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AUV hull lines optimization with uncertainty parameters based on six sigma reliability design

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ABSTRACT

Autonomous Underwater Vehicle (AUV), which are becoming more and more important in ocean exploitation tasks, needs energy conservation urgently when sailing the complex mission path in long time cruise. As hull lines optimization design becomes the key factor, which closely related with resistance, in AUV preliminary design stage, uncertainty parameters need to be considered seriously. In this research, Myring axial symmetry revolution body with parameterized expression is assumed as AUV hull lines, and its travelling resistance is obtained via modified DATCOM formula. The problems of AUV hull lines design for the minimum travelling resistance with uncertain parameters are studied. Based on reliability-based optimization design technology, Design For Six Sigma (DFSS) for high quality level is conducted, and is proved more reliability for the actual environment disturbance.

1. Introduction

Autonomous Underwater Vehicle (AUV) is becoming more and more important in ocean exploitation tasks. Currently, complex mission path and long time cruise need energy conservation urgently, and this is closely related with travelling resistance. In the preliminary design stage, AUV hull lines optimization design becomes the key factor. This led to studies of underwater robots shape optimization design: Joung et al. (2009) (Joung et al., 2009) described a design method using Computational Fluid Dynamics (CFD) for determining the hull resistance of AUV under development; Vasudev (2014) (Vasudev and Lakshmi, 2014) demonstrated the flexibility of Non-dominated Sorting Genetic Algorithm (NSGA-II) and its ability to identify optimum preliminary designs of the AUV; and Xia G (2016) (Guo-qing et al., 2016) proposed a multi-objective optimization study of AUV's principal parameters in conceptual design. However, relevant studies are mostly carried out on simplified (or hypothetic) external marine environment, thus some important parameters, such as principal dimensions and travelling speed, are usually assumed as deterministic and constant in design process.

Uncertainty of such parameters is unavoidable in the actual navigation and experimental observation. If still considering a constant value, there would be errors in result. Although the errors are small in most cases, but in the design process, continuous iteration and mutual coupling may cause the final result to have a large deviation. Then greater quality risk would come into sight. So neglect of uncertainty influence would lead to a low reliability result with some potential hidden dangers in practical application. Apparently, it's more reasonable to set such uncertainty parameters as form of uncertainty random variable in calculation, and the effect of uncertainty on the response target should be considered.

In recent years, the influence of uncertain parameters is gradually taken seriously in the naval architecture and ocean engineering. M Diez (2009) (Diez and Peri, 2009, 2010) takes the lead in considering influence of uncertain parameters on ship design: principal dimensions of container ship are optimized by Robust Design (RD) and Robust Optimization Design (ROD). Afterwards, M Diez team (2011–2015) introduced RD and ROD to ship hull Simulation based Design (SBD) system, and series of researches are conducted: design objective is developed from principal dimensions to hull lines (Wei et al., 2013; Diez et al., 2014), single uncertain parameter to multiple, speed disturbance to wave response (Leotardi et al., 2015; Campana, 2015), which reflects the idea: "from coarse to fine, from simple to complex". Meanwhile, S Hannapel (2010) (Hannapel and Vlahopoulos, 2010)introduced uncertain factors to constraint condition, the expectation and

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variance of objective function are considered. A Papani (2014) (Apostolos et al., 2014) considered the wave load and ship sway response uncertainty, hydrodynamic response of ship structure is described by cross spectral combination. The common characteristic of above researches was: uncertainty parameters are introduced into the design or optimization system as a priori knowledge, but the result's quality and reliability are not evaluated, that would lead the design result having low quality level, and a high failure probability when attending in the further detailed design.

From the statistical point of view, Reliability-based Optimization Design (RBOD) (2016) (Fang-yi et al., 2016; Richard et al., 2016; BaAbbad et al., 2015)considers the uncertainty of probabilistic model of constraints, at the beginning of design. By means of reliability analysis and quality optimization, RBOD can obtain high quality results that meet the requirements of performance, reliability and constraints. As a high demand and special kind of RBOD, Design for Six Sigma (DFSS) (Sebastian and Derlukiewicz, 2012) could effectively ensure the quality level to reach "6σ", which is widely used in many engineering design fields.

