Numerical experiment with investigation of hydroelastic systems constructions dynamics and strength with according verification

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Abstract. The paper is devoted to the analysis of numerical modeling data exact as it possible to determine hydrodynamic loads on different constructions and objects of the modern energetic machine building with definition of pressure and flow velocities distributions on the surfaces for specified objects and also with special investigation of amplitude-frequency characteristics for the individual construction elements. According to proposed special verification methodical approach it confirms efficiency and correctness of the results obtained by authors. This includes too the application of the main original combined numerical approaches as for calculation process so as for effective verification of these results with support of special experiment analysis and proposed different verification schemes with the cutting of investigation costs. It is really also now that last 10-15 years the role of calculation methods became essentially increased.

1. Introduction

The article is devoted to the analysis of the problem statement and carrying out complex multi-faceted studies with receiving results for real physical processes connected with determination of dynamic parameters and constructions in modern power engineering durability (Fig. 1) on the example of water-water reactors WWR -1000, -440, etc. This research represents currently a set of computational and experimental directions. At the same time they are carried out complementary sequentially or in parallel with a reasonable improvement of their verification quality and decrease relative total research error and cost. [1-5,7]. It should also be noted that the role of numerical experiment in the last 10-15 years has grown significantly in both foreign and domestic works and research [2, 4, 13].

WWR is one of the main basic considerable power domestic structures for the development of the modern Russian power engineering system. WWR – 1000 reactor main characteristics: electrical power – 1000 mW, thermal output - 3000 mW, height - 19300 mm, the reactor mass – 573 t, coolant flow through the reactor – 80000 m³ per hour, pressure – 120 MPa, coolant flow velocity – up to 10 m/sec, reactor water inlet temperature – 300°C, pressure in the primary circuit – 16 MPa.

The article proposes successfully proved approach for effective planning and implementation of experimental and numerical investigations complex to get the most correct output (experimental and numerical) for hydroelastic systems critical structures parameters to determine dynamics and strength (durability) in Power industry.
Figure 1. The schematic layout of reactor system WWR – 1000 (EZCS - Emergency Zone Cooling System, MCU - Main Circulating Pump Unit).

The main error of structures dynamics and strength complete study for this type of hydroaelastic systems is usually determined by the main research purpose. In conducting this type of studies, it is necessary to:

1. Prevent the occurrence of design-hazardous self-oscillation modes with stability loss, which cause intense destruction of structure and the object.
2. Implement reasonable errors agreement and related additional conditions for complex research individual directions.
3. Upgrade coordinated planning of experimental and complex computational studies
4. Determine the initial data from amplitude-frequency loading process composition and dynamic structure response in order to estimate its durability by known methods.

Accuracy level to be striven for should be determined by reasonability criterion [1]. Increasing the accuracy twice can lead to a rise in measurements (and calculations) cost of several times. At the same time, the decrease in measurements (or calculations) accuracy below the norm leads to errors in research up to accidents [1, 7, 13]. Thus, at the loads on structure from the medium flow determining stage, the error is primarily determined by finding dimensionless coefficients of hydrodynamic forces in the classical formulation specifically $C_y$ - lift and $C_x$ - drag forces errors (section N G Valles in [1]).

Matching particular directions errors complex research with the relative error required in accordance with the main problem to be solved [1, 8] is set which includes a thorough estimation of the basic error, which is an important problem that is usually solved by successive approximations method taking into account parameters, characteristics and type of the selected information and measurement system (its components) and problem specifics. This solution requires obtaining and analyzing an extensive experimental and numerical data Bank, as well as its distribution laws and studied processes sensitivity to theoretical, computational and dynamic models parameters and coefficients variations analysis [1-3, 6, 7, 10, 13].

Therefore, errors effectiveness analyses evaluation is carried out and is held in terms of their agreement for implementation of complex researches such as aerohydrodynamic loads determination on structures (tube bundles of heat exchangers, reactor and etc.), using models of numerical and physical (model) experiments [7-11].

