FOREWORD

For those who have chosen cavitation as a field of study, the publication of this book is an event for celebration. It signifies that the field has come of age. For those without previous knowledge of this many-faceted subject, the book provides an opportunity to become well acquainted. Here Dr Young has recognized, and met, the need for a single-authored volume which brings together material from many technical reports, book chapters, student theses and countless journal publications. The material includes basic hydrodynamical and acoustical theory, as well as experimental findings in physics, chemistry and biology laboratories. Cavitation-related phenomena include such diverse examples as erosion of ship propellers, ultrasonic cleaning, detection of high energy particles, fragmentation of biological cells and sonoluminescence.

As can be seen from the quotations and references which are interspersed throughout this volume, the ideas of bubbles and cavitation have been known and invoked over a long period of time and in many circumstances. Aristophanes and Shakespeare found dramatic potential in bubbles, while musicians and painters have incorporated them into their art. The romantic and the scientific were brought together by Minnaert, who evidently delighted in the musical sounds of running waters; he identified vibrating bubbles as the source of the sounds, and developed differential equations which govern the vibrations.

Lord Rayleigh did much to impress the scientific public with the possibilities inherent in a *cavity*. He considered what the consequences would be if a spherical 'void' were somehow created in an otherwise infinite and homogeneous quiescent body of liquid. Using energy principles he predicted that the surrounding liquid would fill the void, i.e. the cavity, by flowing inward with increasingly great speed as the cavity shrank. As a result, closure would occur violently, accompanied by dramatically high values of the pressure and temperature. It is tempting to view the moments during cavity collapse as analogous to those during the astrophysical 'Big Bang'; the high pressure and temperature exist only in a very small region, and only for an instant. Subsequent theoretical development and experimentation confirmed the prediction that cavity collapse can occur, along with high temperatures and pressures, the specific results depending on circumstances.

Rayleigh's differential equation for the collapsing cavity is nonlinear, in contrast to Minnaert's linear one. Since the times of Rayleigh and Minnaert, the understanding of cavitation and bubble action has advanced greatly by utilizing both linear and nonlinear theory.

Linear equations apply in sound fields when the pressure amplitudes are small or moderate, and receive much attention (Section 3.1 here), since they can be solved analytically, and general insight can be obtained from the solutions. Since Minnaert's time, his equation for the spherical bubble has been elaborated and extended by taking into account surface tension, viscosity, heat transport and other features of realistic situations. Experimental tests have shown that the modified linear equations lead to fairly accurate predictions of resonance frequencies and damping coefficients for a wide range of conditions.

Nonlinear theory is required in order to deal with the behaviour of bubble containing gas or vapour in hydrodynamical applications, and in acoustical applications where the pressure amplitude is relatively high. Theorists have modified Rayleigh's equation and extended its applicability, by taking into account viscosity, surface tension, heat transfer and the processes of condensation and evaporation, as well as compressibility of the liquid. Solutions of the resulting equations are obtained primarily by computational means. The proliferation of computers during the past decade has led to an explosion of knowledge based on nonlinear cavitation theory.

In computations of acoustically generated cavitation there has been considerable interest in the conditions under which a spherical gas-filled bubble, when subjected to the time varying pressure in a sound field, would execute motions leading to a sudden decrease in size, as in the classical Rayleigh collapse. This kind of response of a bubble/cavity to a sound field has come to be called *transient* cavitation, as suggested by Flynn; it is an important and dramatic kind of activity.

There are also many other ways in which a bubble can respond to a sound field, especially when the pressure amplitude and bubble size are such that the motion is governed by a nonlinear equation. Plots of radius R versus time t (R vs t curves) for a bubble in a sound field of frequency f can often exhibit harmonics of frequency $2f$, $3f$, etc., even for modest pressure amplitudes. At somewhat higher levels the motion becomes aperiodic; subharmonics of frequency $f/2$, $f/3$, etc., occur, as do ultraharmonics of frequency such as $3f/2$, etc. The R vs t curve becomes very complex and is critically dependent on the parameters of the bubble and the sound field. Under some conditions the solution becomes indeterminate, allowing multiple values for the radius R. Such indeterminacy has been shown by Lauterborn and others to be characteristic of nonlinear systems. Under the name of *deterministic chaos*, this intriguing new area of study is taken up in Section 3.7.

