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Software for Acoustic Design

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Abstract

We present the CATEC software, which implements the solution to the problems of computational acoustics. The software is based on the use of the superelement method and finite element modeling algorithms, including hydrodynamic noise. The paper presents the main possibilities of software for solving acoustic design problems.

Keywords

Software, Acoustic Design, Acoustic Radiation, Superelement Method, Finite Element Methods, Absorbing Boundary Conditions, Hydrodynamic Noise, Mode Analysis

1. Introduction

Evaluation of vibroacoustic characteristics (VAC) is relevant for a number of acoustic design problems. Currently, with allowance for the computer technology development, such predictive estimates can be carried out numerically using finite element (FE) and superelement (SE) models of different degrees of detail.

In the interests of the above, the IAP RAS developed the CATEC (Computational Acoustics Technologies) software. The software is designed for high-performance numerical simulation of vibroacoustic processes and acoustic diagnostics of various complex mechanoacoustic systems.

The CATEC software makes it possible to solve different applied and research problems in the field of acoustics. The author's numerical algorithms developed using the software enable one to predict the VAC on the hardware of average performance in an acceptable time. High accuracy of modeling of sound radiation and propagation and high speed of calculations are provided at the same time due to innovative technologies. The solution to the problems of sound emission by elastic bodies, which interact with a turbulent fluid flow, is also provided in the software. It is also possible to single out the possibility of evaluating the spectral characteristics of objects with allowance for the properties of the surrounding fluid and acoustic radiation losses.

The developed software has a modular client-server architecture and a convenient modern graphical user interface and allows to download experimental data and interface with extraneous software packages in terms of importing FEM and hydrodynamic calculation results.

2. Superelement Method of Modeling of Mechanoacoustic Systems

Harmonic analysis (HA) is an important tool for analyzing the VAC of objects. The HA principle consists in solving the problems of finding steady-state oscillations at a certain frequency in the presence of harmonic excitation. The problem can be solved using both the direct method (calculation of mechanical vibrations and acoustic waves caused by periodic force) and the reciprocity principle (calculation of vibrations caused by an external acoustic source). The result of the calculations is the dependence of the pressure amplitude or vibrations on the frequency, *i.e.*, the amplitude-frequency response (AFR). In the field of acoustic design, a series of calculations take place, which are performed from various options of external sources and input parameters to identify the effectiveness of layout solutions and acoustic protection means. All this leads to an excessive increase in time resources and computing power.

The above difficulties led to the creation of the technology of acoustic superelement method in the CATEC software. The essence of this technology is the fact that a numerical object is divided into components, namely, superelements that interact with each other at the junction, *i.e.*, in the interface nodes. **Figure 1** shows an example of a design consisting of three superelements: front and rear structures in the fluid volume and internal shock-absorbing equipment. Interface nodes are highlighted with green markers.

The fundamental point of the developed algorithm is its use to describe harmonic processes for which all calculations are performed in the complex domain at a given frequency. Due to the alternate loading of the SE into memory, the requirements for the amount of random access memory (RAM) can be significantly reduced and the calculation matrices of the systems can be decreased to a much smaller size, as a result of which the estimate time can be dramatically

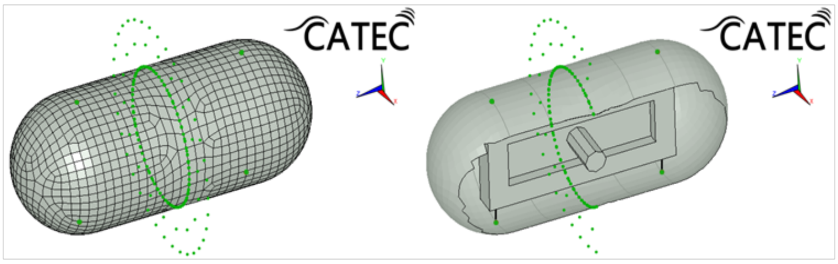

Figure 1. Superelement model of a mechanoacoustic system.

reduced as well.

The SEM makes it possible to exceed 10 million degrees of freedom even without the use of supercomputers and enables one to study the acoustic properties of objects with an overall length exceeding the length of an acoustic wave in a liquid by 20 times and the length of an elastic bending wave on a deformable solid body by 100 times. The superelement method is well adapted to the cluster architecture, since the calculation of Schur complement [1] for different SEs (or for one SE, but for different frequencies) can be performed at different nodes in parallel. The division of the model by interface nodes at the structure joints is the most rational way of dividing the problem to distribute it among computing nodes and allows to achieve a good ratio of data transmission costs to computing costs.

