Paper

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Wing weight estimation considering constraints of structural strength and stiffness in aircraft conceptual design

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Abstract

According to the requirement of wing weight estimation and frequent adjustments during aircraft conceptual design, a wing weight estimation method considering the constraints of structural strength and stiffness is proposed to help designers make wing weight estimations rapidly and accurately. This method implements weight predictions on the basis of structure weight optimization with stiffness constraints and strength constraints, which include achievement of wing shape parametric modeling, rapid structure layout, finite element (FE) model automated generation, load calculation, structure analysis, weight optimization, and weight computed based on modeling. A software tool is developed with this wing weight estimation method. This software can realize the whole process of wing weight estimation with the method and the workload of wing weight estimation is reduced because much of the work can be completed by the software. Finally, an example is given to illustrate that this weight estimation method is effective.

Key words: weight estimation, aircraft conceptual design, weight optimization, load computation, parameterized modeling

1. Introduction

Aircraft conceptual design is one of the most important phases during the aircraft design process and each decision in this phase has significant effects on aircraft performance and cost [1-3]. Thus, it is important to improve the quality of conceptual design. Weight estimation is a key step in the aircraft design process because of its direct influence on further analyses and aircraft performance evaluation [4]. Thus, accurate weight predictions are important, and beneficial for the exact assessment of aircraft design quality and design decision impact. Allowing for the aircraft conceptual design process including a large number of variable changes and trade studies [5-7], aircraft mass properties needs to be recalculated frequently with changes in design. Research on more accurate, rapid, practical, and design-sensitive weight estimation method remains a focus in the field of aircraft conceptual design [7-10].

As an important component, the wing provides lift force and bears aerodynamic loading. Because the wings account for almost a third of total aircraft structure weight [11] and have great influence on the total weight and the center of

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gravity position of an aircraft, improving the accuracy of wing weight prediction is important for aircraft conceptual design.

Traditional methods of weight estimation during conceptual design have been based mostly on the use of statistical data and basic performance equations [8, 10]. Such methods are quick and simple, but not sufficiently precise, especially in current circumstances where more new materials and new types of structures are applied in aircraft. On the other hand, such methods must also have enough sensitivity or they may not fully reflect a change in design.

One method, that uses a physics-based analysis instead of statistical data, appeared in the 1990s. This method was studied by many scholars, such as Droegkamp[12], Bindolino[13], Laban[14], Hurlimann[15], and Sensmeier[16]. Such methods are generally based on finite element analysis to size the various components of the primary structure and compute their weight with material density and volume information[10]. These methods are obviously more exact. However, they are not used widely in aircraft conceptual design because it is time-consuming to prepare a FE model and perform the analysis, as well as their requirement for much detailed geometry information, which is likely unobtainable in the early design stage.

This paper presents a method for wing weight estimation, that is suitable for use in the conceptual design phase. This method, using parametric modeling of the wing, incorporates the process of structural weight optimization with strength and stiffness as constraints. The analyses and calculations are based completely on the wing CAD model, so this method can be used with conventional and non-conventional layouts. A wing weight estimation software was developed with the method to make weight estimation work quick and accurate. This software can generate finite element models and perform the analyses largely automatically. It also can quickly update the model and data when the design changes, which is well-adapted to engineering applications.

2. Overall Idea

The process for weight estimation by this method is shown in Fig. 1.

The specific steps are as follows:

1) Wing shape model creation according to parameters of the wing shape.
2) Wing structure and wing tank layout in accordance with the wing shape.
3) Wing structure FE model generation and wing aerodynamic characteristics computation.
4) Inertial and aerodynamic loads computation and concentrated loads setting.
5) Wing structure analysis with finite element technique and wing structure geometric parameters optimization for lighter weight.
6) After optimization, the weight and center of gravity of each component was calculated to obtain the weight characteristics of the wing.

