated with respect to the pressure in the bubble, there is a minimum size bubble which will grow by diffusion for any given peak sound pressure. An order of magnitude approximation can be made by equating peak sound pressure to $2\sigma/R$, the increase in internal pressure due to surface tension. For a 10 micron bubble in water the pressure must be at least on the order of 10^{-1} atmospheres. For a 1 micron bubble we get 1 atmosphere overpressure necessary. These magnitudes agree with observations made by Strasberg /30/.

8. Observations in Standing Wave Fields.

A. Description of Equipment.

Two set-ups were used in studying the behavior of gaseous cavitation bubbles in water. The first consisted of an Hewlett-Packard audio oscillator driving a McIntosh 200 watt industrial amplifier. The amplifier was connected to a small array of four piezo-electric transducer elements through an impedance matching network consisting of an ultrasonic transformer and a tuning inductor. The resonant frequency of the transducer array was nominally 18 kilocycles per second. The array was placed in a glass tank approximately one by one by two feet. The bubbles were illuminated from the end of the tank by a slide projector.

Two instruments were used for observing the bubbles with the first set-up. A small laboratory telescope was used because it was easy to position and focus. A binocular microscope was also used to assist in determining depth in observing microstreaming and for greater magnification. Additional lighting was used in the form of a small microscope spotlight when necessary.

The second set-up differed from the first in the transducer array, tank, matching network and in the addition of a parabolic reflector. A 25 element array, approximately one foot square, was used. A large tank two by three by five feet was filled to 20 inches with water. A 20 inch, Celtite ⁴-lined, aluminum, parabolic reflector was placed in front of the transducer. The reflector was positioned in order to tune the system for greatest standing wave ratio. The reflector was designed by the author to create a pressure maximum at the focus in accordance with the basic equations set forth in HUETER and BOLT /41/. A two inch hole was cut on

⁴Trade name.

the axis of the reflector for insertion of surfaces of various materials and to allow easy observation of the focus.

A small (1/8 inch diameter) ceramic probe hydrophone was available for sonic field measurement and calibration. Quantitative measurements were made but for a multitude of reasons proved to be of little or no value. A Tektronic dual trace oscilloscope was used to monitor input voltage and current to the transducer and to measure the sound field.

B. Behavior of Free Bubbles.

The entire range of behavior of air bubbles in water as set forth in the literature was verified by the author in these simple experiments. A typical sequence as observed by the naked eye in the small glass tank follows.

With equipment energized and warmed up the amplifier gain was set for a sound field intensity of about 1/4 watt per square centimeter. This power level was generally a little below the threshold of cavitation in this aged water.

At first there was little observable action in the tank. Then slowly a stream of very small bubbles became visible in front of the transducer on centerline. These bubbles would stream throughout the tank following the nodal pattern set up by the standing waves. At the pressure nodes common to one or more dimensions of the tank they would coalesce forming larger bubbles, approaching resonant size. Occasionally a very large bubble would form and rise to the surface. More often, when slightly larger than resonance they would dash off from the node toward an antinode about which they would orbit for long periods of time. The surface of these bubbles appeared very shiny, as if luminescent (they were not, however) ⁵. This apparent luminescence later proved to be a combination of the particular lighting employed and the violent surface

vibrations of the bubbles. At times two of these wild bubbles would collide forming one not so near resonance and would settle, perfectly still, at an antinode. Surface vibrations in this case ceased altogether. The whole process extending over about 8 wavelengths of sound is a fascinating one to watch.

The wildly oscillating bubbles were carefully observed under the binocular microscope. The bubble itself appeared as a streak of light because it was moving so rapidly, but a very interesting phenomenon was discovered.⁶

Under the microscope (or telescope) one can detect a very great number of tiny bubbles being thrown radially outward from the orbit near the antinode. About 50% of these disappeared almost immediately, and were probably vapor bubbles or bubbles much smaller than the minimum size required for growth by rectified diffusion. The other half of these bubbles streamed outward from the antinode growing all the while. These small bubbles entered the nodal pattern behaving the same as those discussed earlier.

