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Systematic Method of Applying Structural Characteristics of Natural Organisms to Mechanical Structures*

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Abstract: Structural bionic design lacks mature and scientific theories, and the excellent structural characteristics of natural organisms sometimes cannot be transferred into engineering structures effectively. Aiming at overcoming the existing problems, this paper summarizes three related theories: similarity theory, fuzzy evaluation theory and optimization theory. Based on the related theories, a method of structural bionic design is introduced, which includes four steps: selecting the most useful structural characteristic of natural organism; analyzing the structural characteristic finally chosen for engineering problem; completing the structural bionic design for engineering structure; and verifying the structural bionic design. Similarity theory and fuzzy evaluation theory are employed to achieve Step 1. In Step 2 and Step 3, optimization theory is employed to analyze the parameters of structures. Together with the thoughts of simplification and grouping, optimization theory can reveal the relationship between organism structure and engineering structure, providing a way to structural bionic design. A general evaluation criterion is proposed in Step 4, which is feasible to evaluate the performance of different structures. Finally, based on the method, a structural bionic design of thin-walled cylindrical shell is introduced.
Keywords: structural bionic design; similarity theory; fuzzy evaluation; optimization; evaluation criterion

In human history, many creative design and innovation were invented through inspiration from nature[1]. For natural organisms, billions of years of evolution was a slow but effective process of optimization, and many excellent properties and ingenious frames, which artificial design could not always match, have been developed. They provide a new way to solve engineering problems[2,3].

Design of mechanical structure is an important engineering field. Light structure is needed in aircraft, because it is one of the most important ways to improve the mobility of aircraft. The development of high speed machining tool demands structures with high stiffness and light weight. As a result, high demands are put forward to structure design, and light weight design, drag reduction design etc become the key issues[4,5]. However, some of the issues have been well solved by natural organisms. Zhao *et al*[6] improved the specific stiffness of a machine tool column with bionic stiffening ribs, inspired by biological skeleton and sandwich stem. By analyzing the structural characteristic of dragonfly wing, Ma *et al* [7] designed a bionic aircraft reinforced frame, and its specific stiffness and specific strength were increased by 2%—6% and 1%—8%, respectively. Inspired by soil-burrowing animals like dung beetle, Ren *et al* [8] designed bulldozer blades with rough surfaces, and found that the bionic surfaces could reduce the mean draft force compared with smooth ones. Selecting the dung beetle as bionic prototype, Gao *et al* [9] designed the working layer of an impregnated diamond bit, and their tests showed that the bionic bit improved the drilling speed and lifetime by 44% and 74%, respectively, compared with a common bit. Through learning from natural organisms, some researchers have done structural bionic design for engineering structures successfully. However, they could not provide a systematic method of applying the structural characteristics of natural organisms to engineering structures.

Some efforts have been made to approach a systematic method of structural bionic design. Ren[10] summarized several types of geometric constitutive units on the body surfaces of soil animals, which was very helpful for drag reduction design of a structure. Vincent and Mann[11] compared solutions of some engineering problems such as cleaning and joining surfaces by natural organisms with those by TRIZ (Teoriya Resheniya Izo-

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bretatelskikh Zadatch) method worked out by Russian researchers for inventive problem solving, and noted that TRIZ seemed to have the main qualifications of an effective bridge between biology and engineering. However, they gave a good proposal rather than a systematic method. Zhao *et al*[12] introduced a flowchart of structural bionic design, but one of the most important parts analyzing the structural characteristics of natural organisms was nearly neglected. This paper is aiming at providing a systematic method, which will overcome the existing problems.

1 Summarization of related theories

Although it solves many engineering problems successfully, structural bionic design lacks mature and scientific theories. Here, three related theories are summarized: similarity theory, fuzzy evaluation theory and optimization theory. They are employed in the following method of structural bionic design.

Similarity theory is the basic theory to find the similar characteristics between different objects. This theory can help designers with the search of organisms, which are similar to engineering structure.

Fuzzy evaluation theory is a quantitative evaluation method for multi-factor problem. It gives a quantitative value by calculating the weighted average of all the factors. Fuzzy evaluation theory provides a feasible way to find the most useful structural characteristic of organism among several ones.

Optimization theory is to optimize the objective function by mathematical iteration in the design domain. Optimization theory is used during structural bionic design to reveal how parameters affect the whole structure and the function of an organism, and to optimize some of the parameters for the engineering.