3. Parameterized Modeling of Wing Shape Surface

3.1. Coordinate systems

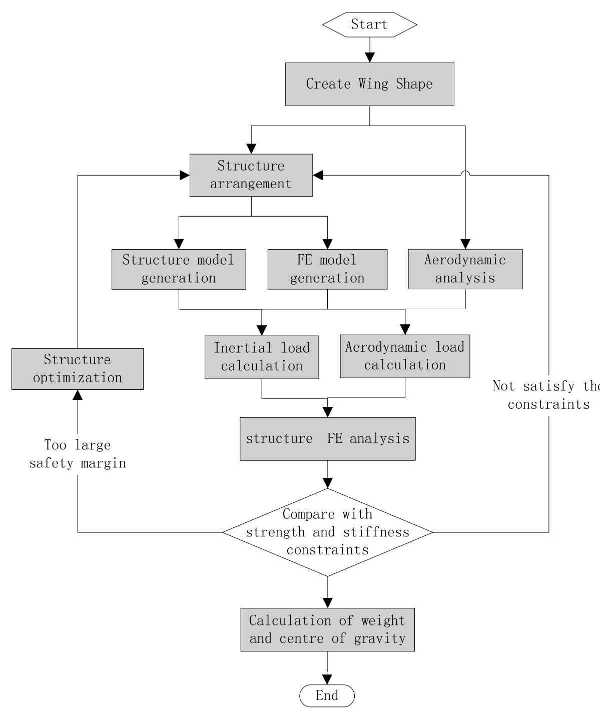

Fig. 1. Weight estimation process

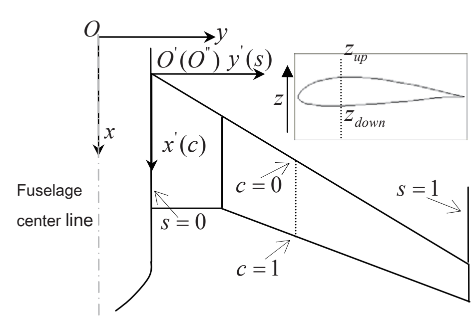

Fig. 2. Coordinate systems

The coordinate systems shown in Fig. 2 were adopted in this research. The absolute coordinate system of the design space is Oxyz with its origin at the most anterior point of the aircraft nose. The coordinate system of the wing is O'x'y'z' and its origin point is at the leading edge of the root. O" cs, with its origin at the same O'x'y'z', is a dimensionless two-dimensional coordinate system of the wing. The coordinate 's' represents relative position in the span-wise direction; the coordinate 'c' shows the relative position in the chord-wise direction.

3.2. Parameterized description of wing shape

Wing shape is a constraint on structure layout. Thus, the description and modeling method of the wing shape directly affect the implementation of subsequent modeling and analyses. According to Ref. [17] and Ref. [18], the wing is composed of several wing segments in this paper. Wing segment is divided into two categories by its plane geometry: those where the leading edge and trail edge are straight and those where the edges are curved. The description parameters are shown in Table 1 and some of them, marked with "√" are controllable. The description parameters are similar to those in Ref. [17], Ref. [18], and Ref. [20]. Airfoil group information includes the data of points on the airfoil curves and the span wise location on the plane where the airfoil is.

3.3. Shape modeling method

The process of wing shape modeling is stated as follows. First, the leading edge and trailing edge are generated with the plane shape of the wing, the incidence, and the anhedral and twist angles. Then, the airfoil curve is generated according to airfoil group data. Finally, model the wing shape with airfoil curves as sections and edges as guidelines.

4. Wing Structure Rapid Layout and FE Model Automated Generation

4.1. Parameterized modeling of wing structures

Wing structure modeling uses the same coordinate system as that used in wing shape modeling. Wing structures include six elements: spar, wall, rib, reinforcing rib, stringer, and skin.

1) Spar

The spar is composed of web and flanges. The description parameters of a spar include profile, material, and arrangement points list that set the position of the spar. The modeling process is divided into four steps: obtaining actual arrangement points on the surface according to arrangement parameters, choosing profiles, scaling profiles to actual profiles of structure, and generating a model according to the profiles.

