

Application of optimization algorithms to improve the vibroacoustic characteristics of pumps

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Abstract: The article describes an attempt to optimize the flow part of the centrifugal pump by vibroacoustic characteristics, suggests a method of evaluation of these properties by methods of hydrodynamic modeling based on the analysis of force pulsations and moments acting on the rotor and stator of the flow part. The obtained data are decomposed into a spectrum by the Fourier method and presented in the form of dependence of sound pressure level on frequency. By results of optimization, the model with the best vibroacoustic characteristics within the limits of numerical modeling is found.

Introduction

In certain areas of application, the characteristics of the pumps may be subject to requirements for vibration and noise characteristics, for example, when it takes to design pumping units for the submarine fleet [1–3].

Improving the vibroacoustic characteristics of the pump (reducing the noise and vibration generated by a pump) is a non-trivial task for the engineer. In addition to the well-known recommendations for the design of such equipment (the choice of basic sizes, the selection of the number of impeller blades and guide diffusers) there is a possibility to improve the vibroacoustic properties by varying the values of a large number of geometric parameters of the flow part (angles of impeller blades, diffusers and return guide vanes, the shape of the blades, etc.), which affect to the noise and vibrations [4–8]. Thus, it is necessary to carry out optimization on the specified parameters. It should not be forgotten that it is often necessary to consider other criteria, such as efficiency, NPSH value, etc. Therefore, the following purpose was set in our work: to improve the vibroacoustic characteristics of the centrifugal pump flow part by means of optimization methods.

The following tasks had to be solved for this purpose:

- Select the optimization parameters and criteria;
- Choose the method of evaluation of vibroacoustic characteristics based on CFD methods;
- Perform optimization and compare the obtained results.

The object of the study in this work was chosen as the flow part of the four-stage hermetic pump, presented in Figure 1, for which the vibroacoustic characteristics are a priority.

Optimization method — an algorithm based on global and targeted search methods. Optimization parameters are presented in Table 1. First of all these are design parameters directly affecting the flow, namely: the angles of blades in the impeller and diffuser and return guide channels, the number of blades and their angular length, width and diameter of the wheel.



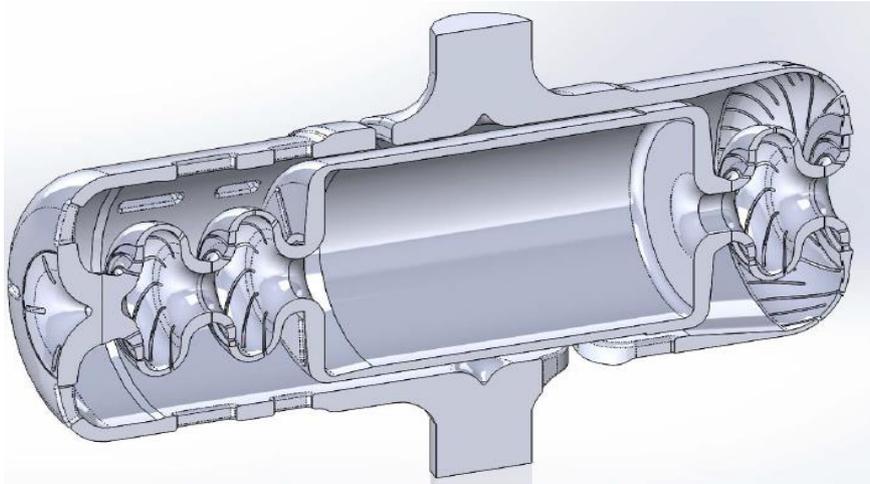


Figure 1. The flow part of the hermetic pump

The optimization criterion was the sum of sound pressure levels at 5 different frequency ranges. Also limitation on the pressure of one stage was introduced like a criterion.

Table 1. Parameters of optimization

Parameter	Value	
	Min	Max
Blade angle at the impeller output, deg	10	30
The angle of the blade at the entrance to the guide diffuser, deg	5	40
Output impeller width, mm	12	25
Diameter of impeller, mm	190	220
Blades of impeller	6	8
Blades of guide diffuser	8	12
Angular length of impeller blade, deg	80	140
Angular length of diffuser blade, deg	50	110

Methods

The main question in setting the task of optimizing the presented pump by its vibroacoustic characteristics is the completeness of the used mathematical model [9]. The direct method of calculation is the solution of the conjugate problem, i.e. the calculation of the flow field and the calculation of the housing wall deformation simultaneously. However, such statement of the problem requires long-term preparation of models and is demanding to computational resources, so in the process of optimization it is inexpedient to use it [10–13]. To compare the vibroacoustic characteristics of the flow part, it is most convenient to use a calculation model that includes only the flow part. At the same time, we will calculate the force influence of the flow on solid walls as integral parameters of the pressure field and evaluate the spectral characteristics of this influence.

