

## Research on A Wing Structure Design Under Bionic Methods

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**Abstract**—This article describe a three-step structure layout grow method for a wing structure design. In the first step a ground structure is applied to get the initial structure d method data. In the second step, a bionic method simplified by the slime mould is present to guide the layout grow. In the last step, an optimization method of genetic algorithm is used to guide the tendency to the optimize result. Together, these three strategies create a hybrid approach which ensures high performance.

**Keywords**-Wing Structure; Layout Design; Ground Structure Method; Bio-Inspired Generative Design; Computational Geometry

### I. INTRODUCTION

Light-weight and high load capacity are two critical requirements in the aeronautics structure design. These two aspects often combined as a load-efficiency (the ratio of load bearing to weight) improvement problem for the designer to find an appropriate configuration for the specific loadings. Structure layout optimization which contains size, shape and topology optimization approaches is one of the most challenging set of problems in structural optimization field and also a general way to improve the structure efficiency. In this paper, we focus on a box-like wing structure design, and a tough load-efficiency is needed to establish a proper structure layout for the surface.

The ground structure method is as a discrete element-base topology optimization approach for the designer to get an approximated optimal truss connection from the structured orthogonal domain. This method denotes a union of all potential members connected between a set of

nodal points. The optimization is a procedure of eliminating unnecessary members from the ground structure with some criteria. The size judgement to the delete operation makes the structure topology shape to a design size problem. Recently, exact solutions for complicated domains have been numerically approximated and obtained, and there is ongoing work to extend the library of known analytical solutions for complicated domains. Achtziger studied the difference between simultaneous and iterative strategies for the geometry and topology optimization of a truss structure. Zegard use a Centroid Voronoi Tessellation (CVT) as the base mesh and provide an easy-to-use implementation for the optimization of least-weight trusses embedded in any domain geometry.

Biological structures, which inspired by the natural structures are widely used for solving engineering problems and has a great potential in the property enhancement. These advantages attribute to the cruel natural selection in the continuous struggle for survival of the species. With the evolution, the nature structure become more efficient and more suitable for the environment. These evolved structure offered various high- efficiency solutions for the designer to choose in the conceptual design stage. As the evolution characteristics, the similar engineering problems may have different structure selection and bionic application, so it is necessary to analyze and store the biological solutions into a type spectrum, which is the database for structure convenience and accurate selection. Zhao described the selection and adaptation of appropriate biological models for the lightweight construction of a plate. Christian Hammand and his group establish an ELiSE (Evolutionary Light

Structure Engineering) concept which uses pre-optimized lightweight structures from similar geometry in the nature to widen the design space, and present a new method for the abstraction from bionic structure [1-3].

In this paper, we present a new concept to abstract lightweight design principles from element based ground structure method and combined a structure data to a nature creature behavior to get novel lightweight design proposals for engineering problems in a systematic way.

## II. METHODOLOGY

The following section describes the details of a two-step structure layout design method: the geometry discrete strategy which based on the ground structure method and a layout grow approach which inspired by the growth of slime mould in nature. The detailed design process is shown in Fig. 1.

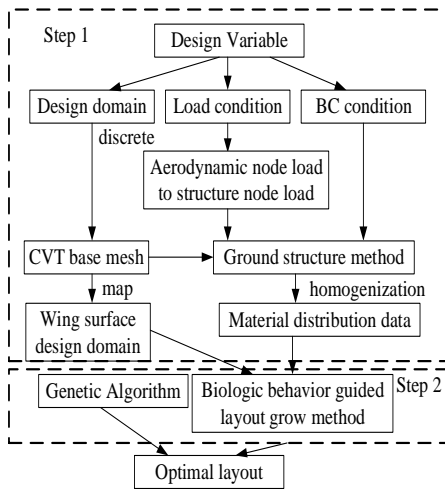


Figure 1. A flow chart of two-step topology optimizing procedure for curved stiffener layout design.