2) Wall

The description parameters and modeling method for the wall are the same as for the spar.

3) Rib

The rib, maintaining the shape of wing, has the following parameters: starting and stopping point of rib arrangement, shape and area of flange, web thickness, material, and reinforcing rib or ordinary rib. Ribs are grouped for

Table 1. Description parameters of wing segment

Parameter	leading edge and trail edge are straight		leading edge and trail edge are Curved
	first wing panel	Other wing panels	
Taper ratio	√	√	
Sweep angle	√	√	
Root chord	√		√
Span	√	√	√
Incidence angle	√		√
Twist angle	√	√	√
Dihedral angle	√	√	√
coordinate of leading edge Root	√		√
Airfoil group	√	√	√

manageability; parameters of every group include the amount of ribs, type of arrangement, and the number of spar/wall perpendicular to ribs in the group. Boolean operation is used to combine web models and flange models with rib models. The modeling process has three steps: obtaining the actual shape of the rib profile, generating the upper flange, lower flange, and web, and combining the flanges and the web to the rib.

4) Stringer

The stringer is between the skin and ribs; its parameters are starting and stopping point of arrangement, relative height at arrangement point, profile, and material. Stringer modeling steps are similar with spar/wall; the only difference is that the stringer clings to skin instead of connecting upper and lower skins.

5) Skin

The description parameters of the skin are the root thickness, tip thickness, and material. A skin model is generated by contacting the surface, based on thickness.

Moreover, on the basis of the wing structures having been modeled, it is convenient to complete the layout of a wing tank, which can be determined with these structures as a sealed boundary. The description parameters of each tank include the starting spar/wall number, the stopping spar/wall number, starting rib number, and stopping rib number. This program obtains geometric data through these numbers to generate a wing tank model.

4.2. FE model automated generation

To realize further weight optimization with the structural analysis data as a constraint, it is necessary to build the structure finite element model automatically. According to the characteristics of wing structure and the description method of a finite element model, the wing structure components are replaced by shell and beam elements. The spar flanges, wall flanges, rib flanges, and stringers are replaced by beam elements. The spar web, wall web, rib web, and skin are replaced by shell elements. Because this method is used mainly in the early aircraft design stage, it only deals with the actual structure nodes, without considering further refinement of the finite element mesh. The details of implementing process are specified in Ref. [19].

4.3. Automated adjustment

The procedure for the wing structure rapid layout and finite element model automatic build is illustrated in Fig. 3. The process is divided into three steps:

1) The upper layer is wing surface modeling. The inputs for modeling are the parameters of wing shape.

2) The intermediate level is wing structure modeling. The structure-modeling inputs are the parameters of the wing structure and wing surface.

3) The final step is the generation of the structure finite element model and tank modeling. The inputs for finite element model generation are all the models of the wing structures. The tank modeling inputs are the numbers and parameters of these structures used as seal components.

Based on this process, the system can realize the automatic adjustment in two layers:

① When the structure's geometry changes, the structural finite element model will be rebuilt in accordance with the new geometric information of the structure and the tank model will automatically update as well as volume data, according to the changes.

② Because the structure arrangement parameters are managed with relative coordinates, these layout parameters are not affected by the actual parameters of the wing. To adjust to a surface change, the structure model will be regenerated automatically and structure weight will be recalculated as well as the center of gravity, moment of inertia, and other data. Uniting with ①, automatic adjustment of finite element model and wing tank is completed.

5. Weight Calculation Based on Modeling

The weight and center of gravity are calculated with the weight estimation method based on parameterization modeling (Ref. [20]). Weight, center of gravity, and moment of inertia can be directly obtained from the model and material information for these parts and components is modeled in the software.