In this work, we used the STAR CCM + software product specializing in hydrodynamic modeling as an applied software package.

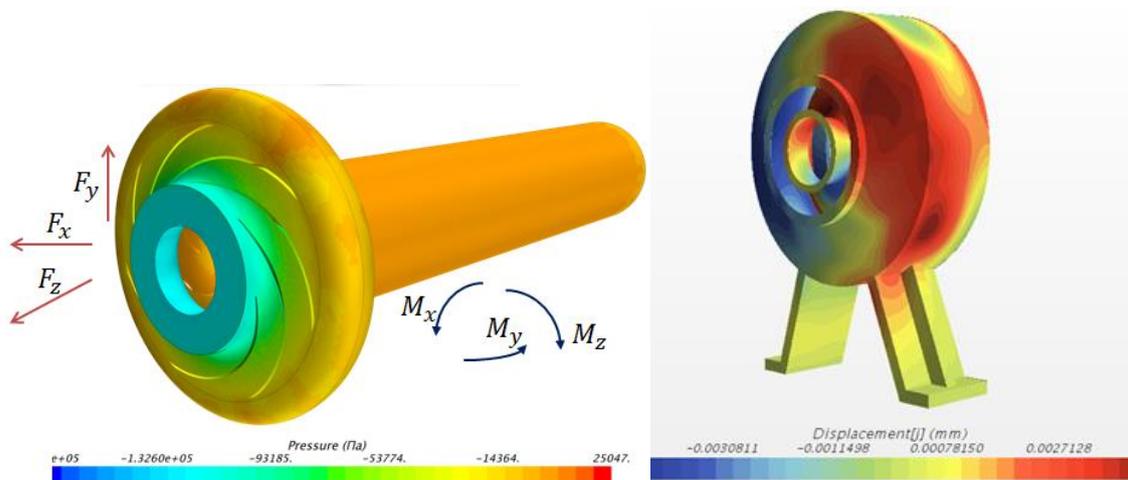


Figure 2. Methods of estimation of vibroacoustic characteristics at CFD modeling

The method of numerical modelling is based on solving discrete analogs of the basic hydrodynamic equations [14–15]. In the case of an incompressible fluid model ($\rho = \text{const}$), this is:

Mass conservation equation (continuity equation):

$$\frac{\partial u_j}{\partial x_j} = 0 \quad (1)$$

where u_j — the averaged value of the fluid velocity in the projection on the j axis ($j = 1, 2, 3$);

The equation of momentum conservation (Reynolds averaging):

$$\rho \left[\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_j} \right] = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} [T_{ij} - \rho \overline{u'_i u'_j}] \quad (2)$$

where u , p — averaged speed and pressure;

$$T_{ij} = 2\mu s_{ij} - \frac{2}{3} \frac{\partial u_j}{\partial x_j} - \text{viscous stress tensor for incompressible fluid};$$

$$s_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \text{instant strain rate tensor};$$

$$\overline{\rho u'_i u'_j} - \text{Reynolds stresses};$$

$$u'_i - \text{ripple component of velocity}$$

$$\mu - \text{the dynamic viscosity coefficient of the fluid}$$

The introduction of the Navier—Stokes equation, Reynolds-averaged, makes the system of equations non-closed, since additional unknown Reynolds stresses appear. A semiempirical $k-\omega$ SST model of turbulence has been used for solving the system in this task, which introduces the necessary additional equations: the transfer equations for the kinetic energy of turbulence and the relative dissipation rate of the energy:

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \nu_t) \frac{\partial k}{\partial x_j} \right]; \quad (3)$$

$$\frac{\partial \omega}{\partial t} + u_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} P_k - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(v + \sigma_\omega v_t) \frac{\partial \omega}{\partial x_j} \right] + 2 \cdot (1 - F_i) \sigma_{\omega 2} \cdot \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, \quad (4)$$

The following combination of boundary conditions was used to calculate the flow rate in the pump:

- Stagnation on inlet;
- Velocity on outlet

The simulation was carried out in an unsteady statement with a time step of 10^{-5} s and 10^{-4} s. The number of internal iterations per time step is 10.

The calculation grid has different topology. In the core of the cell flow are polyhedrons of different shapes and sizes. Cells near solid walls are polyhedral prisms stretched in the direction perpendicular to the wall. The number of prismatic layers is taken equal to 5 with a stretch coefficient of 1.3. The thickness relative to the base size of the polyhedral cell is 35%. The total number of cells was about 1 million elements. The calculation was carried out on one pump stage.

