Рабочая программы дисциплины

1. Название дисциплины: Acoustic cavitation

2. Лекторы

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3. Аннотация дисциплины

The course focuses on a systematic presentation of the laws of cavitation phenomena caused by intense acoustic waves in liquids. Along with the study of the gas bubbles' behavior, the accompanying acoustic cavitation processes in the surrounding liquid are considered. Learning material is relevant to widespread cavitation phenomena in nature and their many applications in ultrasound technology and medicine. The course examines the basic laws of dynamics of gas bubbles in acoustic fields and the specific application of acoustic cavitation in research and industry, as well as in medical diagnosis and therapy.

4. Цели освоения дисциплины

The main objective of this course is to familiarize students with how the presence of steam and gas cavities affect the mechanical strength of the liquid, what is the character of acoustic cavitation in different regimes, what conditions determine these regimes, what are the laws of propagation of acoustic waves in a medium with gas bubbles, and how the ultrasound-induced bubble activity impacts the liquid itself and objects located in it.

5. Задачи дисциплины

Objectives of the course are: (1) a systematic description of the physical foundations of the phenomenon of acoustic cavitation; (2) a description of the current state of research in this area; (3) acquaintance with the principles of specific devices that use acoustic cavitation in the industry and medical practice.

6. Компетенции

6.1. Компетенции, необходимые для освоения дисциплины

ПК-1, ПК-6, М-ОНК-2;М-ИК-2; М-ПК-8;

It is assumed that the students are familiar with basic methods of mathematical physics, as well as know the basics of acoustics and wave physics.

6.2. Компетенции, формируемые в результате освоения дисциплины

М-ПК-1; М-ПК-2; М-ПК-3; М-ПК-4, М-ПК-5; М-ПК-6; М-ИК-3; М-СПК-1

After listening to the course, the students will learn how to apply the methods of mathematical physics to solve a wide class of problems related to acoustic cavitation.

7. Требования к результатам освоения содержания дисциплины

As a result of learning the discipline the student should: (i) know about the effect of microbubbles on the mechanical strength of liquids; (ii) be familiar with the behavior of a single bubble under the influence of an alternating pressure of a sound wave; (iii) know the equation of bubble dynamics in general; (iv) be able to calculate the behavior of the bubble and acoustic waves in the approximation of small perturbations; (v) know the basic mechanisms of action of cavitation bubbles on the liquid itself and the objects contained in it; (vi) understand why bubbles are effective energy concentrators; (vii) be familiar with the physical phenomena which manifest this unique property of bubbles.

8. Содержание и структура дисциплины

Вид работы	Семестр				Всего
	1	2	3	4	
Общая трудоёмкость, акад. часов			72		72
Аудиторная работа:					
Лекции, акад. часов			18		18
Семинары, акад. часов			18		18
Лабораторные работы, акад. часов					
Самостоятельная работа, акад. часов			36		36
Вид итогового контроля (зачёт, зачёт с оценкой, экзамен)			зач.		