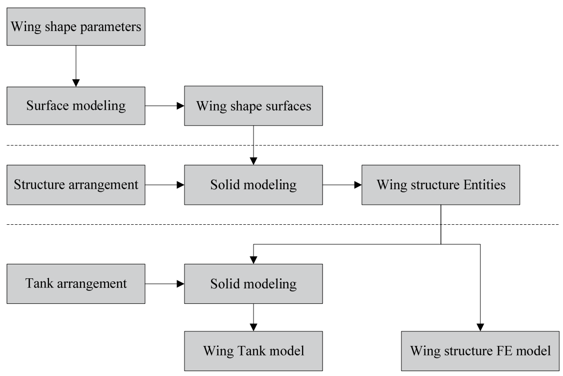

Fig. 3. Process of wing structure layout and finite element model generation

5.1. Mass characteristics computational method for rigid body

In this paper, wing weight characteristics are computed with the computational method of rigid body mass characteristics. Mass property parameters of rigid body include mass, center of mass, moment of inertia, and product of inertia.

The moment of inertia of a rigid body about the x, y, and z axes can be calculated with following formula.

$$\begin{cases} I_x = \sum m_i \left(y_i^2 + z_i^2 \right) \\ I_y = \sum m_i \left(x_i^2 + z_i^2 \right) \\ I_z = \sum m_i \left(x_i^2 + y_i^2 \right) \end{cases} \tag{1}$$

The following formula shows the calculation of the product of inertia for a rigid body.

$$\begin{cases} I_{xy} = \sum m_i \left(x_i y_i \right) \\ I_{xz} = \sum m_i \left(x_i z_i \right) \\ I_{yz} = \sum m_i \left(y_i z_i \right) \end{cases} \tag{2}$$

It is often required to compute the moment of inertia and the product of inertia about other coordinate systems. Two coordinate systems are shown in Fig. 5 and the moment of inertia can be computed with Eq. (3).

Coordinate transformation of the two coordinates is:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} + \begin{bmatrix} u_{1x} & u_{2x} & u_{3x} \\ u_{1y} & u_{2y} & u_{3y} \\ u_{1z} & u_{2z} & u_{3z} \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} \tag{3}$$

where $\begin{bmatrix} u_{1x} & u_{2x} & u_{3x} \\ u_{1y} & u_{2y} & u_{3y} \\ u_{1z} & u_{2z} & u_{3z} \end{bmatrix}$ is the transformation matrix, $\begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}$ is the translation vector from the origin of coordinate xyz to the origin of coordinate $x'y'z'$. In the rotation transformation matrix, $\begin{bmatrix} u_{1x} & u_{1y} & u_{1z} \end{bmatrix}$, $\begin{bmatrix} u_{2x} & u_{2y} & u_{2z} \end{bmatrix}$, $\begin{bmatrix} u_{3x} & u_{3y} & u_{3z} \end{bmatrix}$ are the unit vectors of the x-axis, y-axis, and z-axis of coordinate $x'y'z'$ in coordinate .

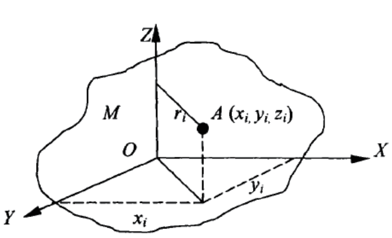

Fig. 4. Moment of inertia calculation

In the coordinate systems used in this paper, transformation from the coordinate $x'y'z'$ to coordinate xyz is a translation transformation and the axes of coordinate $x'y'z'$ are parallel to and in the same direction as the axes of the coordinate xyz. In this case, the rotation transformation matrix is $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$. The expressions of the moment of inertia and product of inertia according to the transformation between these two coordinates are:

$$\begin{cases} I_x = \sum m_i y_i'^2 + \sum m_i z_i'^2 + \sum m_i y_0^2 + \sum m_i z_0^2 + 2y_0 \sum m_i y_i' + 2z_0 \sum m_i z_i' \\ I_y = \sum m_i x_i'^2 + \sum m_i z_i'^2 + \sum m_i x_0^2 + \sum m_i z_0^2 + 2x_0 \sum m_i x_i' + 2z_0 \sum m_i z_i' \\ I_z = \sum m_i x_i'^2 + \sum m_i y_i'^2 + \sum m_i x_0^2 + \sum m_i y_0^2 + 2x_0 \sum m_i x_i' + 2y_0 \sum m_i y_i' \\ I_{xy} = \sum m_i x_0 y_0 + \sum m_i x_i' y_i' + y_0 \sum m_i x_i' + x_0 \sum m_i y_i' \\ I_{yz} = \sum m_i y_0 z_0 + \sum m_i y_i' z_i' + y_0 \sum m_i z_i' + z_0 \sum m_i y_i' \\ I_{xz} = \sum m_i x_0 z_0 + \sum m_i x_i' z_i' + x_0 \sum m_i z_i' + z_0 \sum m_i x_i' \end{cases} \tag{4}$$

5.2. Weight characteristic computation of parts

The steps to obtain the weight characteristics of a part are:

1) Determine the weight characteristics of the part at a standard density of $1000 kg/m^3$.

2) Multiply the mass, moment of inertia, and product of inertia by the ratio of the actual density to $1000 kg/m^3$. Then, the actual weight characteristics are acquired.

5.3. Weight characteristic computation for components

The weight characteristics of components are computed with expressions of mass characteristics computation for a rigid body.

The mass of a component equals the sum of the masses of the subcomponents or parts.

The computational expression of the center of gravity is:

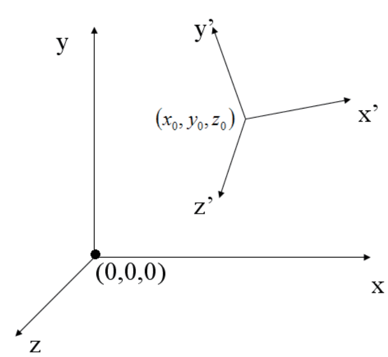

Fig. 5. Coordinate transformation

$$\begin{cases} x_{cg} = \dfrac{\sum W_i x_i}{\sum W_i} \\ y_{cg} = \dfrac{\sum W_i y_i}{\sum W_i} \\ z_{cg} = \dfrac{\sum W_i z_i}{\sum W_i} \end{cases} \quad (5)$$

where x_{cg}, y_{cg}, and z_{cg} are the gravity center coordinates of the component in the coordinates *xyz*, W_i is the weight of the i^{th} subcomponent of part, x_i, y_i, and z_i are the gravity center coordinates of the i^{th} subcomponent of the part in the coordinates *xyz*.

The moments of inertia and products of inertia of component are computed by this method:

$$\begin{cases} I_x = \sum\left[I_{xi} + W_i\left(y_i - y_{cg}\right)^2 + W_i\left(z_i - z_{cg}\right)^2\right] \\ I_y = \sum\left[I_{yi} + W_i\left(x_i - x_{cg}\right)^2 + W_i\left(z_i - z_{cg}\right)^2\right] \\ I_z = \sum\left[I_{zi} + W_i\left(x_i - x_{cg}\right)^2 + W_i\left(y_i - y_{cg}\right)^2\right] \\ I_{xy} = \sum\left[I_{xyi} + W_i\left(x_i - x_{cg}\right)\left(y_i - y_{cg}\right)\right] \\ I_{xz} = \sum\left[I_{xyi} + W_i\left(x_i - x_{cg}\right)\left(z_i - z_{cg}\right)\right] \\ I_{yz} = \sum\left[I_{xyi} + W_i\left(y_i - y_{cg}\right)\left(z_i - z_{cg}\right)\right] \end{cases} \quad (6)$$

where I_x, I_y, I_z, I_{xy}, I_{xz}, and I_{yz} are the moments of inertia and products of inertia of a component in its barycentric coordinate system, I_{xi}, I_{yi}, I_{zi}, I_{xyi}, I_{xzi}, and I_{yzi} are the moments of inertia and products of inertia of the i^{th} subcomponent or part in its barycentric coordinate system.