Results

Figure 3 shows the pressure field established by the calculation. The forces and moments in the unsteady statement and processing of the received data were taken by means of the tool of the frequency analysis built in a program complex. Fast Fourier Transform was used to isolate amplitudes and frequencies of the spectrum of forces and moments obtained.

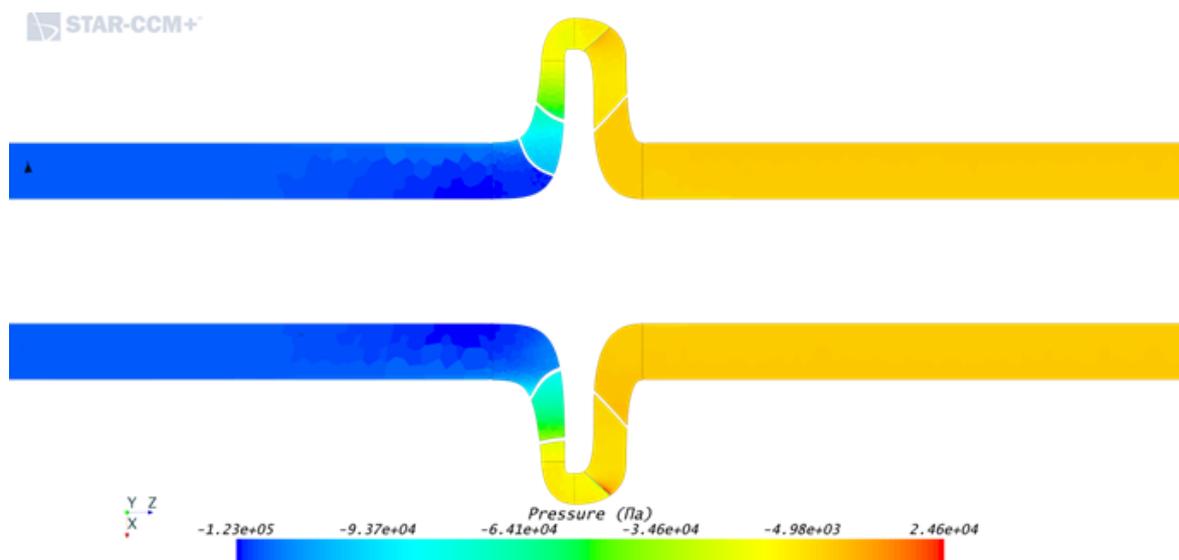


Figure 3. Pressure field across the flow section of the pump stage

According to the results of the numerical experiment, the forces and moments depend on time in the flow parts of the wheel and the guide apparatus. Figure 4 shows a graph of forces in three axes of coordinates acting on the impeller.

The graph below shows that these forces fluctuate with several frequencies. To determine the frequencies and amplitudes we used the Fourier transform, the essence of which is to decompose the function into elementary components — harmonic oscillations with different frequencies. As a result, we obtained the spectrum shown in Figure 5, where the level of sound pressure as an axis of ordinates, and the frequency as an axis of x. The reference pressure is $1 \mu\text{Pa}$ for water. Green graph is the best model as a result of optimization, red and blue graphs are the results obtained in the calculation of models with available experimental data. As can be seen, the best result was shown by 106 model from the optimization, the amplitudes of oscillations were significantly lower than those of other models in the low-frequency part of the spectrum.