N раз-дела	Наименование раздела	Трудоёмкость (академических часов) и содержание занятий			Форма текущего контроля
		Аудиторная работа		Самостоятельная работа	
		Лекции	Семинары по теме		
1	Basic information of acoustic waves. Properties of fluids. Physical phenomena that play a role during acoustic cavitation	*Lecture №1 (2 hours)* Derivation of the wave equation from the hydrodynamic equations. Brief summary of the acoustic waves in liquids and gases. Traveling and standing waves. Wave beams. Spherical waves. Monopole radiation. Structure of liquids in terms of the molecular-kinetic theory. The phenomena of the surface tension, thermal conductivity, viscosity. Theoretical mechanical strength of liquids and its comparison with the experimentally observed values of tensile strength of the liquid.	*Seminar №1 (2 hours)* Study of theoretical material and solving problems relating to the lecture № 1	Derivation of solutions of the wave equation in the case of plane and spherical waves. Solution of the problem of the radiation of acoustic waves and infinitely large piston and pulsating sphere. *(2 hours)* Derivation of the Laplace pressure in the cases of spherical and cylindrical shapes of the liquid surface. Solution of three tasks to study the effects of surface tension, viscosity and thermal conductivity. *(2 hours)*	H, D, WT
		Lecture №2 (2 hours) Equations of dynamics of classical viscous fluid and some problems related to the dynamics of bubbles in the liquid: the drug force for a uniform translational motion of a solid sphere and the empty sphere; water hammer and its manifestation on impact of a liquid jet on the surface; added mass during the fluid motion. The solubility of gases in liquids. Henry's Law. Diffusion of the gas into the liquid. Examples of events where dissolved gas in the liquid plays the role.	*Seminar №2 (2 hours)* Study of theoretical material and solving problems relating to the lecture № 2	The solubility of gases in liquids. Henry's Law. Diffusion of the gas into the liquid. *(2 hours)* Movement of empty and solid sphere under the influence of a harmonic force in a viscous fluid *(2 hours)*	

2	Role of bubbles in mechanical strength of liquids	*Lecture №3 (2 hours)* Definition of cavitation. Varieties of cavitation: hydrodynamic, thermal (boiling), and acoustic cavitation. A brief discussion of mechanisms. Tension strength of fluid in the presence of gas bubbles. Laplace pressure in the bubble. The response of a single gas bubble to the static pressure. Blake threshold. Natural mechanisms of liquid purification from air bubbles.	*Seminar №3 (2 hours)* Study of theoretical material and solving problems relating to the lecture № 3	Types of cavitation. Features of acoustic cavitation in liquids. *(2 hours)* Tensile strength of fluid in the presence of gas bubbles. Laplace pressure in the bubble. Blake threshold. *(2 hours)*	H, D, WT
		Lecture №4 (2 hours) Features of bubble motion in a viscous fluid. Cavitation nuclei. Mechanisms to stabilize microbubbles. Experiments to measure the strength of the liquid.	*Seminar №4 (2 hours)* Study of theoretical material and solving problems relating to the lecture № 4	Motion of a bubble in a viscous liquid. Cavitation nuclei. *(2 hours)*	
3	Linear dynamics of a single gas bubble in a liquid with bubbles. Interaction of bubbles with acoustic field	*Lecture №5 (2 hours)* Derivation of equations of the dynamics of an empty cavity in the approximation of an incompressible fluid (Rayleigh equation). Accounting for the Laplace pressure and the gas pressure in the bubble. Linearization of the equations of bubble dynamics. The natural frequency of small oscillations (Minnaert frequency). Free and forced vibrations of the bubble. Stable cavitation. Emission of acoustic waves by an oscillating bubble in a linear approximation. Radiation and viscous losses.	*Seminar №5 (2 hours)* Study of theoretical material and solving problems relating to the lecture № 5	Rayleigh equation for bubble motion in an incompressible fluid. *(2 hours)* Stable cavitation. Stable cavitation threshold. Liquid degassing *(2 hours)*	H, WT
		Lecture №6 (2 hours) Gas bubble as an effective acoustic scatterer. Scattering cross-section and its dependence on the frequency. Sound propagation in a fluid with gas bubbles. Effective-medium model, the nature of the absorption and dispersion.	*Seminar №6 (2 hours)* Study of theoretical material and solving problems relating to the lecture № 6	Scattering cross-section of the gas bubble and its dependence on the frequency. *(2 hours)* Sound propagation in a liquid with bubbles. Effective compressibility. Speed of sound. *(2 hours)*	