6. Automatic Load Calculation

Wing load is divided into three categories: aerodynamic load, inertial load from the mass of wing structure and gas in the wing tank, and concentrated load caused by other components and external stores hinged to the wing [21]. The first two are the main forms of wing load, which are distributed load and act on the wing structure according to a certain rule of distribution. In this paper, the main work of the load calculation is to obtain the distributed loads and convert them into equivalent nodal forces with the purpose of carrying out the finite element analysis.

6.1. Aerodynamic load calculation

The aerodynamic load calculation is divided into two parts, to compute aerodynamic forces on the wing and convert them into equivalent nodal forces according to the finite element model of wing structure. Because this study focuses on the aircraft conceptual design stage, during which the design is modified repeatedly and there is a lack of detail, aerodynamic prediction methods with less time cost are required in this study and the requirement for calculation accuracy can be appropriately relaxed. At the conceptual design stage, the common aerodynamic prediction methods include an engineering estimation approach, as described in Ref. [2], the vortex lattice method, the panel method, and numerical calculation methods. There have been some aerodynamic prediction programs based on these methods. Thus, an existing program selected according to the actual needs of engineering was integrated into the weight estimation software to compute the aerodynamic forces on the wing.

PANAIR, a computer program developed to predict subsonic or supersonic linear potential flows about arbitrary configurations using a higher-order panel method, has been used widely in the field of aircraft design[22-24]. Refs. [25-27] describe comparisons and evaluations of the program and method. The PANAIR program was used in B737 design process by Boeing Company[28-30]. Additionally, the time cost of this program is acceptable. Accordingly, this study integrated PANAIR to calculate aerodynamic forces. One caveat is that the applicable scope

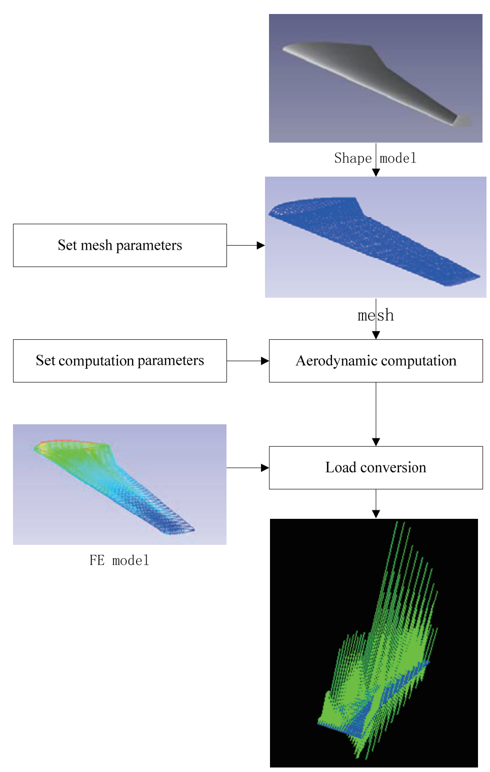

Fig. 6. Aerodynamic load calculation process

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of the method is limited, especially its inapplicability to cases with significant viscous effects and flow separation, and would be necessary to integrate another program or write a new program in these cases, which is beyond the scope of this study.

The calculation progress is shown in Fig. 6:

1) Set the parameters of a surface mesh of the wing.
2) Generate the mesh according to the surface mesh settings and wing shape automatically.
3) Set the parameters of aerodynamic prediction.
4) Call PANAIR to compute the aerodynamic forces on the wing and output the result, including the aerodynamic forces, at all mesh nodes.
5) Convert the aerodynamic forces at the mesh nodes of the aerodynamic calculation into equivalent nodal forces at the mesh of the finite element model.

6.2. Inertial load calculation

The inertia force induced by the mass of the wing structure and the fuel in the wing tank and the inertial force calculation is to obtain the mass distribution. In this paper, the wing model is cut into several blocks (see Fig. 7) and mass characteristics of each block are counted. Then, the mass distribution of the whole wing is determined. Because the wing thickness is far less than the chord length and span length, the grid used to cut the model is plane. Inertia force will be converted into equivalent nodal forces and loaded onto the finite element mesh according to the static equivalence principle.

