Propeller of Amphibious Robot Optimizing Design
Based on Integrated Software Platform

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Abstract—The propeller of amphibious robot is a device facilitating the robot to swim and climb. Integrated software platform (ISP) is an optimization tool coupling some commercial design software with optimization software iSIGHT. Two types of commercial software are integrated in the ISP for optimizing mass and thrust of propeller. CAD software is used to design the propeller and calculate its mass, and CFD software is used to compute propeller thrust. The two optimization objectives as minimizing mass and maximizing thrust at the same time conflicts, thus a modified objective function including both objectives is formulated as the design function. In the paper, design of experiment (DOE) has been applied and variable effects on design function based on Pareto plot have been analyzed. The design process uses response surface model (RSM) to approximate mathematical model of the design objective as the function of design variables, and the approximated polynomial model is given. The optimal combination of the design variables affecting the propeller performance has been plotted using contour line.

Keywords—amphibious robot, iSIGHT, DOE

I. INTRODUCTION

Amphibious robot is a mechanism with the ability to swim in water and climb on land without interrupt of human. The propeller is intentionally designed by the combination of traditional propeller and wheel, with the appearance of figure 1. The amphibious robot propeller works as generic propeller while the robot swims in water, and the propeller will turn into wheel as it climbs on beach. The functions of propeller are indicated in figure 2.

Unlike other problem, the matter of this engineering optimization extensively relies on application software. The need for ISP is becoming more evident, especially when data exchange is concerned. The whole procedure of
developing the ISP includes CAD modeling software in which a fully parameterized amphibious propeller model is made, and CFD software which solves the propeller’s thrust. By using the software called iSIGHT the data transition from CAD model to CFD model has been achieved autonomously. The design variables have been changed in iSIGHT which also controls the execution of these software packages. Figure 3 shows the ISP. With the help of ISP, the mathematical function of the design objective is approximated with the design variables, and the function is given in explicit manner in the paper.

II. MATHEMATICAL MODEL

The design optimization problem is formulated with the objectives to obtain the propeller’s shape with the maximum thrust and minimum mass within the constraint bounds. Our optimizing problem at hand concerned multi-objective, which can be formulated as shown in (1):

\[
\begin{align*}
\text{Max } J(\bar{x}) = & \left[ -M(\bar{x}) \right] \\
\text{S.t. } & \bar{x}_{LB} \leq \bar{x} \leq \bar{x}_{UB}
\end{align*}
\]

(1)

Where \(M(\bar{x}), T(\bar{x})\) are objectives as to mass function and thrust function to judge the performance of amphibious propeller. \(\bar{x} = [P / D \ Ae / Ao]^T\) is variable vector referred to pitch diameter ratio and the expanded area ratio which influence the geometry topology of the propeller, and \(\bar{x}_{LB}, \bar{x}_{UB}\) are design variables’ lower bounds and upper bounds respectively.

There are some approaches to handle the multi-objective problem, such as weighted sum of the objectives. Another simplified objective is used in the paper, which is defined as the force produced by per unit mass physically. This objective is to develop a viable practical procedure for efficiently obtaining minimum-mass-maximum-thrust. Now the mathematical model of the optimizing problem is described as (2):

\[
\begin{align*}
\text{Max } f(\bar{x}) = & \frac{T(\bar{x})}{M(\bar{x})} \\
\text{S.t. } & \bar{x}_{LB} \leq \bar{x} \leq \bar{x}_{UB}
\end{align*}
\]

(2)

III. ANALYSIS PROCEDURE

The analysis of amphibious propeller adopts a basic building block approach using systematical analysis embedded in ISP, as figure 4. The design matrix is specified in iSIGHT which is the input of DOE. For each design experiment, feasibility of the design objective is obtained, and optimization is executed within the feasibility region.