The CATEC software allows for supercomputer modeling with the ability to control calculations in real time for both shared memory systems (OpenMP) and distributed memory systems (MPI). The use of MPI in terms of resource-intensive calculation modules, which are based on the function of solving a sparse system of linear algebraic equations, makes it possible to reduce the requirements for the amount of RAM on computing nodes and speed up the calculation. Parallel models use a solver from the MUMPS library, which is compiled from source codes. Maximum performance in solving systems of linear algebraic equations is achieved by employing hybrid parallelism MPI+ OpenMP. In this case, one instance of the MPI process is launched on each computing node, within which parallelism is achieved due to multithreading in a single address space.

Significant efficiency, in terms of ensuring both high speed and low calculation error in the technical description of mechanoacoustic systems, has been achieved due to the introduction of the author's algorithm for non-conformal discretization of the two-phase surface "a deformable solid body—acoustic environment" with a significant reduction in the requirements for the size of the grid step of the latter [2]. In this formulation, the interaction between individual fragments of the FEM is performed not at the expense of common grid nodes but using special contact interfaces (contact pairs). This allows efficient non-conformal discretization of the computational domain relative to the two-phase surface, *i.e.*, different grid partitioning for the space regions occupied by a deformed solid body and a liquid region without a significant reduction in modeling accuracy. The advantage of this approach is the ability to reduce computational resources by using grids of fluid region in increments of the larger value and increase the accuracy of modeling by reducing the number of low-quality elements.

For numerical modeling of mathematical physics problems, the boundary conditions for which are set at infinity, the CATEC software provides the possibility of employing absorbing boundary conditions. They provide absorption of incident waves and account for the added mass fluid. The algorithm developed for this purpose uses the advantages of the FE and boundary element (BE) methods, since it enables one to form boundary conditions accurately enough without resorting to FE approximations, and due to the use of the axisymmetric geometry of the external fluid region, the algorithm provides a significantly faster formation of boundary conditions than in the GE method. The discretization of the grid model on a surface remote from the surface of the emitting body is determined by the acoustic wave length, which positively affects the speed of calculations.

3. Hydrodynamic Noise Modeling

The CATEC software implements the author's numerical method for solving the problem of calculating hydrodynamic noise based on the FEM. A significant difference in the scale of hydrodynamic and acoustic processes leads to the need to divide the problem into two independent parts, namely, hydrodynamic and acoustic. In this case, the noise radiation of bodies moving in a fluid is interpreted as a scattering process on a streamlined surface of short-circuited pseudosonic waves created by turbulence [3].

The calculation of hydrodynamics is carried out using various extraneous software [4] [5], where the sources of hydrodynamic noise are determined through hybrid numerical methods [6] [7]. **Figure 2** shows an example of a hydrodynamic vortex flow in a cavity.

The calculation of acoustic radiation, which is performed in the CATEC software within the framework of the used method, can be carried out by 2 algorithms:

1) Short-circuited turbulent pseudosonic sources are represented by a set of quadrupoles moving along the flow with a local hydrodynamic velocity, which avoids the occurrence of unbalanced monopole sources that make the pseudosonic field scattered by an elastic body noisy as a result of interpolation of the results of solving the hydrodynamic problem on an acoustic grid.

2) Modeling of the hydrodynamic noise radiation is performed on the basis of information on pressure fluctuations on the surface of a streamlined body. Obtaining the distribution of the sound field provides an inhomogeneous Helmholtz equation with allowance for the boundary conditions of non-flow through

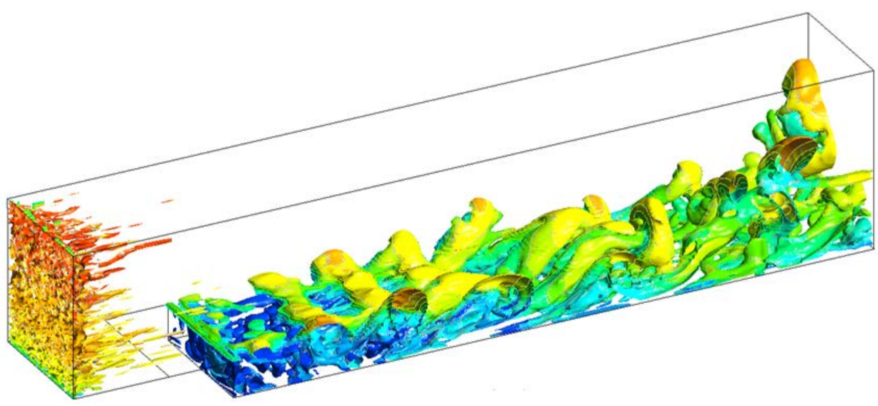

Figure 2. Hydrodynamic vortex flow.

the elastic body surface and the boundary conditions of radiation at infinity.