The calculation progress is shown in Fig. 8:

1) Set the parameters of the plane mesh used to cut the wing model.
2) Generate several planes according to the mesh.
3) Use these planes to cut the wing model into many parts.
4) Compute the mass characteristics of each part to obtain the mass distribution and the inertial force.
5) Convert the inertial force into equivalent nodal forces at the finite element mesh.

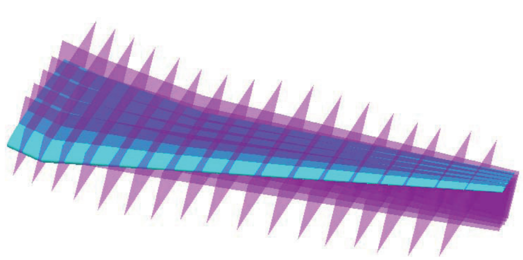

Fig. 7. Cut wing model into several blocks

6.3. Equivalent nodal force conversion

Converting aerodynamic load and inertia load to finite element nodes should follow the static equivalence principle. There are two feasible methods, as described below.

One method is to distribute each load to three adjacent finite element nodes. Suppose there are three finite element nodes and a load, as shown in Fig. 9. The loads assigned to the three nodes can be calculated with the following

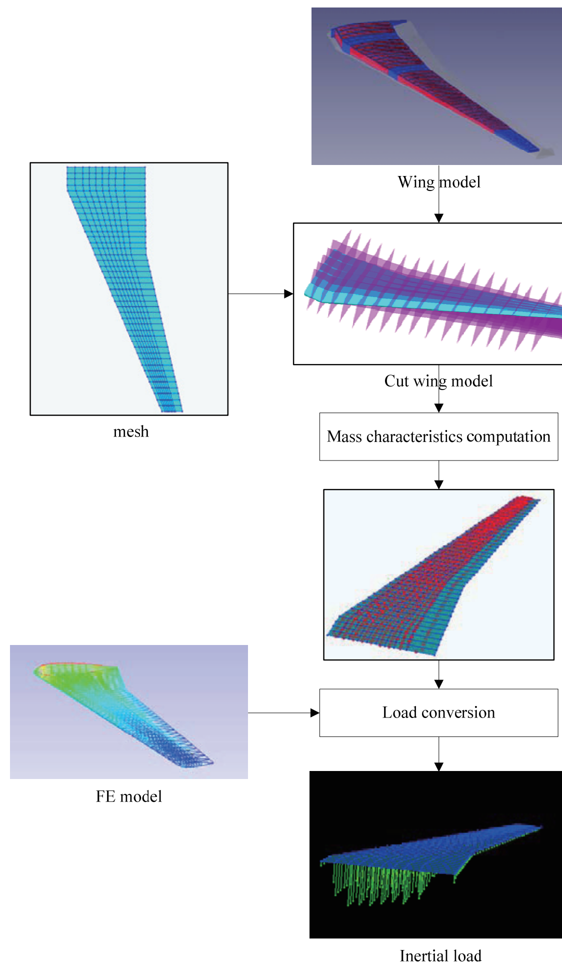

Fig. 8. Inertia load calculation process

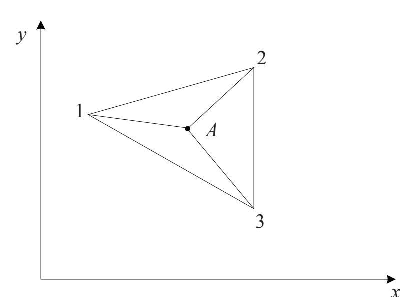

Fig. 9. Three nodes around the load

formula:

$$P_j = \frac{A_j P_A}{A} \tag{7}$$

where P_A is the load at point A, A is the area of triangle 1, 2, 3, A_1 is the area of triangle A, 2, 3, A_2 is the area of triangle A, 1, 3, A_3 is the area of triangle A, 1, 2. Calculate the forces distributed to the three adjacent nodes for each load with Eq. (7) to obtain the equivalent nodal forces of the finite element model.