4	Nonlinear phenomena in cavitation. Rectified diffusion of gas during the bubble oscillations	*Lecture №7 (2 hours)* Nonlinear bubble oscillations induced by the acoustic wave. The generation of harmonics and subharmonics. Artificial polymeric shell bubbles and their use as contrast agents in medical diagnostics. Bjerknes forces. Radiation force acting on bubbles in traveling and standing acoustic wave. Interaction force between two vibrating bubbles. The role of gas diffusion in the dynamics of the bubble. Rectified diffusion. Stable cavitation.	*Seminar №7 (2 hours)* Study of theoretical material and solving problems relating to the lecture № 7	Cavitation detection. The generation of harmonics and subharmonics. Experimental measurement of the cavitation threshold in liquid. *(2 hours)* The forces acting on the bubble in the acoustic wave. *(2 hours)*	H, D
5	Extreme events in the collapse of bubbles	*Lecture №8 (2 hours)* Rayleigh problem of the collapse of an empty cavity in an incompressible fluid. Exact solution based on the availability of gas in the bubble. Bubble as an energy concentrator. The degree of increase of pressure and temperature in the collapse. Time of onset of collapse. Sonoluminescence. Its mechanisms and characteristics. Sonoluminescence in a cavitation cloud and in a single bubble. Sonochemistry. The hypothesis of the possibility of reaching a thermonuclear reaction in a collapsing bubble.	*Seminar №8 (2 hours)* Study of theoretical material and solving problems relating to the lecture № 8	The collapse of the bubble in the sound wave. Sonoluminescence. *(2 hours)* The possibility of a thermonuclear reaction during the collapse of bubbles. *(2 hours)*	H, D
6	Transient acoustic cavitation. Acoustic cavitation in medical ultrasound applications	*Lecture №9 (2 hours)* Transient acoustic cavitation. Its thresholds. Instability of the bubble shape. Creation of microjets in the collapse and their role in the cavitation erosion of solids. Experimental methods for the study of transient cavitation. Passive and active detection of cavitation. Mechanical Index in the ultrasound application to medical diagnosis. Cavitation thresholds in tissues. Role of acoustic cavitation in the destruction of tissues in ultrasound therapy. Cavitation histotripsy and boiling histotripsy.	*Seminar №8 (1 hour)* *Demonstration (1 hour).* Observation of cavitation in a high-intensity ultrasonic beam emitted by a piezoceramic source at a frequency of 1 MHz. Observation of cavitation caused by the ultrasonic magnetostrictive source at a frequency of 18 kHz. Discussion.	Transient acoustic cavitation threshold. Generation of microjets and shock waves. *(2 hours)* Role of cavitation at the drug delivery. Mechanical Index. *(2 hours)* Lithotripsy and the role of cavitation in the destruction of kidney stones. *(2 hours)*	H, WT

Предусмотрены следующие формы текущего контроля успеваемости:

1. Homework (H);
2. Written test (WT);
3. Oral test (OT);
4. Discussion (D).

9. Место дисциплины в структуре ООП ВПО

1. Дисциплина является обязательной.
2. Вариативная часть, профессиональный блок, научно-исследовательский семинар.
3. The teaching is based on the knowledge gained in the earlier all-faculty courses on mathematical physics and undergraduate programs of the Department of Acoustics, in particular, "Fluid Mechanics", "Introduction to Acoustics," "Wave Theory" and "Theoretical Foundations of Acoustics."
   3.1. Дисциплины, которые должны быть освоены для начала освоения данной дисциплины:
   Mathematical Analysis, General Physics courses
   3.2. Дисциплины, для которых освоение данной дисциплины необходимо как предшествующее:
   Research practice, research work

10. Образовательные технологии

Presentation is given mainly in the traditional way (using chalk and blackboard). Some laws of cavitation phenomena are illustrated using computer projector. In addition, experimental demonstration are conducted of cavitation in the field of high-power ultrasonic sources. During the colloquium, a general discussion is performed on the topic of the course.