Elimination of non-physical synthetic vortices formed at the boundaries of the transition between the regions of averaged flow (RANS) and turbulent flow (LES) in the hybrid hydrodynamic model is carried out in the CATEC software using a smooth spatial filter.

Figure 3 shows the result of calculating the acoustic pressure field formed during the interaction of the turbulent flow (**Figure 2**) with the deformable solid body.

4. The Method of Mode Analysis of Mechanoacoustic System

Mode analysis is one of the methods for evaluating the acoustic characteristics of mechanoacoustic systems. Mode analysis makes it possible to find such dynamic characteristics as sound-emitting forms of resonance oscillations and the corresponding complex values of eigenfrequencies and damping factor.

Knowledge of eigenfrequencies and sound-emitting forms of structures allows one to competently design a complex object and choose the optimal layout of equipment. It should be noted that the mode analysis is one of the important preparatory stages before applying more complex analysis methods.

Despite the fact that mode analysis is a standard function of common commercial software, analysis in the presence of fluid or damping has not yet been implemented in any of the known packages. The authors of the CATEC software have developed an original algorithm based on the Lanczos method [8]. The modernization of this method allows solving the problem of determining acoustic radiation of a deformable solid body oscillating in contact with a compressible fluid. The algorithm is also performed for systems in which energy dissipation takes place, *i.e.*, vibration damping. During damping, the frequency values are complex.

For example, **Figure 4** shows the results of a mode analysis for a FEM test design (**Figure 4(a)**) performed using the CATEC software in a certain frequency range.

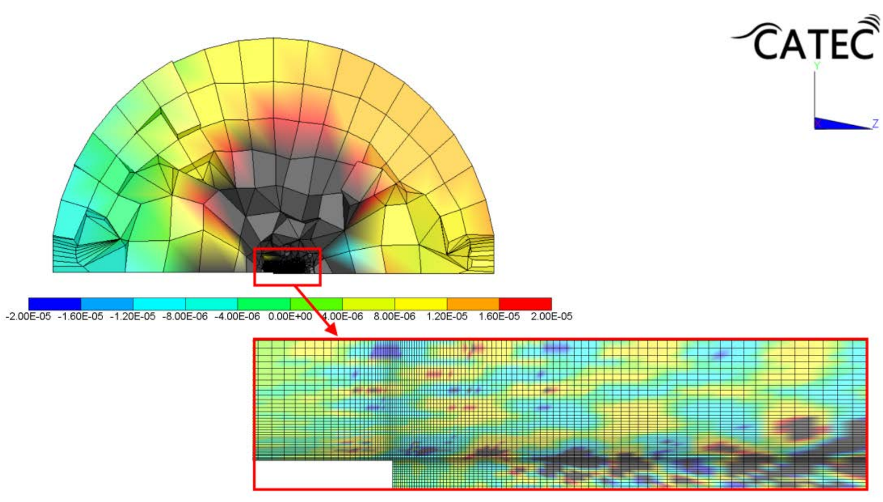

Figure 3. Acoustic pressure field.

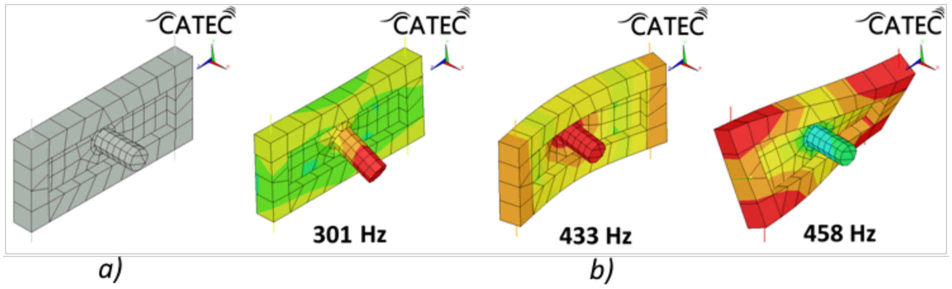

Figure 4. Eigenmodes for mechanoacoustic system.