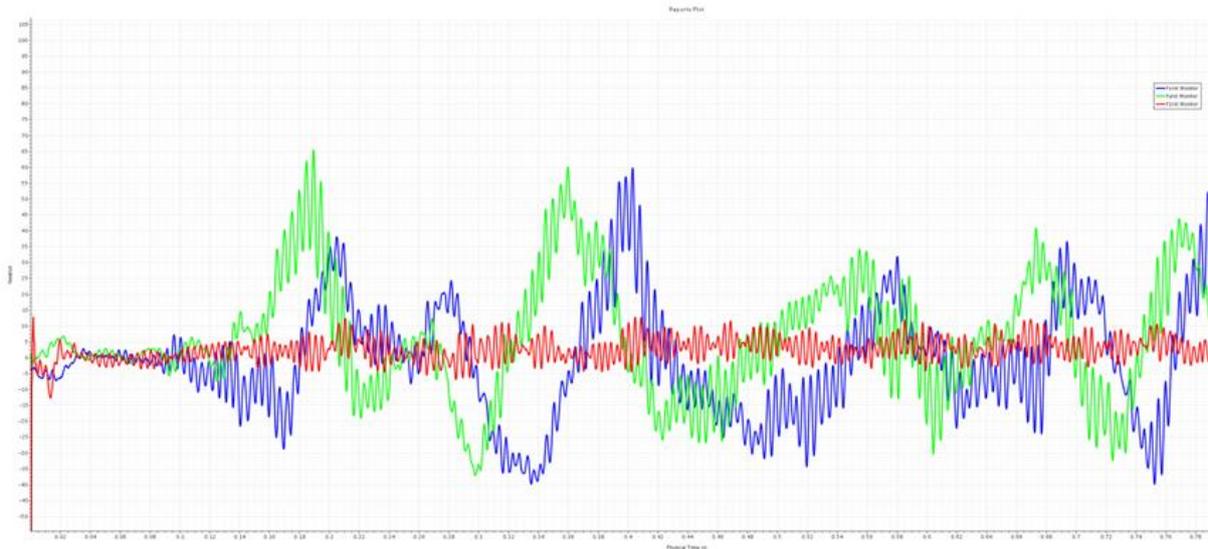


Figure 4. Graphs of forces on the impeller in three axes

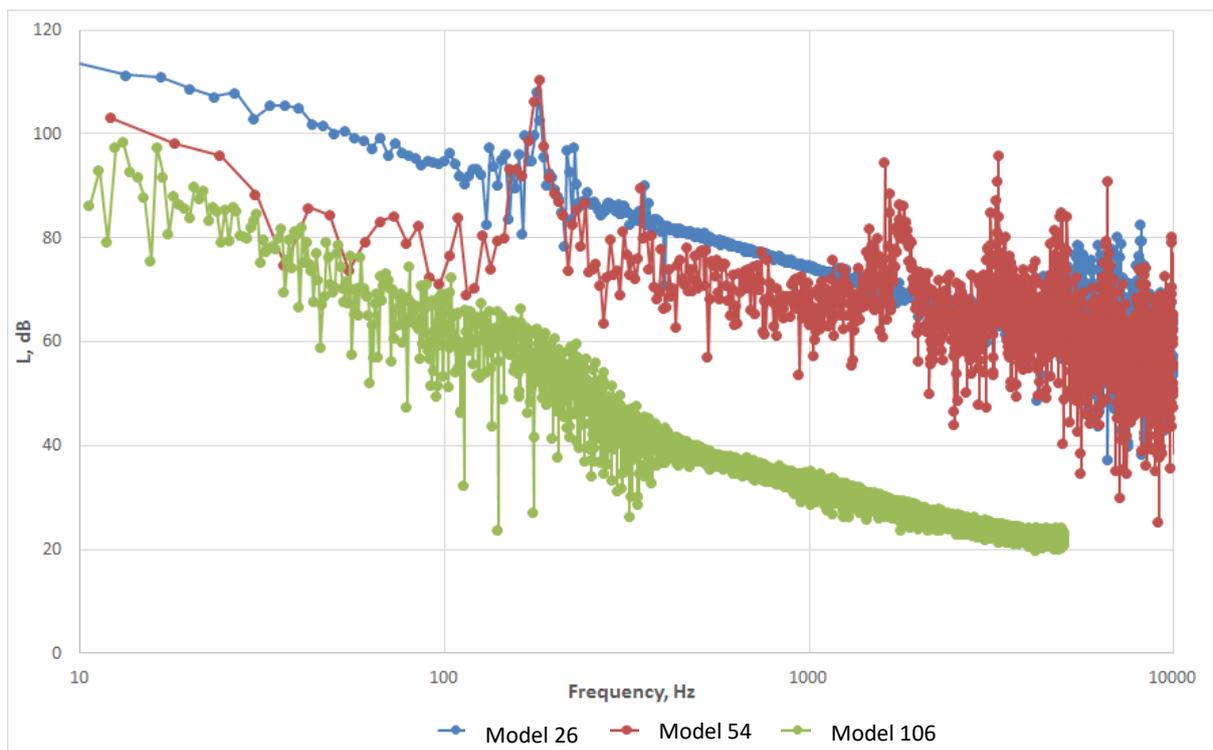


Figure 5. Sound pressure level depending on frequency

Conclusion

Thus, we can draw the following conclusions from the work done:

- With the help of optimization methods, the vibroacoustic properties of the flow part of the hermetic centrifugal pump have been improved;
- Numerical calculation of the flow part with calculation of the force influence of the flow on the solid walls and their subsequent decomposition into the amplitude-frequency spectrum allows us to evaluate the vibroacoustic characteristics.

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