The subject of the thesis of P. Yuldashev is devoted to the problem of high intensity acoustic waves propagation in turbulent and randomly inhomogeneous nonlinear media. Investigations in this field are stimulated in particular by increasing of requirements for diminishing noise of aircrafts and by necessity to develop objective criteria for ecological security. On the other hand, the investigations are stimulated by rapid development of medical ultrasound technology, in particular, the methods of non-invasive surgery based on use of high intensity focused ultrasound. The great attention is devoted to accuracy of focusing of intensive ultrasound pulses on objects in the presence of inhomogeneities of biological tissue. Development of ultrasound diagnostics methods with use of second harmonic generated in tissue explains the high interest to detailed investigation of focusing of harmonics of nonlinear acoustic waves in media with randomly distributed inhomogeneities.

In the thesis original experimental and theoretical results of investigations of shock waves propagation in media with thermal turbulence and of the process of generation and focusing of acoustical harmonics of nonlinear waves propagated through phase screen with random inhomogeneities are presented.

The methods of numerical modeling of nonlinear wave processes become more important in the modern investigations of sound propagation in turbulent and randomly inhomogeneous media. The numerical methods are of special importance in those cases, when realization of the full-scale experiments is problematic and capability of analytical methods is essentially limited. In spite of rapid evolution of modern computational facilities and methods, three-dimensional multi-scale problems, similar to those considered in the thesis, require considerable amount of computational resources, so that the solution can be obtained only using specially developed algorithms adapted to the particular physical problems. Considerable part of the thesis is devoted to development of such algorithms and their application to numerical modeling of nonlinear wave processes in randomly inhomogeneous media.

The studies presented in the thesis were realized in the framework of international scientific collaboration with Laboratory of mechanics of fluid and acoustics of Ecole Centrale de Lyon (France).

The dissertation consists of introduction, five chapters, conclusions, four appendixes and list of references, expounded in 157 pages.

In the introduction the problem setting is presented, the targets of the work are formulated, the obtained new results are listed and the scientific and applied values are pointed out.

The first chapter is devoted to measurements of the shock rise time of spherical N-wave in air using acoustical microphones and optical shadowgraphy methods and to the comparison of experimental results with numerical simulations data. Description of experimental setup for acoustical and acoustooptical measurements is given. Simulations of N-wave waveform based on augmented Burgers equation taking into account molecular relaxation are presented, influence of different physical effects on N-wave propagation in gas is analyzed.

The wave generated by a spark source is measured by acoustical and optical methods, and the comparison of experimental data with simulations data is provided. It is important that for interpretation of data of optical measurements, numerical simulations of intensity distributions of light diffracted on N-wave is done. It is shown that, contrary to acoustical measurements, processing of optical measurements data allows to measure the shock rise time as small as 0.1 µs and gives the results which are in good agreement with numerical simulation data of N-wave propagation.

In the second chapter 2 propagation of N-wave in medium with thermal turbulence is studied experimentally. Description of original experimental setup built in Graduate Engineering School of Lyon (ECL) which is designed for investigation of sound propagation through turbulent medium is given. The spatial maps of statistical moments of turbulent fluctuations, measured close to the propagation path of the wave, are presented. Spatial correlation functions of thermal turbulence and spectra of acoustical refraction index are determined experimentally. The experimental spectra are compared with modified von Kármán spectra. The measured characteristic waveforms of N-wave distorted after propagation through the turbulent layer are presented. Histograms and averaged characteristics of peak positive and peak negative pressures, the shock rise time, arrival time, and duration are also provided. The comparison of statistical characteristics of media with thermal and kinematic (vector) turbulence is done. The distribution functions of peak positive pressure, shock rise time and arrival time of acoustic wave, measured in thermal turbulence by author, are compared with those measured in kinematic turbulence and reported in other studies. It is shown that, in the similar conditions, the kinematic turbulence leads to stronger distortions of N-wave parameters, demonstrating higher probabilities of random focuses with amplitude two times greater than for the wave in homogeneous medium.

The third chapter contains the results of theoretical investigations of statistical characteristics of N-wave propagated behind random phase screen. The author developed numerical model of N-wave propagation behind one dimensional phase screen taking into account diffraction effects in the framework of KZK equation. The numerical model of phase screens is presented and spatial distributions of peak positive pressure of N-wave behind the screen are calculated. Formation of multiple caustics in the acoustic field is demonstrated and characteristic examples of distorted N-waves are given. Statistical characteristics of peak positive pressure of the N-wave are also provided. It is shown, that the phase screens which lead to equivalent results in statistical sense in the approximation of nonlinear geometrical acoustics, produce different statistical distributions of acoustic field for different characteristic scales of phase fluctuations of the screen. The distortions of N-wave waveform close to caustics are demonstrated. Influence of nonlinear effects on statistical characteristics of N-wave behind phase screen is studied.

