# SURROGATE-BASED OPTIMUM DESIGN FOR NON-UNIFORM GRID-STIFFENED SHELLS WITH ADAPTIVE SAMPLING

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*Summary* For the cylindrical stiffened shells under internal pressure and non-uniform axial compression, a force loading pattern based on the nonlinear explicit dynamic analysis is employed. Due to the non-uniform load, numerous variables are involved in structural design whereas it is practically impossible to perform the optimization for the overall variables directly, even if surrogate model is adopted. The framework of a bi-step surrogate-based optimization with adaptive sampling is presented in this study, which aims to build relatively high-fidelity surrogate models with less computational cost for complex engineering designs. Comparison of direct surrogate-based optimization and the proposed method shows that the bi-step surrogate-based optimization with adaptive sampling can achieve a larger weight saving with less computational cost. Consequently, it can be concluded that the proposed method provides an efficient and practical approach to find the optimum designs for structures with numerous variables and various variable types.

## INTRODUCTION

Stiffened shells have been widely used in aerospace designs due to the high efficiency in terms of stiffness, strength and environmental robustness. The stiffening pattern can increase the resistance of bending, torsion and stretching, thus further improve structural capacity against buckling. Numerous design optimizations [1-3] have been performed to find the minimum weight and maximum performance for stiffened structures. Nevertheless, for some stiffened shells, especially when loads are non-uniform, uniform properties of the structure in one direction may be far from optimal. Hence more segments are needed for design to deal with the non-uniform load, although uniform design parameters are considered in one segment region due to the requirement of manufacture. Obviously, more design segments more design variables. Aiming at reducing the computational cost, the framework of a bi-step surrogate-based optimization with adaptive sampling is presented in this paper, which is proved to be efficient for the optimization of multivariable stiffened shells. In the first step, the original optimization is decomposed into several sub-optimizations, and each sub-optimization is performed individually. In the second step, the screening of variables can be done by the optimum results of the first-step optimization, and then the adaptive sampling and second-step optimization can be performed in a reduced design space. The optimum design can be achieved with less computational cost through the proposed bi-step method. A typical fuel tank example configured for use in the booster of launch vehicle is established to demonstrate the efficiency of the bi-step surrogate-based optimization method. Three adaptive sampling strategies with different distributions of sampling points are compared with the direct surrogate-based optimization. Results indicate that the bi-step surrogate-based optimization with adaptive sampling provides an efficient and practical approach to find the optimum designs for structures with numerous variables and various types. Moreover, the proposed method allows parallel processing and further enhances the time-saving benefits. In addition, different specialized optimization algorithms and surrogate models can be employed for different sub-optimizations. Simultaneously, the bi-step surrogate-based optimization can provide much useful information, such as the variable efficiency, the trend of material distribution, etc.

## ALGORITHM AND OPTIMIZATION RESULTS

### Key points of the Bi-Step Surrogate-Based Optimization with Adaptive Sampling

The main framework of the surrogate-based optimization with adaptive sampling in this paper can be decomposed into two steps. In the first step, the original optimization is decomposed into several sub-optimizations according to an assumed principle, which is based on the following considerations. If all the variables are optimized together, it will cause serious concern for computational cost. If each variable is optimized respectively and then all the optimum results are added to generate a synthesized model, the coupling and interaction effects of design variables will be ignored. Thus, a trade-off principle is introduced to solve this problem: decomposing the original optimization into sub-optimizations according to variable types, and each sub-optimization is performed based on the initial design individually. In the second step, a synthesized design built by the optimum results in first-step optimization is considered as the initial design of second-step optimization. Afterwards, adaptive sampling is performed based on the synthesized design, aiming at reducing the design space with a small sacrifice in fidelity. In order to guide the reduction of design space rationally, two factors are introduced herein, including non-dimensional variable variation factor $\Delta$ and efficiency factor $\eta$.

Non-dimensional variable variation factor $\Delta$ is defined as a ratio of the non-dimensional variation of the design variable compared to its initial value. Subsequently, the ranges and sample sizes for each variable in the adaptive sampling are

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determined by $F(\Delta)$ and $G(\Delta)$ respectively. Simultaneously, analysis of the synthesized design needs to be carried out. If the synthesized design does not satisfy the overall constraints, efficiency factor $\eta$, which describes the contributions of different variable types to the objective or some key constraints, is introduced to further improve the adaptive sampling. Based on the information above, the scheme of adaptive sampling is determined, and then the second-step surrogate-based optimization can be performed. More details are explained in reference [4].