### A. The ground structure method

For the detailed model of a ground structure method, a formulation based on plastic analysis enforces equilibrium and no explicit compatibility or stress-strain relations. The final form of the plastic layout optimization problem is utilized in Eq. (1) these works [4-6], and can be efficiently solved by using the interior-point algorithm:

$$\begin{aligned} \min_{s^+, s^-} \quad & V^* = \frac{V}{\sigma_T} \mathbf{I}^T (\mathbf{s}^+ + \kappa \mathbf{s}^-) \\ \text{s.t.} \quad & \mathbf{B}^T (\mathbf{s}^+ - \mathbf{s}^-) = \mathbf{f} \\ & s_i^+, s_i^- \geq 0 \end{aligned} \quad (1)$$

With  $a_i = s_i^+ / \sigma_T + s_i^- / \sigma_C$  and  $n_i = s_i^+ - s_i^-$ .  $a_i$ ,  $l_i$  and  $\sigma_i$  are the cross-sectional area, length and stress of the member (for all members), respectively.  $\kappa = \sigma_T / \sigma_C$ .  $N_b$  is the total members in the ground structure. The parameters  $N_i$  and  $N_{sup}$  are the number of nodes and components with supports, respectively, and  $N_{dof}$  is the free nodal components with  $= 2N_n - N_{sup}$  for a two-dimensional ground structure.  $B^T$  is the nodal equilibrium matrix of size  $N_{dof} \times N_b$ ,  $f$  is the forces nodal and its number is  $N_{dof}$ , and  $\mathbf{n}$  is a vector with the internal (axial) force for all members in the ground structure. Stress limits in tension  $\sigma_T > 0$  and compression  $\sigma_C < 0$ . Only one of  $s_i^+$  and  $s_i^-$  is non-zero. The member is in tension if  $s_i^+ > 0$ , and in compression if  $s_i^- > 0$ .

In this paper a modified GSM with CVT (Centroidal Voronoi Tessellation) grid is applied to get the discrete structure information which is shown in Fig. 2. And a Non Uniform Rational Basis Spline (NURBS) method is used by Rhino (CAD software) to transform the parameters from two-dimension plane (x, y) to the reference three-dimensional surface (u, v). The map wing grid node data and load condition is shown in Fig. 3.

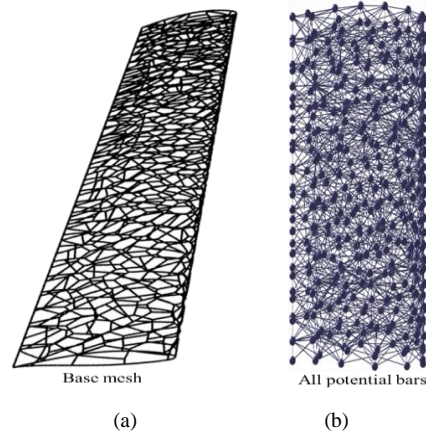


Figure 2. (a) CVT base mesh for the wing design surface and (b) the potential bars for the ground structure method

B. Bionic layout grow method

The topology structure under different load condition, which got from the ground structure method are shown in Fig. 4. Obviously the result has a bad manufacturability, which means post-processed measures should be taken to get an optimal structure. There are two basic points in this strategy to form a bionic structure type.

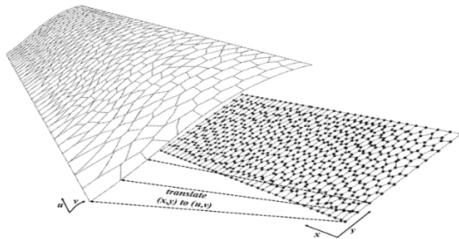


Figure 3. Map the location from (x, y) plane to reference (u, v) surface.

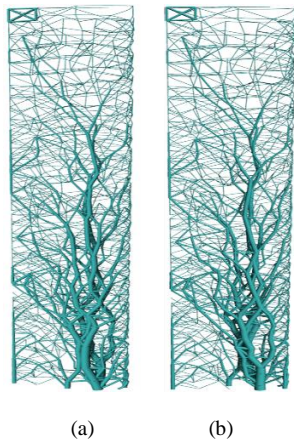


Figure 4. The topology layout computed by the ground structure method (a) is up surface and (b) is down surface.

1) Homogenization

As the ground structure method present a discrete grid mesh and an approximate distribution of the material. So in this stage, a homogenize method is taken to translate the bar connect relationship to the size-weight data in the mesh vertex. Figure 5 is a sample of an individual bar's size data allocation to the corresponding node in the search domain. The size-weight of the individual vertex is computed by Eq. (2):

$$w_i = \frac{W_{inf}}{N_{inf}} \quad i = 1, 2, \dots N \quad (2)$$

Here  $w_i$  is the size-weight of the  $i$ th vertex,  $N$  is the total CVT vertex,  $W_{inf}$  and  $N_{inf}$  are the sum of the influenced size-weight and the number to the influenced vertex, respectively.