2 Method of structural bionic design

The method of structural bionic design includes four steps.

Step 1 Selecting the most useful structural characteristic of natural organism. There are many excellent structural characteristics in nature, but not all of them are suitable for the structure design of the engineering problem that needs to be solved. Hence, useful structural characteristics should be chosen from them.

(1) Several structural characteristics, which are possibly helpful for the structure design, should be picked out. Usually, function, load and geometric structure are the factors, which almost represent an engineering problem, so similarity degree between the structural characteristics of organism and the engineering problem in these three factors represents to what extent the structural characteristics can help engineers with the structure design. If a structural characteristic is very similar to the structure design of engineering problem in any factor of the three, it may be useful, and should be picked out. In this way, several possibly helpful structural characteristics can be found.

(2) The most useful structural characteristic should be chosen from those ones. To achieve this, fuzzy evaluation theory, which uses weighted evaluation vector to evaluate similarity, is employed. The weighted evaluation vector can be expressed as

$$\boldsymbol{B}=\boldsymbol{W}\times\boldsymbol{R}=[B_1,B_2,B_3,\cdots] \tag{1}$$

where $\boldsymbol{B}$ is the weighted evaluation vector; $\boldsymbol{W}$ the weight vector; and $\boldsymbol{R}$ the evaluation matrix. The former three factors, which can mostly describe the engineering problem, are chosen to be the factors in fuzzy evaluation. $\boldsymbol{W}$ is defined as

$$\boldsymbol{W}=[w_1,w_2,w_3]=[0.45,0.35,0.2] \tag{2}$$

where w_1, w_2 and w_3 represent weighting coefficients of function, load and geometric structure respectively. Function is the most important factor of the three, because structural characteristics with different functions is much less useful for the engineering problem. Hence, it is assigned the maximum value. Geometric structure is what needs to be improved, so it is assigned the minimum value.

$\boldsymbol{R}$ is defined as

$$\boldsymbol{R}=[\boldsymbol{R}_1,\boldsymbol{R}_2,\boldsymbol{R}_3,\cdots]=\begin{bmatrix} R_{11} & R_{12} & R_{13} & \cdots \\ R_{21} & R_{22} & R_{23} & \cdots \\ R_{31} & R_{32} & R_{33} & \cdots \end{bmatrix} \tag{3}$$

The evaluation matrix of structural characteristic number i is $\boldsymbol{R}_i$, and R_{1i}, R_{2i} and R_{3i} represent its evaluation value for the factor of function, load and geometric structure, respectively. Values of R_{1i}, R_{2i} and R_{3i} should be carefully assigned according to the similarity between the structural characteristics of organism and engineering problem, because they can affect the weighted evaluation vector, which is the basis to choose the structural characteristics to be used in structural bionic design for the engineering problem.

By comparison of the values in the weighted evaluation vector, the one with the maximum value, which is also the most useful, will be chosen.

Step 2 Analyzing the structural characteristics finally chosen for the engineering problem. After the structural characteristics, such as non-smooth surfaces, graded structures, hierarchical structures, is picked out, it cannot be used in structure design directly, because it is just a guideline. To transfer this guideline into structural bionic design, the following analyses should be done.

(1) Simplifying the structure of natural organism. The structure of natural organism, which is usually complex, is not suitable to be analyzed and machined, so simplification is needed. Aiming at solving engineering problem, simplification should be done according to the function of engineering structure. The function of engineering structure indicates which parts of organisms are important, while the others are not. For example, if the function of engineering structure is to reduce drag force, the surface characteristics of organism should be paid more attention, while the internal structure is not important.

Considering manufacturability, some simple geometric models such as circles, rectangles and cuboids are employed here. Through division, a complex structure of organism can usually be divided into several less complex parts, which may contain surfaces and inner supporting parts. If surfaces are important, some points on surfaces are measured, and then surface fitting method is used to build the complex model. If surfaces are not important, the combined surface from simple surfaces like planes, cylinder surfaces and spherical surfaces will make sense. Common structures in engineering like cylinder bars and cuboid beams can replace the inner supporting parts of organism structure. Fig.1 is an example, which shows the structural bionic design for a thin-walled cylindrical shell based on the cross-section structure of bamboo. In the process of simplification, combined structure of big rings and small rings replace the complex one in bamboo cross-section.