The most interesting part of this behavior lies in the fact that these smaller bubbles are produced without any apparent dissipation of the larger bubble producing them. By turning off the sound field momentarily at intervals of about every minute the original bubble was seen to remain the same size.

⁵The author does not intend to imply that luminescence is not a legitimate observation in cavitation phenomena. He is here concerned with "gaseous" vice "vaporous" cavitation /37/. A convincing theory explaining luminescence as reliably observed in connection with vaporous cavitation is forwarded by WEYL in the literature /35,36/.

⁶The author has not seen such behavior reported in the literature. His research in the literature, while not exhaustive, was lengthy. He therefore takes the liberty of calling this a discovery.

C. Behavior on Surfaces.

Surfaces placed in the tank attracted the wildly oscillating bubbles ⁷. When these surfaces contained a hole, crack or wedge whose smallest dimension of the opening was of the same order of magnitude as the bubble, the bubble would lodge itself in the opening producing erosion of the material at a surprisingly high rate.

Often the bubble would remain at a surface discontinuity even if the sound field was turned off. Most of these bubbles did not re-dissolve, perhaps due to the fact that their surfaces collected a scum clearly visible under the microscope. Under this condition it was possible to study its surface behavior as a function of the acoustic pressure level.

Such a study is illustrated in Figure 14 with remarks concerning the acoustic waveform observed on the oscilloscope. The monitoring hydrophone was placed in a non-cavitating region (near a node) to avoid damage to its surface.

It is interesting to speculate on the mechanism producing these very tiny bubbles illustrated in 14d. Perhaps some air breaks away from the bubble at the tips of the oscillations. Or possibly tiny free vortices are produced which rupture the water, some collapsing, some growing by diffusion. DEAN discusses the vortex theory /6/. High speed motion pictures using a Kerr electronic shutter /23/ with microscopic streaming indicators /8/ would be one method of observing this action in greater detail.

Bubbles greater than resonant size were deliberately introduced into the tank in order to observe their behavior. A glass slide was placed

⁷The attraction could be due to Bjerknes force, which is basically a radiation force occurring near boundaries /41/.

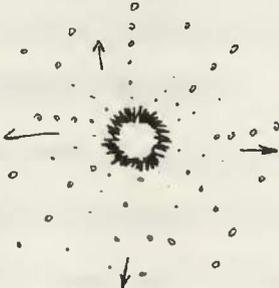
Rough Sketch	Acoustic Pressure	Remarks
a. 	0.0 to 0.22 ATMOS	Pure radial oscillations only as evidenced by growth. No waveform distortion on oscilloscope from monitoring hydrophone.
b. 	0.22 to 0.24 ATMOS	Surface oscillations begin. Slight waveform distortion. Distortion constant from one cycle to the next.
c. 	0.24 to 0.27 ATMOS	Higher mode surface oscillations. Greater waveform distortion in hydrophone, but still constant from one cycle to the next.
d. 	0.27 to 0.95 ATMOS above 0.95 ATMOS	Violent skin oscillations begin. Spectrum transition from discrete distortion to white at 0.95 ATMOS indicated by severe, variable waveform distortion accompanied by audible hiss. Above 0.95 ATMOS sharp chirps occurred from time to time indicating vaporous cavitation.

Figure 14. Behavior of a bubble close to resonant size in an acoustic field of increasing intensity.

horizontally under the water and random sized bubbles were generated and caught under the slide. Unless very close to resonant size they showed no reaction to the sound field for periods as long as one hour.

Holes and cracks filled with air were also introduced into the field and their behavior observed. Those whose resonant frequency was lower than the incident sound showed no reaction to it. Those whose resonant frequency was above the incident sound behaved very erratically. At times bubbles were grown from them while other times no growth at all was observed. When bubbles were grown the hole became wetted after the growth of only a few bubbles at most. Materials of various wetting angles were used. Identical holes in these various substances all had one thing in common - unpredictable and unreproducible behavior.