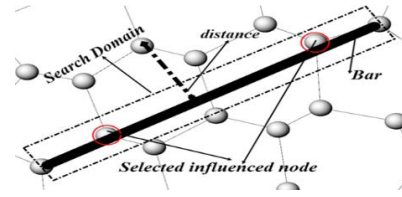


Figure 5. A select method homogenize the size data of the bar member.

2) Bionic

In order to take advantages of the evolution, a bionic layout grow method inspired by the growth of slime mould in nature is presented. When the slime mould grows, it spreads out a dense network of connections to find the needed energy. The connection which find nothing will be cut down and the connections which connect the food sources will be broadened to improve the efficiently. With this characteristic, a small amount of “lines” is established to connect a set of “key-points”. We hypothesized that a similar logic may be beneficial for connecting points which in the design domain to resist structural loads [7, 8].

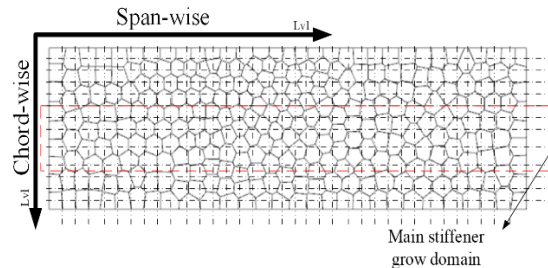


Figure 6. Domain separate to reduce design parameters

To get the “key-point”, the surface design domain is divided in to a number of small block along the span-wise and the chord-wise, shown in Fig. 6. And we specified the vertexes on the boundary as the “boundary points” which are changed by the optimization method and the points in the design domain as the “body points” which are invariant after homogenize method, shown in Fig. 7.

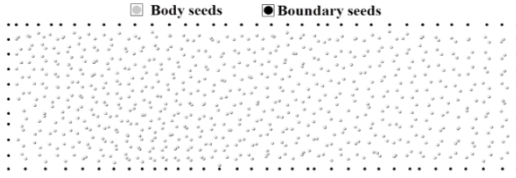


Figure 7. Classification of design variables.

The structural members of each design iteration are then sampled from the edges of the graph based on the following algorithm:

a) Edge-to-edge: the ends of the grown stiffener is the highest weight “boundary seeds” on the edge, and the node separate the stiffener is “body seeds” selected by a searching method, shown in Fig. 8.

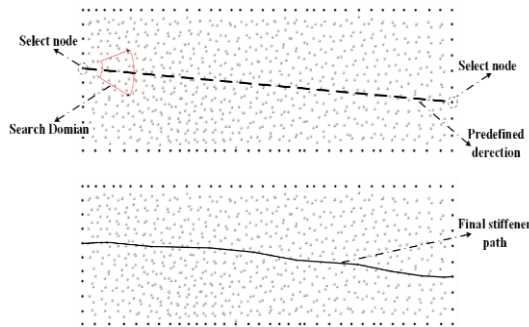


Figure 8. A curved stiffener model method between two selected nodes.

b) Delay: decay the weight of both ends by multiplying them by a decay parameter.

The final structure design is defined by the boundary of the design domain and the connections to the high-weight point. The parameters of this model are the weights ( $w$ ) of the 87 boundary seeds and 20 number parameters of the stiffener to the middle grow base point.

### III. OPTIMIZATION PROBLEM

#### A. Definition of the optimization model

This behavioral generative geometry model can create a large variety of structural designs for the partition based on a relatively small set of input parameters. To find the optimal structure layout, the structure weight is selected as the objective, while the structural maximum stress, torsional rigidity and bending rigidity are selected as constraints. The mathematical equations are:

$$\begin{aligned} \text{Objective : } \min M_{weight} &= f(w_1, w_2, \dots, w_{bc}, n_1, n_2, \dots, n_{mid}) \\ \text{s.t. } \begin{cases} U \leq U_{max} \\ S \leq S_{max} \\ \text{abs}(angle) \leq angle_{max} \end{cases} \end{aligned} \quad (3)$$

Where  $M_{weight}$  is the weight of the structure,  $w_{bc}$  is the size-weight of the boundary seed, and  $n_{mid}$  is the number of the sub-stiffener among the middle main stiffener.  $U_{max}$  is the maximum tip displacement of the design,  $S_{max}$  is the maximum permissible stress of the composite material,  $angle_{max}$  is the max torsion angle for the whole wing structure. The objective and the constraints are got from the static finite element analysis (FEA) under the ABAQUS software. And the geometrical model is produced by the Rhino (3D model built software). The whole optimize processes are implemented in Isight (a parameter optimization software).