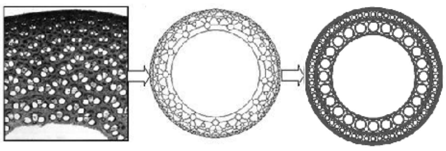


Fig.1 Simplification of bamboo cross-section[13]

(2) Extracting and analyzing the parameters of the simplified structure. The parameters could be found mostly from parameters of the simple geometric models used in the simplified structure. For example, the parameters of the simplified structure in Fig.1 are those of the rings. For each parameter, single-factor optimization is done in finite element analysis software, taking the performance of achieving the function of engineering structure as the objective and the result indicates how the parameter affects the structure of organism. According to the effect, these parameters will be divided into two groups, Groups A and B, and they will be treated differently in the following step. If the optimal value of a parameter makes the structural characteristics of the simplified structure agree with that of organism, it will be included in Group A; otherwise, it will be put into Group B.

Step 3 Completing the structural bionic design for engineering structure.

(1) Designing a preliminary bionic structure. If surfaces are important, the approximate surfaces will be applied to the design of the preliminary bionic structure by surface fitting method with some structural adjustment in its parameters. If the inner supporting parts are important, they should be designed using the simple geometric models, which are employed in the simplified structure of organism, gradually, hierarchically or in branch style according to the chosen structural characteristics. By changing the diameters of different rings according to engineering problem, the simplified structure in Fig.1 can be designed as the preliminary bionic structure.

The parameters of the preliminary bionic structure can be found from those of the simple geometric models, which are employed here.

(2) Assigning the values of parameters. After the preliminary bionic structure was achieved, it is time to handle the parameters. If a parameter is in Group A, its final value is the optimal value coming from single-factor optimization of the preliminary bionic structure. Values of parameters in Group B will be decided by multi-factor optimization. However, there is a possibility that the preliminary bionic structure is too complex to do multi-factor optimization. If so, do several single-factor optimizations to give every parameter an initial value, and then search groups of values nearby by hand, and find the best group among them. Once the values of all parameters are assigned, the bionic structure is completed.

Step 4 Verifying the structural bionic design. There are two important points, the evaluation criterion for comparison and design of the contrastive structure.

(1) The evaluation criterion for comparison is usually dependent on the requirement of the engineering problem. The evaluation criterion should reflect the effect of both positive and negative influencing factors. A general evaluation criterion proposed in this paper is ex-

pressed as

$$\begin{cases} \eta = \prod_{i=0}^{n} F_i \Big/ \prod_{j=0}^{m} f_j \\ F_0 = 1, \quad f_0 = 1 \end{cases} \tag{4}$$

where η is evaluation value; F_i positive factor; f_j negative factor; n number of positive factors; m number of negative factors. η can reflect every factor in a right way, and, to some extent, it can be a quantitative reference for comparison.

(2) The conventional design for engineering structure is the best as a contrastive structure. When there is more than one factor, the contrastive structure should be designed conventionally, eliminating the influence of minor factors. Designing two structures with the same values in minor factors is a good way to eliminate their influences.

There are two ways to compare the two structures. One is through finite element analysis software. Some software like ANSYS is a powerful tool to analyze mechanical properties of structures. Besides, experimental verification is the other effective way for comparison.

Compare the bionic structure with the contrastive one. If the bionic one is better, the structural bionic design for the engineering problem is effective. Otherwise, the design fails, and some other structural characteristics in the weighted evaluation vector are needed to be added into Step 2, which means that the design should restart from Step 2. Under this condition, more than one structural characteristic are used, and they should be combined and analyzed in Step 2.

3 Case study

Thin-walled cylindrical shell is one of the most common structures, and it is widely used in the manufacturing of aircraft, automobiles, missile, boilers, pipelines etc. However, thin-walled cylindrical shells are easy to buckle, and this may significantly reduce the resistance of the shell against other forces like bending. Meanwhile, thin-walled cylindrical shells should be designed as light as possible, which is beneficial especially to aircraft. Hence, there is a great need to improve its buckling load against axial compression and reduce its weight. The process of structural bionic design can be described as follows.

The function of the shell is to improve the load-bearing ability in axial direction and avoid buckling. Buckling problem of thin-walled cylindrical shells is shown in Fig.2. One end of the shell is simply supported (radial displacement is constrained), and bears an axial uniform pressure P. The other end is clamped. According to the similarity in the factors of function, load and geometric structure, three kinds of structural characteristics of organisms were found: gradient structure of bamboo cross-section, porous structure of wood and layered composite structure of seashells.

