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Shape and operation optimisation of a supercritical steam turbine rotor

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ABSTRACT

The presented study discusses the problem of shape optimisation of selected areas of the rotor of the high pressure part of an ultra-supercritical steam turbine together with the optimisation of the turbine start-up method, using the maximum stress objective. The analysis relates to the rotor of a conceptual ultra-supercritical turbine which is characterised by high parameters of operation. The consequence is that the machinery components are subjected to significant stress, which further results in a substantial reduction in its life and reliability. These adverse effects can be contained in two ways, i.e. by optimising the shape of the rotor areas characterised by high stress values and by optimising the method of the turbine start-up. In the case of the rotor under analysis, it is the thermal stress caused by large temperature gradients occurring in unsteady states of operation that has a predominant impact on the stress level.

The performed research prove that the manner in which the power unit start-up is initiated and carried out depends largely on the limitations of the materials used to make the machinery components. This, in turn, has an impact on the assessment of the power unit in terms of energy and economy. The obtained optimisation results translate directly into the power unit energy effectiveness.

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1. Introduction

The need to meet environmental requirements concerning the reduction in greenhouse gas emissions necessitates the development of highly efficient technologies of power units for supercritical steam parameters. This in turn entails a further development in the design of both boilers and turbines. The components of these machines operate not only under a greater load but also in higher temperatures. To manufacture them, it is then necessary to use new materials resistant to high-temperature failure processes, such as creep and fatigue. Apart from the selection of the appropriate material, the choice of the design form is also essential [1]. The shape and the size of a component determine the level of thermal and mechanical stress that will arise at different phases of the operation, which has a decisive impact on the component life [2–4]. From the point of view of operational safety, the turbine rotor is an element of particular importance. The temperature gradients appearing in it in unsteady states are the cause of significant stress [5]. One of the ways to reduce the stress and to improve the rotor life is the optimisation of its shape. In the further part of the paper, a mathematical model for the optimisation of the turbine components is defined. The basic objective function assumed here is the rotor life. The optimised values are selected rotor dimensions, especially in stress concentration zones. The fundamental problem in the optimisation of the shape of components as complex as the rotor is the need to model the stress state in their subsequently changing forms. Consequently, the modelling has to be done with a variable numerical grid. In this study, the response surface method is used, which makes the problem easier to solve thanks to appropriate approximations.

2. Optimisation problem formulation

Each structure treated as an object of design is characterised by a number of features which are given specific values in the design process. The selection of those features has a decision-making nature and is conditioned, to a large extent, by the system of objectives. To facilitate the decision-making processes and to make them more objective, the technique referred to as the optimum design method is often used. The optimum designing of a structure is aimed at the creation of the optimum design, i.e. one that not only makes it possible to meet all the requirements the structure is faced with, but also ensures that the structure is the best in respect of the selected optimisation objective.

By assuming the optimisation objectives it is possible to build the mathematical model of the structure which includes:

- design variables $\boldsymbol{X} = (x_1, x_2, \ldots, x_n)$, i.e. the values to be optimised;
- constraint functions $\psi_i(x_1, x_2, \ldots, x_n) \leqslant 0$, defining the permissible area of the variability of the optimised values;

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– objective function $V(x_1, x_2, \ldots, x_n)$, which depends on the variables under optimisation and which constitutes the mathematical notation of the optimisation objective.

In the case of heat turbines operating in creep and fatigue conditions, one of the basic design objectives is the life objective, which can be written as:

$$V = t_e \quad (1)$$

where t_e is the component life, i.e. working time to failure.

Therefore the aim of the optimisation is to maximise the component life.

$$V \to V_{\max} \quad (2)$$

Certain dimensions of the component may be the variables to be optimised. This means that the desired structure form of the rotor is the one with the longest operation time. This time is limited by the damage done to the component due to life degradation processes. Because of the fact that both creep and fatigue processes depend on the stress level, the optimisation objective related to working time may be replaced with the optimisation objective related to stress minimisation. Therefore the following may be assumed:

$$V = \sigma \quad (3)$$

$$V \to V_{\min} \quad (4)$$

The dimensions to be optimised will only be those that have the most significant impact on the stress level of the component. Typically, these are the dimensions in stress concentration zones, e.g. curvature radii. The material properties, operation conditions, as well as the main dimensions of the component may be the optimisation parameters.