On the numerical experiment models functioning analysis [1, 2, 4, 7, 11] it is necessary to identify consistently used values of parameters and coefficients which are determined by physical experiment taking into account the real errors of the latter as well as an algorithm for intrinsic numerical experiment model of effective error compensation by final result discrepancy relative value - values (or functions) of hydrodynamic action coefficients $C_y$ and $C_x$, or $C_y(t)$ and $C_x(t)$ [1, 3, 7, 10, 11].
In solving this problem, the following is assumed:

1. The total considered complex studies stage error is determined by the ultimate aim – in this case, the evaluation of structure under the medium flow force influence on durability.

2. Consider only independent random errors components with a normal distribution [1].

3. It is assumed that selected reliability or the same degree of reliability data identity used to determine the relative error in the experiment is ensured [1, 3, 9].

4. Partial relative errors with a standard value less than 10% of the total value are not taken into account [1, 3, 11].

5. Analysis of hydrodynamic processes is carried out without taking into account thermal crisis phenomena [1-4, 7, 10].

6. All conclusions and results correspond to identical probability (reliability) P and number of experiments n (all control error calculations are carried out, for example, for P=0.95 and n=5).

7. The turbulent flow of a single-phase coolant or its simulator is considered in the range of numbers $Re=10^3-10^6$ as a random quasi-stationary process with signs of ergodicity and a number of regular components [1-3, 7].

When carrying out complex studies, usually including theoretical, computational (numerical), experimental model and full-scale objects or models, as well as a stage or technique of physical modeling the main task is reasonable separate stages or researches directions errors coordination with application of the above models and approaches.

\[ \delta_{\Sigma} \leq K_\delta \delta_{\Sigma} \]  

(1)

$\delta_{\Sigma}, \delta_{\Sigma}$ - total evaluation errors change ranges from experimental and numerical studies; $K_\delta$ - coefficient.

Equation (1) is insufficient because for complex studies it is necessary to consider the full ratio, the initial starting value of which is the permissible relative error of the parameter or dependence, which is the ultimate aim of research. Therefore, this ratio in this case looks like this:
where \( [\varepsilon_e] \) - acceptable in terms of durability prediction relative error for determining dynamic strains in nature (models), which is clearly above the measurement error when construction perfect fatigue curves [8, 9];

\( \varepsilon_{cnn} \) - error of numerical (calculated) determination of dynamic deformations for full-scale construction;

\( \varepsilon_{eph} \) - experimental determination of dynamic deformations error of full-scale construction;

\( \varepsilon_{en} \) - finding dynamic deformations on the basis of hydrodynamic force coefficients obtained by numerical experiment error;

\( \varepsilon_{cnn} \) - hydrodynamic forces on the model of numerical experiment for nature error in determining the coefficient;

\( \varepsilon_{phm} \) - physical modeling method error (approximation);

\( \varepsilon_{phe} \) - experiment with physical model error;

\( \varepsilon_{ne} \) - experiment with numerical model error;

\( \varepsilon_{nm} \) - actual model numerical experiment error;

\( \varepsilon_{cnn}, \varepsilon_{phm} \) - hydrodynamic forces;

\( C_{yx} \) - error in determining the coefficients, using the model of numerical experiment and physical model experiment, respectively.

Since the same model of numerical experiment is used for nature and physical mode \( \varepsilon_{cnn} = \varepsilon_{cnn} \).

Errors \( \varepsilon_{phm} \) and \( \varepsilon_{fe} \) are independent random variables, so the total value \( \varepsilon_{phm}^\Sigma \) can be found from the expression in [11]:

\[
\varepsilon_{phm}^\Sigma = \left( \varepsilon_{phe}^2 + \varepsilon_{phm}^2 \right)^{1/2}
\] (3)

Numerical experiment error model consists of numerical algorithm realization with all the implementation assumptions error and errors of direct or indirect parameters measurement, coefficients and functions from physical experiment which are then used directly in the numerical experiment model or serve for final testing, i.e. to detect results errors or deviations from experimental physical. In this case the algorithm error estimation itself and the assumptions of numerical experiment model \( \varepsilon_{nm} \) approximately can be taken from [1, 11]:

\[
\varepsilon_{nm}^\Sigma \approx \left( \varepsilon_{ne}^2 + \varepsilon_{phe}^2 \right)^{1/2}
\] (4)

The most effective, but not always feasible, is the error ratio, when formally the relative physical experiment error is greater than or equal to numerical experiment error with the convergence of the averages, when all or most random parameters values range in a numerical experiment is determined, basically, by relative error of the physical experiment.