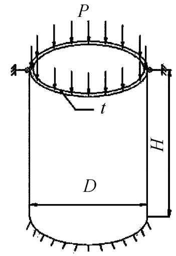


Fig.2 Buckling problem of thin-walled cylindrical shells

The weighted evaluation vector was calculated in Eq.(5), and gradient structure of bamboo cross-section got the maximum value, 0.845. Gradient structure was chosen for the structural bionic design of thin-walled cylindrical shell.

$$\boldsymbol{B} = \boldsymbol{W} \times \boldsymbol{R} = [0.45, 0.35, 0.2] \times \begin{bmatrix} 0.9 & 0.6 & 0.8 \\ 0.8 & 0.7 & 0.4 \\ 0.8 & 0.8 & 0.4 \end{bmatrix} = [0.845, 0.675, 0.58] \tag{5}$$

Fig.1 shows the process of simplifying bamboo cross-section. Small cylindrical shells were employed in the process, and they were simple and easy to machine. For the simplified structure, seven parameters were found to describe it (shown in Fig.3(a)). The basic parameters affecting the performance and distribution were d and T.

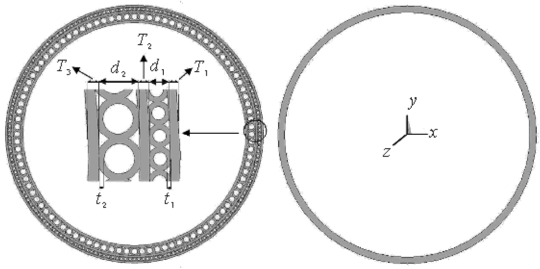
The function of the shell was to improve the buckling load, so the buckling load was taken as the objective. Meantime, the total mass was kept invariant. Through analysis in finite element software ANSYS, it was found that the value of d made the structural characteristics of the simplified structure agree with gradient distribution of bamboo cross-section. Parameter T made the structure tend toward a uniform distribution. Hence, d_1 and d_2 were included in Group A, and the others were in Group B.

As mentioned above, the simplified structure in Fig.3(a) could be used as the preliminary bionic structure with some structural adjustment in its parameters. Values of parameters d_1 and d_2 were assigned through single-factor optimization, and values of other parameters were given by searching among groups of values. There are two factors influencing the evaluation of the thin-walled cylindrical shell against buckling, i.e., the buckling load and mass. The buckling load needs to be designed as high as possible, and it is a positive factor. In contrast, the mass is a negative factor. Hence, the evaluation criterion can be expressed as

$$\eta = \frac{F}{M} \tag{6}$$

where η is the evaluation criterion; F critical buckling load; and M structure mass.

The contrastive structure (its cross-section is shown in Fig.3(b)) was designed with the same mass as the bionic structure. Their values of η were compared as listed in Tab.1. The bionic structure is much better than the contrastive one, and the improvement is 44.7%.



(a) Bionic structure (b) Contrastive structure

Fig.3 Cross-sections of bionic structure and its contrastive one

Tab.1 Comparison of bionic structure and its contrastive one

	Contrastive structure	Bionic structure	Percentage of improvement
Load-bearing efficiency / ($kN \cdot kg^{-1}$)	159.9	213.5	44.7%

4 Conclusions

(1) Three related theories, similarity theory, fuzzy evaluation theory and optimization theory, are summarized. They are the basis of the method proposed in this paper.

(2) Analyses of the structural characteristics of organism for engineering problems, which are usually neglected, are emphasized, and a feasible way is introduced. This step is the main part, which builds bridges between the structural characteristics of organisms and engineering structures, and it is crucial for the method of structural bionic design. Through simplifying organism structure and grouping its parameters, the structural characteristics of organisms can be extracted and transferred into engineering structures.

(3) A general evaluation criterion is proposed. It can reflect the effect of both positive and negative influencing factors in a right way, and is a quantitative reference for the comparison between two different designs for engineering problem.

(4) This paper proposes a systematic method of structural bionic design. Based on the method, a bionic thin-walled cylindrical shell is designed, and its load-bearing efficiency is improved by as much as 44.7%. Through structural bionic design of the shell, the method is confirmed to be a feasible and effective one.

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