#### B. Finite element model parameters

The wing structure design domain and load and boundary condition are shown in Fig. 9 with a length 2.7 m and width of 0.4 m. Each beam-like member of the curved stiffener has a uniform cross-section and the stiffener elastic modulus is found from the Halpin-Tsai semi-empirical relation because of its anisotropic and composite characteristics. The engineering constants used to define the beam element are listed in Table 1.

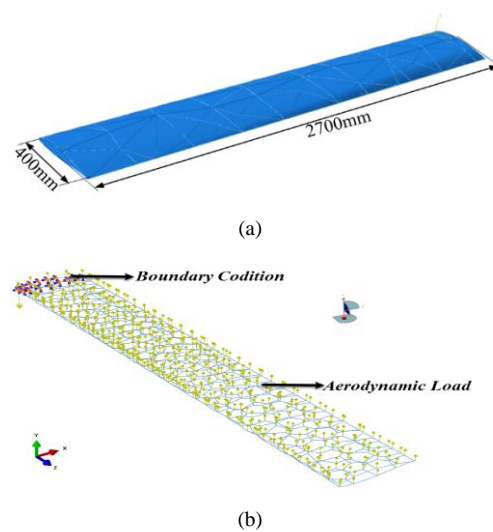


Figure 9. (a) Design parameters; (b) boundary conditions and loads distribution

TABLE I. COMPOSITE MATERIAL ENGINEERING CONSTANTS.

Material Properties	Value
Longitudinal stiffness, $E_1$ [N/mm <sup>2</sup> ]	157,650
Transverse stiffness, $E_2 = E_3$ [N/mm <sup>2</sup> ]	13,280
Shear stiffness, $G_{12} = G_{13}$ [N/mm <sup>2</sup> ]	4,561
In-plane shear stiffness, $G_{23}$ [N/mm <sup>2</sup> ]	4,538
Poisson's ratio, $\nu_{12} = \nu_{13}$	0.256

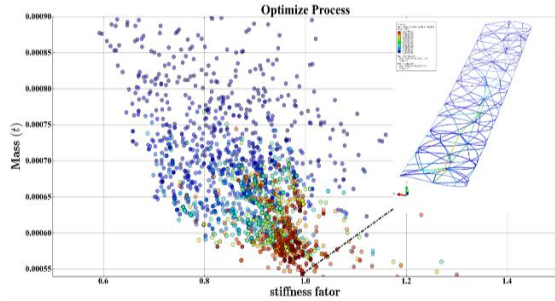


Figure 10. All designs explored during the optimization process plotted.

### C. Model Optimization

Using this model, we performed an optimization using a variant of the multi-islands genetic algorithms with the following settings:

- Number of designs per generation: 30
- Number of generations: 50
- Number of island: 10
- Mutation rate: 0.05
- Cross-over rate: 0.9

Figure 10 shows each layout design explored by the optimization plotted as a point on a scatter plot where the y-axis represents the weight of the partition, the x-axis represents the stiffness factor, and the color represents the generation in which it was created.

Once the optimization process was complete, we selected the final design as the one, which minimally met our 15% weight reduction goal. The detailed FE result is shown in Fig. 11.

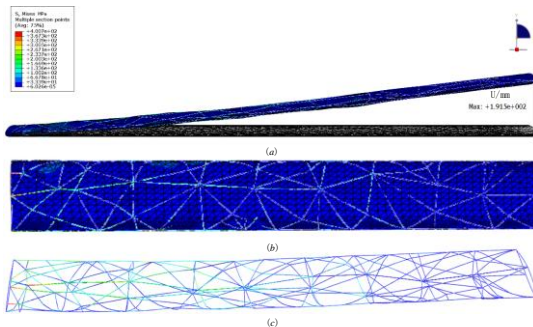


Figure 11. Final structure layout FE result

## IV. CONCLUSIONS

In this paper, a new concept of bionic curved grid-surface structures is proposed for a wing structures design. Draw on the biological structure of nature, a generative geometry model based on the ‘bottom-up’ agent-based growth processes is founded and with the evolution of genetic algorithm a unique result is produced which get a 15% weight loss to the traditional design. Also this article present a novel computational bionic geometry system which motivate the designer to explore a wider range of novel designs than would be possible using traditional design methods.

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