In detail, a similar analysis in determining the coefficients \( C_y \), \( C_x \) and the dependencies \( C_y(t) \) and \( C_x(t) \) errors in was carried out in [1, 7]. Based on these data an approximate accuracy of the model
numerical experiment estimation $\varepsilon_{nm}$ which is independent value constitute for reliability $P = 0/95$, $\varepsilon_{nm} = \pm1.5 - 2.0\%$.

2. **Approach using examples**

1. As examples, let’s consider some WWR-1000 reactor (large-scale model 1:4.5) inner shell circumferential oscillations determined from physical model experiment in liquid medium (water) flow.

![Natural forms of WWR-1000 reactor shaft oscillations in cross section](image)

**Figure 3.** Natural forms of WWR-1000 reactor shaft oscillations in cross section: a – measuring of oscillations points; b - frequency 63 Hz; c - frequency 116 Hz; g - frequency 165 Hz.

The presented graphs let you make sure the complex frequency composition of shaft vibrations. The highest level of oscillation is observed at a frequency of 49 Hz and its multiples 98, 147, 196, 245 Hz and at a frequency of 294 Hz at these frequencies, the spectral density peaks are close in appearance to the Delta function that corresponds to the deterministic forced oscillations excited by the rotational and blade frequencies of the pump nature. Along with this, there are other components in the spectrum characterized by a more broad-band maximum spectral density.

2. In addition, we present some dynamic strains and stresses results in the main elements of the WWR-440 reactor studies, obtained in full-scale tests during cold and hot running-in of the power unit (Lovisa NPP, Finland). Graphs of the ring deformations spectral density refer to shaft middle part during reactor operation with parameters close to the nominal ones in the frequency ranges for the model 0-300 Hz and 0-70 Hz for full-scale (Figure 4).
Figure 4. Circumferential dynamic deformations spectral density in WWR-440 reactor shaft middle part (1–7 ...... – model (experiment-conversion to nature) computation for nature, 8 ___ experiment nature.

Here, the vertical dotted lines show the values of natural frequencies, recalculated from the model (1-7), which almost coincide with computation for nature, the solid line-8 corresponds to the values obtained by the experiment on the full-scale object. The obtained results testify to their good compliance (the relative error, generally, 5-10 %), taking into account that they are obtained by modeling and calculation, as well as based on the results of model and full-scale strain-gauge transducer researches.

3. Conclusions
Based on the analysis and authors experience it became possible:
1. To realize reasonable errors coordination and associated additional conditions for complex research individual areas.
2. To upgrade coordinated planning of full-scale and model experimental and complex studies (computational and experimental).
3. To carry out correct numerical and experimental (full-scale and modeling) study of design hydrodynamic reactions to flow in power engineering with the definition of their main characteristics and parameters [1-4, 7-9, 13].
4. Efficiency and significant savings of account time and cost (about 20-30 %) when using the combined approach and like that [2] proposed by authors to calculate structures dynamics and strength parameters are confirmed (flow force influence on bodies and designs of a cylindrical and other cross-section form coefficients, as a function of time, frequency parameters and characteristics of their oscillations excitation in flow, etc.), as well as stresses distribution in structures, pressure and velocity under flow influence on their surfaces, etc. [1-4].
5. A systematic approach is realized for verification of calculated data on the experimental data Bank available at IMASH RAS basis [1, 2, 3, 7], using known standard models for testing in different media flows, for plane flow problems and comparison them with results of calculations in 3D – formulation (ANSYS CFX, etc.) on various flow examples that allowed authors to obtain finally
relatively small errors and stable results in verification (relative results deviation is not more than 15%) [2].

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