As previously mentioned, cracks and holes are capable of entrapping gaseously cavitating bubbles. Drilled holes (1 to 10 mils diameter) and cracks with parallel sides trapped bubbles where they cavitating without dissipation. But wedge shaped holes (made with a sharp pointed instrument) and cracks (such as a razor cut in the surface) whose openings were about the size of the bubble caused the bubbles to dissipate themselves. Scratches and cracks which were much smaller than the bubbles, and which were wetted, did not affect the bubbles at all. Long thin cracks whose sides were not parallel cleansed themselves of air by surface tension effects.

Because of many foreign particles in the water the microstreaming was easily observed. The streaming patterns were similar to those in section 6 observed by Elder. This microstreaming together with radiation forces probably accounts for the bubble entrapment in holes and cracks.

9. Conclusions.

Holes and cracks are capable of participating in the phenomenon known as gaseous cavitation. As observed by the author this participation was erratic and to some extent unreproducible. The exact mechanisms by which the holes and cracks participate are still undetermined, but the many theories concerning bubble behavior and origin are very helpful in understanding and describing the processes.

The effect of holes and cracks on the threshold of cavitation has not been determined by this study. Quantitative measurements made by the author show no difference in thresholds for cavitation in the presence of air-filled voids or in their absence. However, observations of voids capable of interaction with the sound field (that is, capable of growth) were very few due to the difficulty in producing and observing such sites. Perhaps some correlation can be obtained in more closely controlled experiments.

Wetted holes and cracks together with a gaseously cavitating bubble are capable of producing erosion of surfaces. The resulting localization of damage will present problems in most applications of high level sonic energy. This damage can take place at energy levels which are lower than that required for vaporous ⁸ cavitation.

Hydrophobic cracks cannot explain nucleation of bubbles grown by rectified diffusion. An examination of Figure 15 will reveal the opposite relationship between direction of diffusion and available surface area than that necessary for growth by this process (see Sections 3 and 7).

⁸Gaseous cavitation is defined as that behavior reported herein and illustrated in Figure 14d. Vaporous cavitation differs in that its acoustic spectrum is white, indicating an impulse or shock wave, which implies the collapse of a "vapor" filled cavity resulting from a rupture in the structure of the water.



Compression-
gas diffuses out
of bubble.

Rarefaction-
gas diffuses into
bubble.

Figure 15. A hydrophobic crack in an acoustic field.
 A = surface area, A_0 = equilibrium surface area.

The phenomena observed and described in this paper occurred in standing wave fields. The author was not able to observe the behavior of bubbles in progressive wave fields such as those which are produced by echo ranging sonar equipments. It is felt however that standing wave patterns are probably set up between transducer and sonar dome, and are certainly set up between the elements of a large flooded array. Additionally, such behavior as the gaseously cavitating bubbles observed could conceivably take place on the transducer side of the sonar dome. It is therefore believed that the following set of rules should be followed in the design and construction of transducer arrays and sonar domes in order to minimize the probability of cracks and holes participating in or promoting gaseous cavitation.

10. Rules for Designers.

a. Avoid cracks and holes whose dimensions are of the same order of magnitude as the diameter of a resonant bubble at the frequency of the sonar.

b. Avoid cracks and holes capable of becoming air filled whose resonant frequency would be near or greater than the sonar frequency.

c. Cracks and holes which must be present should have sides which are not parallel to promote wetting.

d. The materials used in fabrication should have the lowest wetting angles possible consistent with other design criterion.

e. Porous materials, that is those capable of containing gas (for example, certain rubbers previously used in manufacturing transducer "boots"), should be avoided.

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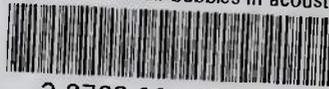
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