11. Оценочные средства для текущего контроля успеваемости и промежуточной аттестации

Вопросы к зачету по спецкурсу «Акустическая кавитация»

1. Write linearized hydrodynamic equations and deduce from them the wave equation for the acoustic waves.
2. What are the features of sound radiation by an oscillating sphere?
3. Write the formula for the Laplace pressure in the case of cylindrical and spherical interfaces between a liquid and a gas.
4. Write the heat transfer equation and explain the physical meaning of the relevant quantities.
5. Write expression for the drag force at a slow uniform motion of a solid sphere in a viscous fluid.
6. Provide expression for the pressure that appears during water hammer effect.
7. Response of a single gas bubble to static pressure. Blake threshold.
8. Derive the equation of the dynamics of an empty cavity in the approximation of an incompressible fluid (Rayleigh equation).
9. Write Rayleigh equation and make its linearization. Derive the natural frequency of small oscillations (the Minnaert frequency).
10. Based on the solution of the linearized Rayleigh equation, express the scattering cross-section of the bubble and its dependence on frequency.
11. Apply the method of successive approximations to the Rayleigh equation to obtain an expression for the signal emitted by the bubble at the second harmonic of the incident harmonic wave.
12. Get exact solution of the Rayleigh equation for the dynamics of an empty spherical cavity in an incompressible fluid. Time of onset of collapse.
13. What is sonoluminescence? Types of sonoluminescence and its mechanisms.
14. What is the Mechanical Index and how it characterizes the safety levels of ultrasound? Cavitation thresholds in tissues.
15. Role of acoustic cavitation in ultrasound therapy. Cavitation histotripsy and boiling histotripsy.

Образцы задач для самостоятельного решения

Problem 1. Under the influence of the acoustic wave radius of a gas bubble in a liquid decreased from R_1=10 μm to R_2=5 μm. Assuming an adiabatic compression process, calculate the final temperature t_2 and the gas pressure in the bubble p_2. The initial parameters t_1=20°C and p_1 = 1 atm. Adiabatic exponent is γ = 5/3.

Problem 2. Free oscillations of a gas bubble in a liquid are described by the following equation for the bubble radius R:

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho_0}\left\{\left[p_0+\frac{2\sigma}{R_0}\right]\left(\frac{R_0}{R}\right)^{3\gamma}-\frac{2\sigma}{R}-p_\infty\right\},$$

where the dot denotes differentiation with respect to time, $\rho_0,\ p_\infty,\ \sigma,\ \gamma$ are constants equal respectively the fluid density, external pressure in the liquid, the surface tension of the liquid and gas adiabatic exponent, R_0 is unperturbed bubble radius. Linearizing the equation, obtain an expression for the free oscillation period.

Problem 3. A gas bubble of radius R_0 = 1 μm performs small oscillations in the liquid at ambient pressure (p_0 = 1 atm = 10^5 Pa). Determine the period of free oscillations of the bubble. Adiabatic exponent is γ = 5/3, the surface tension is σ = 0.08 N/m.

Problem 4. A gas bubble is sitting in a fluid. In the initial state, the pressure in the liquid is p_0 , the initial bubble radius R_0 . The pressure of the liquid is very slowly (so that the state of the gas in the bubble can be assumed isothermal) is lowered to a value p. It is known that the gas pressure in the bubble p_{bubble} is expressed through fluid pressure p as follows: $p_{\text{bubble}} = p+2\sigma/R$, where σ is the surface tension of the liquid.
Questions:

1) Find a formula relating the final bubble radius R with finite pressure p;
2) Find the negative pressure threshold $p_{\text{threshold}}$ in the liquid, from which a further decrease of the pressure p will lead to instability of the bubble (i.e., a lack of equilibrium values of the radius of the bubble) - Blake threshold.

Problem 5. Find a threshold for the negative fluid pressure $p_{\text{threshold}}$, from which a further decrease of the pressure will lead to instability of the bubble (i.e. lack of equilibrium values of the radius of the bubble) - the so-called Blake threshold, for a bubble with an initial radius of 0.5 μm.