In the fourth chapter processes of focusing of harmonics in the finite amplitude wave behind random two-dimensional phase layer are studied theoretically and experimentally. Original numerical algorithm is developed for this purpose. The algorithm is based on integration of three-dimensional Westervelt equation using method of fractional steps with the operator splitting taking into account effects of diffraction, nonlinearity and absorption. Realistic model of distribution of acoustic pressure on the source is constructed. Model of random phase layer is thoroughly elaborated. The results of simulations are shown which are demonstrated the processes of selective destruction of focusing of separate harmonics if 180° and 90° phase shifts are inposed on inhomogeneities of the layer. A possibility of focusing of higher harmonics in the case of destruction of the focal distribution at fundamental frequency is shown. Results of simulations are compared with the data obtained in the experiment with use of specially fabricated phase layers with 180° and 90° phase shifts of randomly distributed inhomogeneities. Focusing of the first six harmonics at different positions of the layer between the source and the focal plane is analyzed. On the whole, experimental results are in good agreement with simulations data.

The fifth chapter is devoted to modeling of three dimensional nonlinear acoustic fields of multi-element radiating arrays, which are used for ultrasound therapy. Modeling is based on Westervelt equation. High complexity of the problem which is explained by its multiscale properties both in space and in time, required elaboration of special numerical algorithm described in details in the thesis. Results obtained using the new algorithm are compared with known solutions of testing problems in the cases when linear and nonlinear parabolic approximations are valid. A good agreement of results is shown in the comparison. The developed algorithm is applied to simulations of the acoustic field of multi-element array and to establishing the model of equivalent axially symmetric source.

A great scope of theoretical and experimental research is carried out by the author and new scientific results are obtained which are important for applications. Among the results are studies of statistical characteristics of shock waves in the medium with thermal turbulence, development of numerical models of nonlinear wave propagation behind phase screens taking into account diffraction effects and development of new numerical algorithm to resolve three-dimensional problems of nonlinear acoustics. The thesis distinguish careful elaboration of experimental and numerical methods, diversified comparison of the obtained results with the data of different authors and results of asymptotic solutions, which provide reliability and validity of the summarized results of the thesis. The study has undoubted practical value for prediction of the properties of shock waves propagated through the turbulent atmosphere. The proposed algorithms of modeling of nonlinear wave processes in regular and inhomogeneous random media can found direct application in the development of medical equipment.

As remarks I have to note, that in the Westervelt equation, which was used in numerical simulations, the contribution of derivatives of Lagrangian of acoustic field was not taken into account, which, in my opinion, should be additionally verified in the cases of such complex fields as the fields of multi-element arrays. The peak negative pressure data presented in Fig. 2.11, which are demonstrated significant discrepancy between the theory and the experiment, are not commented. As a request for future work, I suggest to consider a possibility to include the PML method into the developed algorithm, which will do it more universal.

The remarks mentioned above do not change the general high appreciation of the presented work. It is carried out at high scientific level. The results of the thesis are well approved at the number international conferences and scientific seminars, and are reported in 21 publications, including 5 papers in the reviewed journals.

Taking into account the scope and profundity of investigations, scientific level, novelty and importance of the results, the presented work undoubtedly corresponds to the grade of PhD thesis. I express my very favorable opinion that P. Yuldashev merits awarding of PhD scientific degree in acoustics.

I have reviewed the English version of the thesis entitled “Nonlinear shock wave propagation in random media with inhomogeneities distributed in space or concentrated in a thin layer,” submitted by Petr Yuldashev to L’Ecole Centrale de Lyon as part of his requirements towards obtaining the title docteur spécialité acoustique. The thesis advances the current state-of-the-art in nonlinear acoustic propagation in two fields: the first is N-wave propagation in air and the second ultrasound propagation in liquids. In both topics advances in experimental and computational fields are presented.

The first three chapters consider the propagation of N-waves in air. This is motivated by the propagation of sonic booms in the atmosphere: a topic that is of renewed interest in the aeronautics community as there is there is reason to be cautiously optimistic that supersonic business jets may be allowed to fly overland in the foreseeable future. One aspect of the approval process is providing limits on the loudness of the sonic boom at the ground in the presence of a turbulent atmosphere. This involves understanding the propagation of shock waves with an N-wave shape that propagate through a random three-dimensional turbulent atmosphere. Of particular interest from the point of view of predicting loudness is getting the shock rise time structure correct because this rise time is one aspect of the waveform that correlates with perceived annoyance. Mr Yuldasehev first presents an optical method of measuring the shock rise time for model shock waves generated by sparks. He uses shadowography to image the propagation of the acoustic wave and by modelling the diffraction of light by the shock wave is able to show how the optical bands can be used to determine the rise time. He shows very elegantly how optical ray theory can not be used to accurately measure the rise time and that it is necessary to account for optical diffraction to correctly determine the rise time from the structure of the diffraction bands.