For the possibility of reducing the numerical modeling error in the CATEC software, the procedure of automatic tuning of the FEM is implemented. The introduced algorithm is based on the calculation of the optimal distribution of the material stiffness of the simulated object. This allows one to change the values of the eigenfrequencies of the FEM while preserving the resonant vibration forms. In this case, a search is conducted for such a distribution of the elasticity modulus that its change is minimal in relation to the basic data, e.g., experimental. The advantage of this algorithm is a significant saving of computational and time resources, since, from the point of view of reproducing dynamic characteristics in the studied frequency range, careful discretization of the object under consideration is no longer necessary.

5. Post-Processing of Calculation Results

Post-processing combines the above calculation algorithms for the analysis of vibroacoustic fields after solving systems of linear algebraic equations. The post-processing includes the export of calculation results, their three-dimensional visualization, the analysis of two-dimensional and three-dimensional radiation pattern and the long-range acoustic field, and the calculation of flow characteristics.

Post-processing provides for averaging the vibration and pressure fields over a given set of sources, and bringing the calculated frequency range to one-third octave bands.

Figure 5 illustrates post-processing for the construction shown in **Figure 1**. To obtain the VAC, the test design is complemented by a certain volume of fluid and a source (spherical wave), the location of which is marked with red. A three-dimensional visualization of the pressure field on a deformable solid body (**Figure 5(b)**), a two-dimensional radiation pattern (**Figure 5(c)**), and the frequency response of acceleration in the node on the object's surface are demonstrated.

6. Conclusions

The presented CATEC software allows to significantly expand the possibilities of acoustic design. The software helps to solve such problems as VAC prediction, evaluation of spectral characteristics, propagation and radiation of sound, and modeling of hydrodynamic noise of elastic mechanoacoustic systems. The

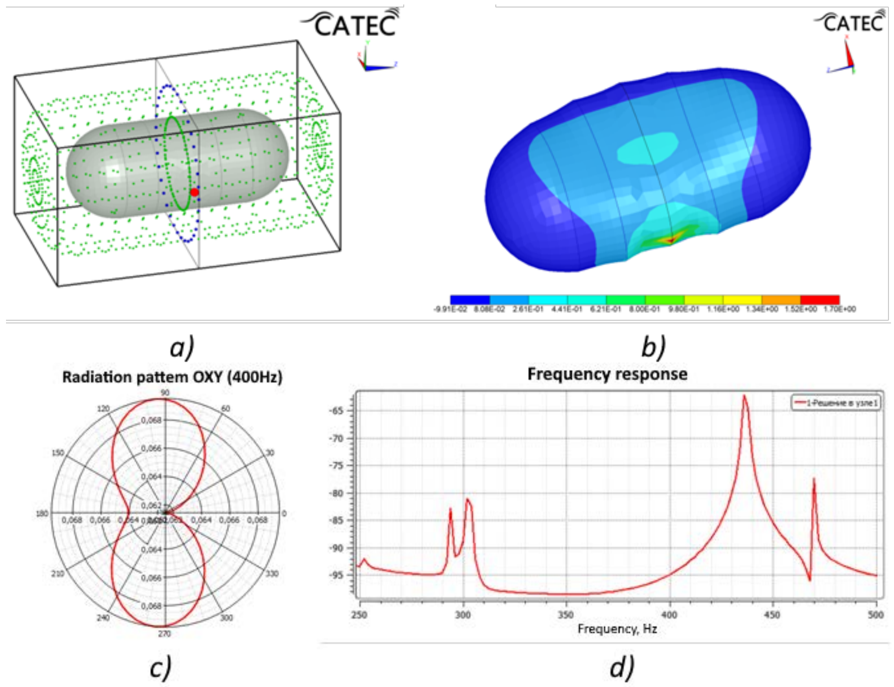

Figure 5. Results of post-processing of the model (a): three-dimensional visualization of the pressure field (b), a two-dimensional radiation pattern (c), and a frequency response of acceleration in the node (d).

developed technologies simultaneously provide high detailing of the required physical fields, the reliability of the results, and the promptness of testing the acoustic efficiency of layout solutions.

The developed software can be used in such fields of science as hydro- and aeroacoustics, environmental acoustics, ocean acoustics, and in industry, namely, shipbuilding and aviation industry.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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