12. Учебно-методическое обеспечение дисциплины

Основная литература:

1. Croxton, C.A. Introduction to Liquid State Physics. - John Wiley & Sons Ltd,1975, 296 pp.
2. Frenkel, J. Kinetic Theory of Liquids. - Peter Smith Publisher, Incorporated, 1984, 488 pp.
3. Hill, C.R., Bamber, J.C., and ter Haar, G.R. (Eds.) Physical Principles of Medical Ultrasonics, 2nd edition. – John Wiley & Sons, 2004, 528 pp.
4. Flynn, H.G. Physics of Acoustic Cavitation in Liquids. In: Physical Acoustics, vol. 1, part B (ed. by Mason, W.P.). - Academic Press, New York, 1964, pp. 57-172.
5. Shutilov, V.A. Fundamental Physics of Ultrasound. - CRC Press, 1988, 378 pp.
6. Akulichev, V.A. Pulsations of cavitation voids. In: High Intensity Ultrasound Fields (ed. by Rozenberg, L.D.) – Plenum, New York, p. 205, 1971.
7. Leighton T.G. The Acoustic Bubble. - Academic Press, 1994 - 613 p.
8. Young F.R. Cavitation. - Imperial College Press,1999 - 418 p.

Дополнительная литература:

1. Резибуа П., Де Ленер М. Классическая кинетическая теория жидкостей и газов. М.: Мир, 1980. - 424с.

2. Гаврилов Л.Р. Фокусированный ультразвук высокой интенсивности в медицине. – М.: Фазис, 2013, 656 с.
3. Перник А.Д. Проблемы кавитации. – Л.: Судостроение, 1966. – 439 с.
4. Пирсол И. Кавитация. – М.: Мир, 1975. – 95 с.
5. Рождественский В.В. Кавитация. – Л.: Судостроение, 1977. – 248 с.
6. Федоткин И.М., Немчин А.Ф. Использование кавитации в технологических процессах. – Киев: Вища шк., 1984. – 68 с.
7. Маргулис М.А. Основы звукохимии (химические реакции в акустических полях): Учеб. пособие для хим. и хим.-технол. спец. вузов. – М.: Высш. шк., 1984. – 272 с.
8. Бергман Л. Ультразвук и его применение в науке и технике. – М.: Иностр. лит., 1957. – 726 с.
9. Бронин Ф.А., Чернов А.П. Удаление заусенцев и диспергирование порошковых материалов при воздействии ультразвука. – М.: Машиностроение, 1978. – 55 с.

Периодическая литература:

1. Apfel R.E. Sonic effervescence: A tutorial on acoustic cavitation. - J. Acoust. Soc. Am., 1997, v. 101, no. 3, pp. 1227-1237
2. Bailey, M.R., Khokhlova, V.A., Sapozhnikov, O.A., Kargl, S.G., and Crum, L.A. Physical mechanisms of the therapeutic effect of ultrasound (A review). - Acoustical Physics, 2003, v.49, no.4, pp.369–388.

Интернет-ресурсы: http://acoustics.phys.msu.ru

13. Материально-техническое обеспечение

В соответствии с требованиями п.5.3. образовательного стандарта МГУ по направлению подготовки «Физика».

Учебная аудитория физического факультета МГУ

Специализированные компетенции профильной направленности обучения (специализированные компетенции магистерской программы)/ Competencies.	
М-СПК-1	Deep understanding of the physics of cavitation phenomena occurring during propagation of intense acoustic waves in liquids. Ability to apply the acquired knowledge about the dynamics of gas-vapor cavities in the liquid in specific experimental situations involving different regimes of acoustic cavitation. The ability to calculate the parameters of acoustic radiation required to create a particular regime of cavitation. Understanding the mechanisms of action of oscillating bubbles on the fluid and embedded objects in relation to the processes used in modern ultrasound technologies. Understanding the role of acoustic cavitation in medical ultrasound applications, the ability to calculate safe levels of acoustic pressure in ultrasound devices used for medical diagnostics. Ability to solve problems on the dynamics of gas bubbles in a liquid with the help of modern mathematical methods. Ability to organize and plan applied and fundamental research on acoustic cavitation using facilities, equipment, and information technology. Skill to describe research results in the form of research reports, articles and presentations.