**Problem Description and Optimization Results**

In this study, the isogrid stiffening pattern is investigated. Four types of design variables are involved in the optimization of isogrid stiffened shell, including stiffener spacing, skin thickness, stiffener width and height. The total fuel tank with stiffened shell are segmented into six regions (three circumferential and three longitudinal segment regions), each segment region is composed of stiffeners, skin and four welds lying at four sides. Different segment regions are manufactured separately and then assembled to form a whole stiffened shell by welding. A non-uniform axial compression approximated as a quintic polynomial is utilized to obtain the collapse load of the fuel tank model by LS-DYNA explicit solver. We want to find the optimum design by minimizing the structural weight subjected to the given collapse load and yield stress constraints.

Predicted buckling deformation shape of the optimum design based on the proposed method is shown in Fig.1c. It can be noted that the collapse occurs at two regions simultaneously, instead of at only one region in initial design (as Fig.1a). Moreover, the von Mises stress distribution of the optimum design is shown in Fig.1d, which is more uniform compared to the initial design (as Fig.1b). Results indicate that the material efficiency of the fuel tank is improved through the bi-step optimization. Comparison of the optimum results obtained by the proposed method and Direct Surrogate-based Optimization (DSBO) is listed in Table 1. As can be seen, under the buckling and stress constraints, only a weight saving of 20% is achieved by DSBO compared to the one of 34% obtained by the proposed method. From the point of view of computational cost, the proposed method also has a definite advantage, as the total sample size $N_s$ is 104 and the total runs of exact FEA $N_t$ is 144. Results indicate that the proposed method is able to find a better optimum design in much less time compared to the traditional method, while not necessarily globally optimal.

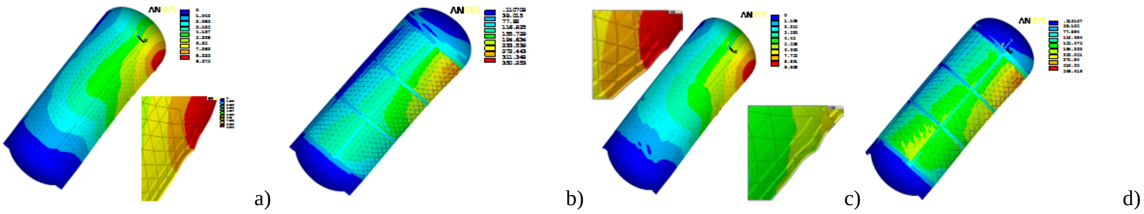


Fig1. Comparisons: a) buckling deformation shape of the initial design; b) Von Mises stress distribution of the initial design; c) buckling deformation shape of the optimum design; d) Von Mises stress distribution of the optimum design

Table 1 Comparison of the efficiencies of the proposed method and DSBO

| Type | Weight, kg | Collapse load, kN | Maximum stress, MPa | $N_s$ | $N_t$ |
|---|---|---|---|---|---|
| Initial design | 285 | 2271 | 350 | --- | --- |
| Traditional Method (DSBO) | 227 | 2271 | 350 | 144 | 152 |
| Proposed method | 189 | 2271 | 349 | 104 | 144 |

## CONCLUSIONS

The framework of the bi-step surrogate-based optimization with adaptive sampling is presented in this paper, which is proved to be efficient for the optimization with numerous variables and various variable types. In the first step, the original optimization is decomposed into several sub-optimizations, and each sub-optimization is performed individually based on the initial design. In the second step, the screening of variables can be done by the optimum results of the first-step optimization, and then the adaptive sampling and second-step optimization can be performed in a reduced design space. Through the proposed bi-step method, the optimum design can be achieved with much less computational cost. A typical fuel tank is optimized by the proposed method. Results show that the optimum design obtained by the proposed approach is potentially close to the global optimum, and the proposed method is more efficient compared to the direct surrogate-based optimization.

**References**

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