For the radial motion of a bubble/cavity under conditions where transient cavitation does not occur, Flynn has suggested the phrase *stable cavitation*. This applies to conditions where the governing equation for the R vs t curve is nonlinear, as well as those where a linear equation suffices. Even when the R vs t equation is linear, principles of nonlinear acoustics must usually be invoked in order to deal with associated phenomena. The latter include 'rectified diffusion', radiation forces between vibrating bubbles and other objects, and bubble-associated microstreaming.

So much has been learned from the cavitation theory discussed above, that it is necessary to be reminded that it is based on a highly simplified model. It deals with a single bubble in liquid away from any boundaries, and assumes spherical symmetry. In spite of this simplification, the theory has proven very useful in explaining the behaviour of real cavitation fields. It is clear that the equation of motion for a single spherical bubble contains a rich mine of information, which has yet to be fully explored.

It is equally clear from findings discussed by Dr Young that a complete understanding of real cavitation fields requires consideration of matters not taken up in the above theory. Thus surface waves are commonly set up on the gas-liquid interface; these are important in that they give rise to high-speed liquid jets and microbubbles. Also, real cavitation fields contain many bubbles of different sizes which form streamers along which they move very rapidly. High repetition-rate holography is yielding valuable information on the details of streamer activity.

An important question arises: where do the bubbles come from, which take part in cavitation activity? In some experiments, means are provided for deliberately introducing gas, from which the bubbles evidently form. However, it is typically found that cavitation can be produced, without any obvious addition of gas bubbles. A widely accepted explanation of this finding is that the original liquid contains microscopic spaces, filled with gas or vapour, too small to be readily obvious. These spaces, often called cavitation *nuclei*, have been and still are the object of investigations which are described in Section 3.2. The nuclei are often gas-filled crevices in solid surfaces or gaseous spheres with 'skins' of organic material but may, alternatively, be 'hot spots' created by high energy particles or even quantum vortices in liquid helium.

When ultrasound first became available for research, investigators discovered an astonishingly wide variety of phenomena. It was found that solid surfaces were eroded, chemical reaction rates were altered and biological systems were affected. Specific tests showed that many of the physical, chemical and biological effects of ultrasound were mediated by some form of cavitation or bubble activity. Dr Young reviews the highly diverse literature on these subjects in Chapters 5, 6 and 8.

Sonoluminescence, the production of light by sound, has intrigued investigators for over fifty years, and still withholds some of its secrets. Much of the experimental evidence is consistent with predictions, for transient cavitation, that the gas or vapour in a bubble is subjected to high temperatures and pressures during collapse. Under these conditions light-producing electronic transitions within and among atoms occur at an accelerated rate. In Figure 5.7 it is shown that the sonoluminescent spectrum in oxygen-saturated water is like that expected from black-body radiation at 8800 K. Under other conditions the effective temperature is apparently lower, and the spectrum is as expected for specific chemical reactions. Under some conditions it appears that sonoluminescence does not require transient cavitation, and is produced by a less violent form of cavitation.

In his last chapter, Dr Young takes up various other applications which have been established, or suggested, for bubbles or cavitation. Like a good chef, he completes a gourmet meal with tasty samples. The diversity of the examples is amazing. Among the established applications are cavitation-based devices used by physicists to detect high-energy particles, instruments used in dentistry which utilize cavitation in descaling, and equipment for ultrasonic cleaning and soldering, which depend on cavitation for their effectiveness. It has been proposed that cavitation provides the high pressures needed to produce natural diamonds. On the other hand, cavitation can cause problems, as in sonar propagation, in oil drilling, in erosion of ship propellers, in liquid sodium used as coolant for nuclear reactors, and in decompression after diving or during space activities. Small gas bodies greatly accelerate effects of ultrasound on plants and insects. Whether the possibility of cavitation poses risk during medical applications of ultrasound is a question receiving close scrutiny. In everyday life, ingenuity and determination in getting the most from bubbles are called for in making bread, foaming beer and whipping egg white, as well as in the design of children's toys and soles for comfortable walking shoes.

Obviously, one's education is not complete without an understanding of the possibilities offered by cavitation in its various forms. Dr Young's carefully constructed and wide-ranging book provides readers an opportunity to become informed on this matter, either in depth, or in breadth, or in any combination of these qualities which may be desired.

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