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Design and analysis of the thermal-stress coupled topology optimization of the battery rack in an AUV

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ABSTRACT

To reduce the mass of underwater vehicles and the temperature gradient of battery racks, the methods of element birth and death is used to study topology optimization. First, with an objective function based on the minimum configuration flexibility, the optimization results can be obtained by varying the proportion of optimization. Second, the structural minimum temperature gradient is considered as the objective function to achieve a further topology optimization by varying the proportion of optimization. Finally, under the condition of a given topology optimization ratio, the thermal-stress coupled topology optimization is applied by changing the proportion of the thermal load to the stress load. The corresponding battery frame structures are obtained, and the correctness of the mathematical model is verified.

1. Introduction

The ocean is a treasure trove of resources that have not been fully exploited. Fully utilizing marine resources has a special significance because of the lack of per capita resources of our country. Autonomous Underwater Vehicles (AUVs) represent an effective tool for the development and use of the ocean. They have become increasingly widely used in the fields of scientific research, military, industry etc.

Increasingly more countries have adopted electric propulsion systems because electric propulsion systems benefit from their simple structure, and they are not affected by back pressure. Numerous high-energy battery groups configured in series or parallel are required to meet AUV power demands. For example, high-specific-energy and high-specific-power lithium batteries have been widely used in AUVs. However, the AUV compact battery compartment is a closed and compact space, and the method of thermal equilibrium has many limitations. Therefore, there exists a series of security problems for the application of lithium battery packs in lithium-powered underwater vehicles. On the one hand, the battery rack is strongly impacted by the large load in the process of vehicle emission, which can destroy the battery rack structure and affect the energy supply of the whole system such that the system cannot operate normally. On the other hand, for underwater vehicles powered by a large number of lithium batteries, the underwater vehicle navigation process generates substantial heat and causes local temperature differences in the battery compartment, which affect the normal performance of the battery groups.

Researchers have only considered the structure of the battery frame for analysis or the thermal characteristics for the battery frame design. The thermal coupling problem is rarely involved. To address the problem of the heat conduction topology optimization of a heat source with structural changes, a method for evaluating the degree of uniformity of the temperature distribution in the design domain is proposed using the temperature variance as the objective function (Hui et al., 2009). The approximation of the geometric average temperature is introduced as the highest temperature to the heat dissipation structure, and a new cooling structure topology optimization model is established, therein using the adjoint method and the function to conduct the sensitivity analysis of the corresponding column type (Qiao et al., 2011). In (Yin, 2015), a stiffness optimization algorithm is proposed to solve the problem of multiple working conditions, therein combining the evolutionary structural optimization method and the weighted compromise programming method, which is applied to a deep hole machine for reducing the mass of the machine tool. In (Xiang et al., 2012), with a stiffness maximum and low-order modal natural frequency, a topology optimization model is established as the optimization goal. The methods of compromise programming and SIMP are used to establish a multi-condition and low-natural-frequency optimization model. Based on the structural stress and strain energy, an evolutionary structural optimization method is studied and applied to the structure of the turret (Du, 2008). A multi-objective topology optimization design method is proposed based

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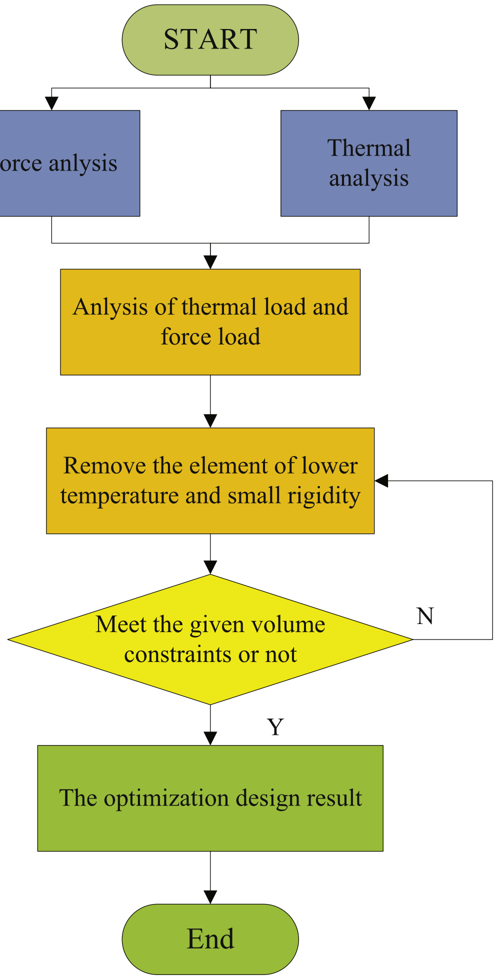

Fig. 1. Thermal-stress coupling topology optimization flowchart.

