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ANSI TECHNICAL REPORT

BUBBLE DETECTION AND CAVITATION MONITORING

ANSI S1.24 TR-2002

Accredited Standards Committee S1, Acoustics

Standards Secretariat
Acoustical Society of America
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Abstract

This Technical Report provides descriptions of 25 techniques that have been found useful for detecting and characterizing small gas-filled cavities or bubbles, and for monitoring cavitation activity. Acoustical, optical and electrical methods are among those employed for determining numbers, sizes and spatial distributions of bubbles. Physical, chemical and biological tests are used in monitoring cavitation activity. The procedures described have been applied to medicine, to oceanography and to materials processing. Guidance is offered on the techniques which have been found suitable for specific applications. Advantages and disadvantages are discussed. References are provided for further reading.

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Foreword

[This foreword is for information only and is not an integral part of ANSI S1.24 TR-2002 *ANSI Technical Report Bubble Detection and Cavitation Monitoring*]

Few liquids or solids are homogeneous; most contain cavities filled with air or other gas. The cavities may be large enough to be obvious, or may be very small. They may be desirable, as in foods or lightweight construction materials, or harmful if they cause weakness in structures or if they cause decompression illness during underwater or space activities. In diagnostic medicine, small gas-containing particles are introduced into the circulation to improve ultrasound images. In lakes and oceans, bubbles produced at the surface provide needed oxygen for aquatic life, but they present difficulties for sonar or other operations dependent on sound propagation. In industries it is sometimes desired to introduce gas into manufactured products, but the appearance of unwanted gas bubbles can be a serious problem.

Gas-filled cavities respond to a sound field in a complex activity known as acoustic cavitation. This includes simple breathing oscillations, shape oscillations, high-speed travel, jet formation, dramatic implosions, fragmentation, and interactions between bubbles. The high temperature produced in the gas phase during implosions leads to production of sonochemicals and/or sonoluminescence. The mechanical stresses and chemicals produced by acoustic cavitation are capable of causing a host of physical, chemical and biological effects which can be desired, as in sonic cleaning or sterilization, or harmful if unwanted chemical action or solid erosion is produced.

Many methods have been devised for detecting and sizing gas-filled cavities, for determining their distributions in space and time, and for monitoring their activity. In this report, 25 techniques are described by authors with knowledge and experience. Principles of operation are explained and applications discussed for each of the varied techniques. It is expected that there will be increasing need for this kind of information in the future, and it is hoped that this report will be a useful resource.

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> *Standards, specifications, methods of measurement and test terminology in the fields of physical acoustics, including architectural acoustics, electroacoustics, sonics and ultrasonics, and underwater sound, but excluding those aspects which pertain to safety, human tolerance and comfort.*

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ANSI Technical Report

Bubble Detection and Cavitation Monitoring

0 INTRODUCTION

Situations involving liquids often arise where properties, structures, or processes are affected, or disturbances are produced, by the presence of a gaseous or vaporous phase in the fluid. Among many non-acoustic examples are bubbling and filling processes used in industry, erosion of ship propellers, and decompression hazards encountered by divers and aviators. Among acoustic examples are noise generation from bubbles at the sea surface, and the diverse physical, chemical, and biological effects that can be produced by sound, especially by ultrasound. In all of these situations the changes can be attributed to some form of *cavitation*, when the latter is defined broadly, as it is in this report.

In some applications, one or more forms of cavitation are beneficial, as in sonochemistry and ultrasonic cleaning; it is then desired to optimize the action. In other applications, as in some applications of medical ultrasound, cavitation can be harmful. In studies of effects produced by sound in systems containing liquids, it is important to determine whether cavitation is occurring and, if so, to determine its nature and extent.

Cavitation activity comes about in response to a change in pressure at some location in a liquid. Under special conditions, a cavity containing vapor or gas can be created in a homogeneous liquid (away from boundaries) and become a site for cavitation, i.e., a *cavitation nucleus*. Much more commonly, the nuclei for cavitation are pre-existing gas-filled cavities; they are often of microscopic size, stabilized in some way against dissolution, and special means are required to detect and characterize them. Acoustical, optical, electrical, and other methods for determining the number and size of small cavities are described in Section 4.