![Figure 4. Analysis block of ISP](image)

A. DOE and variable effects analysis

Design of experiment is a typical design environment consisting of analysis tools related to form a systematical analysis for the problem being designed. For a specified set of design variables, systematical analysis produces the design state information describing the characteristics of the problem. The analysis goal is to modify the set of design variables so that the design is improved. The information of the effects of design variables on the problem leads to make further decisions. In this process, DOE based on full-factorial model is used, and two factors and five levels are set, which calculates twenty five experiments in all. The design space which lines in (0.3, 0.5) and (0.3, 1) for expanded area ratio and pitch diameter ratio is discretized into equal parts which forms the design matrix.

With the help of DOE, factor influence on response can be analyzed among the feasible region of database. The Pareto graph appearing as an ordered bar chart displays the effects of each design variable on the response, where the design variables are displayed in order of largest effect to smallest effect. Blue bars indicate positive effects on response, while red bars figured negative effect. Therefore this plot can be used to distinguish the design variables with the largest contribution to the variability of the response. Figure 5 shows the design variable effects on the objective function, where it can be found that pitch ratio contributes negative effect, while area ratio affects the response in positive manner.
B. Approximation and RSM

Followed the analysis of variable effects, approximation of the response using the main contributors can be manipulated. Integrated system approximation procedure is the key to effective and efficient optimization, and failure can occur without appropriate approximation in the complex engineering designs. Approximate models, also referred to as behavior models, including Response Surface Model, Kriging Model and Taylor Series Approximation, can be used to create design objective and constraint functions which are explicit functions of design variables. Using approximation models can help to eliminate the computational noise for optimization whose outputs oscillate while the design variables change gradually. Approximation models naturally smooth out the response and constrain function, which helps to converge to the optimum point much faster.

Response Surface Model is used more frequently to approximate response based on an actual analysis database produced in DOE with simple algebraic functions, usually polynomials style. The model can be used to optimizing study with very small computer expense, because evaluation only concerning calculating the value of a polynomial for a specified set of design variables. Accuracy of the approximation extensively dependents on the capacity of the analyzed database and the volume of design space. For a volume small enough, any response surface can be smoothed out using quadratic polynomial with sufficient accuracy. As for highly nonlinear problem, the RSM model in maximum order (Quartic) is presented by a polynomial in (3):

\[
f(x) = a_0 + \sum_{i=1}^{N} b_i x_i + \sum_{i=1}^{N} c_{ii} x_i^2 + \sum_{i<j}^{N} c_{ij} x_i x_j + \sum_{i=1}^{N} d_i x_i^3 + \sum_{i=1}^{N} e_i x_i^4
\]

(3)

Where:

- \(N\) is the number of model inputs
- \(x_i\) is the set of model design variables

\(a, b, c, d, e\) are polynomial coefficients

Because the maximum coefficients of the polynomial is ten in this design, while there are twenty five trials, it always can find the coefficients of the polynomial, no matter how many orders have been assumed. In the paper, the quadratic, cubic and quartic polynomials have been performed respectively, and the results show that the quadratic polynomial has fitted most precisely with \(R^2\) up to 0.9865, and the other two fitted precision equal to 0.9651 and 0.9328 respectively. As for precision estimator, the RSM uses \(R^2\) analysis to measure how well the polynomial approximates the actual function at the design points used for its construction. The value of \(R^2\) equal to 1 indicates that values of model polynomial and values of actual design points are identical. The approximated polynomial formulated using matrix with unscaled inputs is given in equation (4).

\[
f = 2.02 + 1.26(P/D) + 16.9(Ae/Ao) + 0.14(P/D)^2 - 6.14(Ae/Ao)^2 - 10.8(P/D)(Ae/Ao)
\]

(4)

With the approximated response function, the contour can be plotted with the design variables \(P/D\) and \(Ae/Ao\), as shown in figure 6. The contour is obtained on the condition that other parameters of the propeller as constants with angular velocity equal to 10.5rad/s in the DOE process, and the propeller’s material is specified aluminum. For every designed force, a pair of parameters can be found on the contour line.
interaction effects of all parameters on the propeller performance.

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