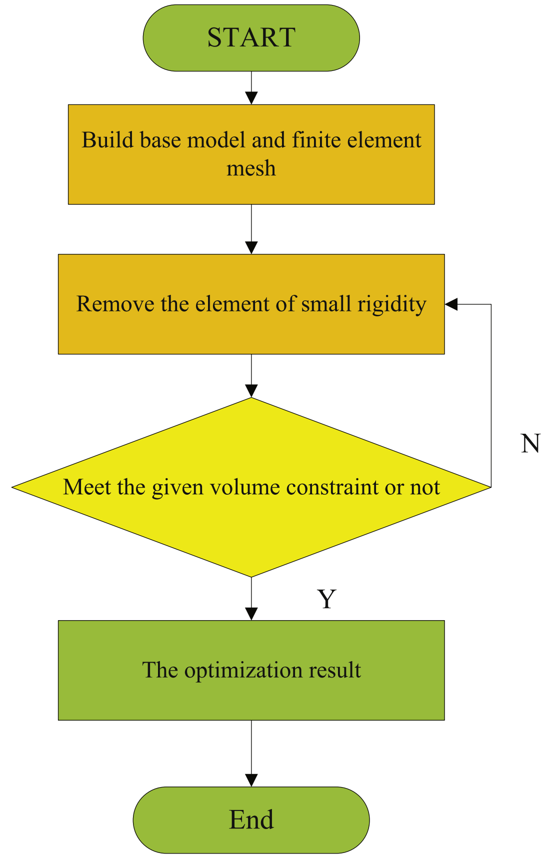

Fig. 2. The optimization process under force loads.

on minimum structure flexibility and structure cooling degree (Zuo et al., 2007). Three types of performance indexes, including the total energy of the unit, the temperature nodes and nodes within the region temperature squared, are derived to obtain the corresponding method of sensitivity analysis (Long and Zuo, 2007). In (Deaton and Grandhi, 2016), a method for the topology optimization of structures with combined mechanical and temperature loads are developed to achieve topology optimization, and a relaxation technique is utilized to remove the singularity phenomenon. The thermal stress and pre-stress are considered to minimize the structural dynamic compliance and reduce the stiffness of the structure in a thermal environment, with structural damping neglected (Yang and Li, 2013). An economic single-leaf masonry wall for the building construction industry is found (Sousa et al., 2011), and the thermal behavior of the units is calculated using three-dimensional finite element simulations. The results currently contribute to the building construction industry. The heat dissipation characteristics of the lithium battery spatial layout in an AUV is investigated, and a model is developed for the heat transfer process based on the energy conservation equation (Mao and Yan, 2016). Maximum stress constrained topology optimization using a novel P-norm correction method for lightweight design and a modified P-norm correction method are proposed to overcome the limitations of conventional P-norm methods by employing the lower-bound P-norm stress curve (Lee et al., 2016). Nearly all of these works concern a single aspect of analysis; this paper will concern two aspects, thermal load and force load, for analysing topology optimization.

The battery rack structure and the mechanical properties of the materials will change when the temperature rises, and the battery rack stress deformation will affect the overall temperature distribution. Therefore, design and analysis for the thermal-stress coupled topology optimization of the battery rack is extremely important. The main contributions of this paper are two fold: (i) Based on the established topology optimization model for only the mechanical and thermal load, a mathematical model of topology optimization is established. (ii) Taking the optimization design of the underwater vehicle battery frame as an example, a practical model is used to verify the correctness of the above thermal coupling topology optimization model. The optimization of the underwater vehicle battery structure is also performed. In addition, according to the machining practical process and topology optimization results, the paper chooses a volume optimization ratio for the further study. Finally, the paper obtains topology optimization results under different coefficient ratios of force load and thermal load.

2. Analysis and modelling of thermal-stress coupled topology optimization

Before analysing the topology optimization model of coupled thermal mechanical interactions, the topology optimization models under the action of force loads or thermal loads are first analysed. For the analysis of force loads only, structural flexibility minimization is taken as the goal to establish a topological optimization model according to the methods of element birth and death (Leng and Zhang, 2011). When analysing thermal loads only, the element birth and death technology can be used to minimize the total temperature gradient. Finally, based on the above two models, the thermal-stress coupled model is established using the element birth and death method when taking unit stress and temperature of unit as the objective function. The corresponding flow diagram is shown in Fig. 1.