In Section 5, methods are described for detecting and/or characterizing the cavitation activity itself. In its simplest form, the basic activity may consist of spherically symmetrical vibrations of one or more gas-filled bubbles. In many applications it involves motions that are more complex; these include surface waves, the formation of microbubbles or liquid jets, radiated shock waves, bubble coalescence, streaming of fluids within bubbles or external to them, and movements of the bubbles themselves. The vibrational motion can be studied by optical methods, or by acoustical methods for analysing the spectra of sound generated by the cavitation. In solutions or suspensions, cavitation produces any of a wide variety of physical, chemical, and biological effects whose results can be assessed and used as indices of cavitation activity. In organized biological tissues, known gas-filled cavities include respiratory channels, lung alveoli, and intercellular channels; sound may cause these to be activated with consequences that can be assessed biologically or by measurements of acoustic emissions. There is evidence that other cavities exist naturally in animal tissues, but little is known about their distribution or about effects resulting from their activation. In addition, in modern medical procedures utilizing diagnostic ultrasound, small gaseous bodies are introduced into the blood stream of patients to increase the contrast in images or add to information obtained with Doppler methods. In Clause 6, five selected applications are described for which needs exist for bubble detection and/or cavitation monitoring. For each of these, an assessment is made of techniques, especially those described in Clauses 4 and 5, which would be suitable in meeting those needs.

1 SCOPE, PURPOSE, AND APPLICATIONS

1.1 Scope

Equipment and techniques are described and compared (A) for detection and characterization of small gas-filled cavities or bubbles, especially those that may serve as sites for cavitation and (B) for monitoring cavitation activity. For purpose (A), optical, electrical, and acoustical techniques are employed. For purpose (B), physical, chemical or biological effects produced by the cavitation are assessed. Terminology is defined. Capabilities and limitations of the methods are discussed for various applications.

1.2 Purpose

The purpose of this technical report is to describe methods and procedures that may be used to detect, determine the size distribution of, or characterize acoustically, small gas bodies, especially those that may serve as sites for cavitation, or to detect and monitor cavitational activity. The procedures are intended for use by individuals (*e.g.*, materials processing engineers, oceanographers, bioeffects researchers, *etc.*) or institutions (*e.g.*, industrial, academic, governmental regulatory and research, *etc.*) with a need (1) to determine existing bubble populations, or (2) to evaluate the potential for, or level of, cavitational activity, or both (1) and (2). This report is intended to allow an informed choice of the methods and procedures best suited to the specific situation of interest, thus maximizing the quantity and quality of the information obtained and enhancing the understanding of the activity (physical, chemical, biological, *etc.*) occurring within the cavitation zone.

2 RELATED GENERAL PUBLICATIONS ON BUBBLE DETECTION AND CAVITATION MONITORING

‘‘Acoustic cavitation,’’ Appendix A, in IEEE Guide for Medical Ultrasound Field Parameter Measurements, Institute of Electrical and Electronic Engineers, New York, IEEE pp.79–90, (1990).

Lauterborn, W., ‘‘Bubble Spectrometry,’’ Part III in Cavitation and Inhomogeneities in Underwater Acoustics, Springer-Verlag, Berlin, (1979).

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WFUMB ‘‘Nonthermal issues: Cavitation—its nature, detection and measurement,’’ Chapter 2 in S. B. Barnett, Ed. WFUMB Symposium on Safety of Ultrasound in Medicine, Ultrasound in Med. & Biol. **24**, Suppl.1, S11–S21, (1998).

Young, F.R., ‘‘Bubble spectrum analysers,’’ Chapter 7 in Cavitation, McGraw-Hill Book Company, London, (1989).

3 DEFINITIONS

Accuracy (with which a bubble parameter can be measured). For a series of independent observations of a bubble parameter, the deviation of the mean from the true value of that parameter. For the accuracy, the numerical value is usually greater than for the precision, because of errors in the experimental procedures or in the interpretation of observations.

Bubble. A cavity that is nearly, or completely, surrounded by liquid.

Cavitation. The mechanical response of one or more cavities in a liquid or other medium of interest subjected to stress produced by acoustic, hydrodynamic, or other means.

Cavitation nucleus. A cavity that can serve as a site for cavitation.

Cavity. A volume filled with gas or vapor, or both.

Encapsulated bubble. A bubble in which the gas and liquid phases are separated by a thin shell of insoluble solid or liquid material.

Inertial cavitation. Cavitation in which the bubble involved contracts from some maximum size in a manner such that its initial motion approximates that of a Rayleigh cavity and its inward speed increases until a rapid rise in pressure within the cavity arrests its inward motion. (Previously called ″transient cavitation″).

Number density. Number of bubbles (or cavities) per unit volume.