In the second chapter he reports on measurements of N-waves through a turbulent atmosphere. Here either a jet was used to generate kinematic vectorial turbulence or a heated grid to create a scalar thermal turbulence. He uses a clever analysis of the spectra of the N-waves to determine their duration even in the presence of complex shock structure. It was demonstrated that kinematic turbulence could have a dramatic effect on the peak pressure, duration and rise time of the shock wave. Although in most cases the effect of the turbulence was to decrease both the peak pressure and rise time, which should decreases perceived annoyance, there were a non-negligible number of N-waves in which the peak pressure was more than double and the rise time was decreased. The experimental work is followed by numerical calculations in Chapter 3. The two-dimensional model accounted for nonlinearity and absorption. The effect of turbulence was accounted for by means of a phase screen and he showed qualitative agreement with the experimental data in Chapter 2. It was also demonstrated that the geometrical acoustics can only be used for a limited propagation range.

Chapters 4 and 5 consider the case of nonlinear ultrasound propagation for biomedical and nondestructive testing applications. In this case a new numerical algorithm was developed to solve the Westervelt equation, this alleviates the paraxial approximation that is invoked in the widely used KZK equation. The development of this new technique is a very significant new advance. In biomedical ultrasound, in particular, the development of therapeutic ultrasound, which employs very large sources, violates the paraxial approximation. Here an angular-spectrum approach is developed to model the diffraction exactly. In Chapter 4 the algorithm is used to model the effect of a phase screen on focused ultrasound propagation. This is relevant to diagnostic ultrasound imaging where it has been shown that “harmonic imaging” where the nonlinear components are used to create the image creates better images than imaging based on linear acoustics. It has been hypothesised that the image improvement occurs because the nonlinear effects are not affected by phase aberration induced by subcutaneous fat. By using a phase screen approach it is shown both with the new computational model and experimental measurements that the harmonics are indeed much less affected by near field aberration. This supports one of the possible mechanics by which harmonic imaging results in better images. In the last chapter the full-diffraction numerical model is used to model a large commercial therapeutic array. The simulation was completely three-dimension and considered a complex source consisting of 256 individual elements. A structured spatial grid was employed in which fine resolution was only used in the focal region where most of the harmonics occurred. Results are shown for the acoustics field and compared with the KZK equation. It is demonstrated that the KZK equation does remarkably well in predicting the field, however, some important details such as peak pressure and off-axis structure are not so well captured by the KZK equation. Therefore depending on the accuracy desired the work here can be used to determine which model is appropriate.

In conclusion the doctoral thesis submitted by Petr Yuldashev represents an important advance in the state-of-the-art of nonlinear acoustics propagation. He has presented both experimental techniques and numerical codes that are significant and important improvement over current methods. He has shown advances in two different fields which are highly relevant to today’s society: N-wave propagation in the atmosphere and biomedical ultrasound propagation. I consider this a tour-de-force of nonlinear acoustics. In my opinion this is an thesis of excellent scientific quality and I recommend, without reservation, the oral presentation of the work of Petr Yuldashev to obtain the title of "Docteur de L'Ecole Cnetrale de Lyon, Specialite Acoustique.”

Dear Sir/Madame,

With this letter I confirm that Mr. Petr Yuldashev has successfully passed the presentation of his Ph. D. thesis in front of the Academic Council D 501.001.67 of M.V. Lomonosov Moscow State University specialized in Optics, Radiophysics, and Acoustics.

The presentation of the PhD thesis took place 10 November 2011 in the presence of the Russian jury (22 members including 7 DrSc members specialized in Acoustics) and French jury (7 members, 6 of which were present). Specialization of the PhD thesis of Mr. Petr Yuldashev was in acoustics (specialization number 01.04.06). The language of defense was Russian, but the members of French jury had slides translated in English. The dissertation received high appreciation by official reviewers and other members of the juries. Prof. Daniel Juve, the member of the French jury, spoke in public as follows:

“As you certainly know, for this “co-tutelle” thesis, we have in parallel to the Russian jury also a French jury with two external reviewers. The first one was common to the two juries, Prof. Vladimir Preobrazhensky, and the second one was Prof. Robin Cleveland from Oxford University, UK. It was not possible for Prof. Cleveland to come to Moscow and participate in the thesis defense. However, he wrote a very detailed report. Let me just cite 2 or 3 sentences from the conclusion of his report to illustrate his opinion on the work done by Petr Yuldashev: “The thesis represents an important advance in the state-of-the-art of nonlinear acoustics propagation. The candidate has presented both experimental techniques and numerical codes that are significant and important improvements over current methods. I consider this as a tour-de-force of nonlinear acoustics”. Let me add a few words from a more personal point of view. This is the second “co- tutelle” thesis with co-direction between the acoustics group of the Physics Department of MSU and our group in Ecole Central de Lyon. This collaboration has proven to be very efficient and productive. I hope that it will continue in the future with a new PhD student.”

The results of voting of the Russian jury were the following: favourable – 22 votes, opposite – none, void – none. Taking into account the voting results, the Academic Council D 501.001.67 graded Petr Yuldashev the PhD degree. The dossier containing official papers which refer to the defence of Mr. Petr Yuldashev was submitted for approval to Higher Examination Committee of Russian Federation on 6 December 2011. The approval is expected to be received in several months.