As summary, with respect to previous studies, key factors of different definitions were listed here:

- Deterministic Optimization Design (DOD): The conventional optimization method with deterministic or certainty variables and constrains.
- Robust Optimization Design (ROD): Optimization process considers uncertainty of the objective or target function;
- Reliability-based Optimization Design (RBOD): This method focuses on constraints, which are treated as probabilistic inequalities and given a statistical feasible region.
- Design for Six Sigma (DFSS): It is a special kind of RBOD with high quality requirement of "6σ" quality level, and is widely used in industrial design.

While ROD is mainly focused on expectation or variance of the objective function, the RBOD and DFSS concentrates on the probabilistic handling of constraints, which can be a fine solving way for the quality requirements and probabilistic constraints.

In this research, Myring axial symmetry revolution body with parameterized expression is assumed as AUV hull lines, and its travelling resistance is obtained via modified DATCOM formula. The problems of AUV hull lines design for the minimum travelling resistance with uncertainty parameters existing are studied. Based on reliability-based optimization design technology, a 6-sigma design target for quality level is conducted, and is proved high reliability for the actual environment disturbance.

2. AUV case study

2.1. Myring axial symmetry revolution body

Regular axial symmetry revolution body of AUV includes Myring type, Nystrom type, Kaax type and Water-drop type, which head and tail shape can be got by specific formula. This study takes Myring type for example, hull lines function is shown in Eq. (1):

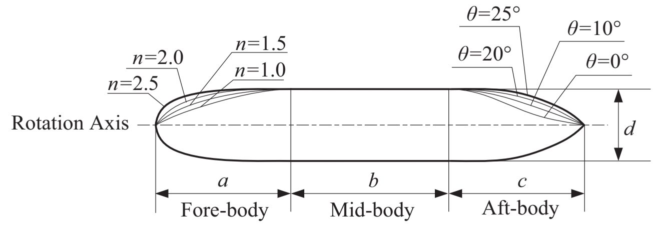

Fig. 1. Illustration diagram of Myring axial symmetry revolution body.

where: a is fore-body length; b is parallel middle body length; c is after-body length; d is middle body diameter; x is the distance from the top of the head; $r(x)$ is radius at position x; n and θ are parameters to control the curve shape. The illustration diagram of Myring axial symmetry revolution body is shown in Fig. 1.

2.2. Resistance calculation formula

As an underwater travelling vehicle, methods for obtaining resistance of axial symmetry revolution body mainly includes empirical formula, CFD method and model test. Relatively speaking, the biggest advantage of empirical formula is high computing speed, but shortcoming is low accuracy in the design process.

DATCOM method is used for calculating missile and torpedo travelling resistance and is introduced to AUV resistance calculation by Barros (Barros et al., 2008 (De Barros and De Sa, 2008)), which is shown in Eq. (2):

$$\begin{cases} Rt = \dfrac{1}{2}C_v \rho S_B u^2 + \dfrac{1}{2}C_f \rho S_S u^2 \\ C_v = 1.02C_f\left[1 + \dfrac{1.5}{(l_B/d)^{1.5}} + \dfrac{7}{(l_B/d)^3}\right]\dfrac{S_S}{S_B} \end{cases} \tag{2}$$

where: Rt is travelling resistance of AUV, C_f is friction resistance coefficient, and 1957-ITTC recommended formula is used here; l_B is the whole body length; S_S is wet surface area of body hull; S_B is cross-sectional area of middle body; u is travelling speed.

In order to validate the enough accuracy of DATCOM formula for this study, CFD results would be used as the criterion, 10 typical cases are both calculated by DATCOM and CFD. Design variables and resistance results are shown in Table 1 and Fig. 2.

There is, in Fig. 2, a certain deviation between DATCOM and CFD results, and this kind of deviation increases along with speed. A modification can be done through binomial fitting the absolute error of the two results, and fitting formula is got as:

$$Rt' = 0.2u^2 + 0.247u - 0.1084 \tag{3}$$

Thus, modified DATCOM formula can be obtained as:

$$\overline{Rt} = Rt + Rt' \tag{4}$$

$$\begin{cases} \text{For}-\text{body shpe: } r_f(x) = \dfrac{1}{2}d\left[1 - \left(\dfrac{x-a}{a}\right)^2\right]^{\frac{1}{n}} \\ \text{After}-\text{body shape: } r_a(x) = \dfrac{1}{2}d - \left(\dfrac{3d}{2c^2} - \dfrac{\tan\theta}{c}\right)(x-a-b)^2 + \left(\dfrac{d}{c^3} - \dfrac{\tan\theta}{c^2}\right)(x-a-b)^3 \end{cases} \tag{1}$$

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