Solving the optimisation problem presented above with mathematical methods, it is necessary to perform multiple calculations of the value of the objective function, which in this case is the maximum stress level in a given component. To determine the stress, the calculations of transient temperature distributions in the entire working cycle have to be made, and then, based on their results, stress distributions are calculated. Each time the calculations have to be performed for a different rotor form, i.e. for a different numerical grid. Therefore, obtaining the optimum solution is very time-consuming. One of the ways to avoid this particular inconvenience is the application of certain approximation techniques discussed in the further part of the paper.

3. Response surface methodology

The optimisation methodology used in the calculations is based on the Response Surface Method (RSM), which is a set of methods of the mathematical analysis and statistics [6,7]. For this purpose, experimental numerical studies are used, i.e. numerical simulations of the real process which is subjected to optimisation. The simulations, called the design of experiments (DoE) consist in finding the response (of the initial values) of a given process to independent input parameters (design variables) which affect the process [7]. In other words, the design of the experiments consists in a series of numerical simulations for changing input data with a view to identifying their impact on the output values. The procedure is to allow the approximation of the real (modelled) process with the use of an assumed approximation function, which in turn will be the object of the optimisation process. The aim of such an approach is to reduce the computational cost related to the optimisation processes which need time-consuming numerical analyses.

3.1. The design of the experiments

The process begins with setting the range of variability of individual design parameters of the simulation model. Based on that, the design of experiments is created that will be used to determine the response surface of the model [8]. Depending on the analysed problem and on the character of the correlation between design parameters and output values, various designs of experiments are assumed. The simplest is what is referred to as the screening design. It makes it possible to examine the impact of the assumed design variables on the system response, and to select for further analyses only those variables which affect the response in a significant way. In this design, permutations of the upper and lower constraints of all design variables are used. Because for each variable calculations are made for two levels of its value (the upper and the lower constraint), the design is referred to as two-level and marked as 2*N*, where *N* is the number of design variables. However, it allows a linear description of the input–output effect only. Also, the possible impact of the interaction between design variables on the result values is lost here. These inconveniences are removed by the application of three-level designs (3*N*) and multi-level, typically five-level ones (5*N*), which allow a non-linear description of the impact of parameters. The number of conducted experiments (in this case – numerical simulations) rises because it is equivalent to the number of levels raised to the power equal to the number of design variables. Thus, an increase in the number of design variables for a given design of experiments results in an exponential rise in the number of their possible combinations. The designs of experiments mentioned above are referred to as full factorial designs which include all possible combinations of the input parameter values. However, they become impractical for a bigger number of design variables and then designs referred to as fractional factorial designs are employed. These designs no longer include all possible combinations of the input values, but only a part of them. The reduction in the number of combinations of the values of variables may entail obtaining results of a poorer quality. Therefore, in order to minimise this effect, it becomes necessary to carefully select the combinations of the values of design variables, as well as their appropriate number. One of the fractional factorial designs which is often used is the Central Composite Design (CCD) [6], which is a two-level design expanded with an axial experiment design. This means that for each variable there are two extreme realisations available (at the edge of the area), plus a central realisation as well as axial ones in the middle of the intervals of all variables. In this case, the number of experiments is reduced compared to the full factorial design, e.g. for three design variables the fall is from 27 to 15 (Fig. 1).

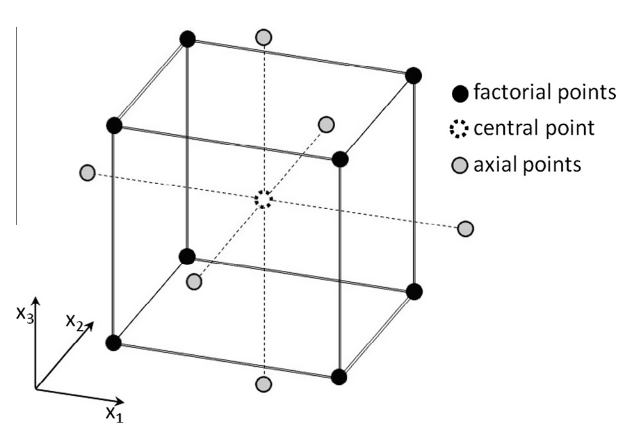

Fig. 1. Central composite design.

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