Precision (with which a bubble parameter can be measured). The standard deviation from the mean in a series of independent measurements of that parameter; e.g., by observation in an optical microscope, the diameter of a bubble can be measured with a precision of 0.002 mm.

Rayleigh cavity. A model for a bubble in which it is assumed that an empty spherical cavity exists within a liquid for which the pressure at large distances is greater than zero and that the cavity remains empty as it contracts from its initial size.

Resolution, spatial. The smallest change in a spatial coordinate for which a change in a bubble-distribution parameter (such as the number density) or in a single-bubble parameter (such as its spatial location) can be measured*.

Resolution, temporal. The smallest time interval during which a change in a bubble distribution parameter, or single-bubble parameter, can be measured*.

Resolution, size. The smallest change in the radius (or other dimension) of a bubble that can be measured*.

Sensitivity (for detecting single bubbles or cavities). The diameter of the smallest bubble or cavity that can be detected*.

Sensitivity (for detecting multiple bubbles in a given range of size or range of linear resonance frequency). The smallest number of such bubbles in a given volume of liquid that can be detected*.

Stable cavitation. Cavitation in which the bubble involved oscillates about its equilibrium radius in a linear or nonlinear manner for an extended period of time.

Void fraction. Ratio of gas volume to total volume in a mixture of gaseous and liquid phases.

*Broad definitions are given here for resolution and sensitivity; specific forms vary somewhat for different applications.

4 TECHNIQUES FOR BUBBLE DETECTION AND SIZE DETERMINATION

4.1 Sound scattering

4.1.1 Quantity measured. The backscattered intensity vs. time, I (t), associated with an assemblage of bubbles whose nominal center is located within a resolution cell at range $c\tau/2$ where c is sound speed of the host medium and τ is time of travel from the sound source to the cell. (See also Section 4.2 on pulse-echo method in ultrasound imaging.)

4.1.2 Significance of method. The single-bubble scattering cross-section at resonance is typically larger by three orders of magnitude than its geometrical counter part [1,2]; the absorption cross-section at resonance is similarly enhanced. This is the basis behind resonant acoustic backscattering techniques to remotely detect and size bubble populations [3–6]. This method is broadly applicable to problems involving bubble detection in both bounded and unbounded media. For purposes of illustration, we discuss here a method that is typically applied to oceanic bubble populations. It can be used to estimate the bubble population's number density and size distribution, as well as the spatial profile of number density along an axis aligned with the backscattering direction (which is most often vertical).

4.1.3 Frequency range and bubble size. The typical frequency range for a sonar application is 20–250 kHz, which corresponds to resonance bubble radii of 160–13 μm. Note that when the resonant approximation is applied (discussed below) the upper limit on frequency should be approximately 75 kHz, which sets the minimum bubble radius at about 43 μm.

4.1.4 Sensitivity. Primary factors that limit sensitivity are range R (i.e., distance from the source transducer) and system noise level. The sensing volume increases as the square of the range, and also depends on sonar beamwidth θ and pulse length τ (see Vagle and Farmer [3] for discussion of sensing volume as a function of sonar system parameters). For example, in an ocean bubble measurement experiment by Dahl and Jessup [4], the sensing volume was approximately 160 m^3 at a range of 28 m. In this same example, backscattered intensities equivalent to that from 1 resonant-sized bubble per cubic meter were registered well above system noise levels, where the resonant bubble radius was close to 100 μm as defined by the acoustic frequency (see Section 4.1.7).

4.1.5 Temporal resolution. The temporal resolution depends directly on pulse repetition period, but is bounded by sonar range owing to two-way travel time. In oceanic applications, the pulse repetition period is typically about 250 ms. It should be noted, however, that backscattering from a random swarm of bubbles generally results in a rather broad exponential probability density function for intensity. The necessary ensemble averaging (usually about 4 pulses) to reduce variance will set the effective temporal resolution closer to 1 s.

4.1.6 Spatial resolution. Spatial resolution in the backscattering direction equals $c\tau/2$. The minimum pulse duration is determined by the resonant Q of the bubble, where $Q = 1/\delta$, and δ is the damping constant at resonance. For the bubble sizes mentioned above, Q is of order 10, so that, for example, a minimum pulse duration of about 1/3 ms is needed to reach the maximum resonant scattering amplitude for a bubble whose resonant frequency is 30 kHz. In practice, requirements to reduce system noise level will require use of longer pulse lengths, typically on the order of 1 ms, giving a spatial resolution of 0.75 m. Spatial resolution in the lateral direction will depend on range R and beam width θ, and is approximately $R\theta$.