Another method is to distribute each load to several finite element nodes, or even the all nodes. Its basic idea is that the closer the finite element node is to the load, the higher the force is distributed to this node.

Assume there is an invisible beam between the finite element nodes and the position of load, which is a cantilever beam clamped to the load position.

When the free ends, the finite elements (see Fig. 10), are assigned a load, the deformation energy is:

$$U_j = \frac{P_j^2 L_j^3}{6EJ} \tag{8}$$

where EJ is the bending stiffness of the imaginary beam. So, the deformation energy of the whole system, including all imaginary beams, is:

$$U = \sum_{j=1}^{n} U_j \tag{9}$$

The loads allocated to finite element nodes should minimize the deformation energy of the system as well as accord with the condition of static equilibrium.

$$\sum_{j=1}^{n} P_j = P_A \tag{10}$$

$$\sum_{j=1}^{n} P_j x_j = P_A x_A \tag{11}$$

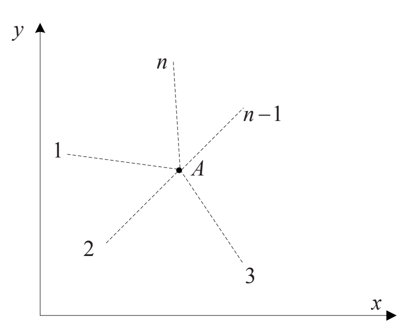

Fig. 10. Imaginary beam between finite element nodes and the position of load

$$\sum_{j=1}^{n} P_j z_j = P_A z_A \tag{12}$$

where n is the number of finite element nodes.

Use a Lagrangian multiplier method to establish the Lagrangian function:

$$F\left(\lambda\lambda_x\lambda_z\right) = \sum_{j=1}^{n}\left(\frac{P_j^2 L_j^3}{6EJ} - \lambda P_j - \lambda_x P_j \overline{x_j} - \lambda L_z P_j \overline{z_j}\right) \tag{13}$$

where $\overline{x}_j = x_j - x_A$, $\overline{z}_j = z_j - z_A$, λ, λ_x, and λ_z are Lagrangian multipliers.

To minimize $F(\lambda\lambda_x\lambda_z)$, let:

$$\frac{\partial}{\partial P_j} F\left(\lambda\lambda_x\lambda_z\right) = 0 \tag{14}$$

Then,

$$P_j L_j^3 = \lambda + \lambda_x \overline{x}_j + \lambda_z \overline{z}_j \tag{15}$$

Substituting Eq. (13) in Eq. (8), get the equations as follows:

$$\begin{bmatrix} \sum_{j=1}^{n} L_j^{-3} & \sum_{j=1}^{n} \overline{x}_j L_j^{-3} & \sum_{j=1}^{n} \overline{z}_j L_j^{-3} \\ \sum_{j=1}^{n} \overline{x}_j L_j^{-3} & \sum_{j=1}^{n} \overline{x}_j^2 L_j^{-3} & \sum_{j=1}^{n} \overline{x}_j \overline{z}_j L_j^{-3} \\ \sum_{j=1}^{n} \overline{z}_j L_j^{-3} & \sum_{j=1}^{n} \overline{x}_j \overline{z}_j L_j^{-3} & \sum_{j=1}^{n} \overline{z}_j^2 L_j^{-3} \end{bmatrix} \begin{Bmatrix} \lambda \\ \lambda_x \\ \lambda_z \end{Bmatrix} = \begin{Bmatrix} P_A \\ 0 \\ 0 \end{Bmatrix} \tag{16}$$

λ, λ_x, and λ_z are obtained by solving Eq. (16) and the loads assigned to these nodes are calculated by substituting λ, λ_x, and λ_z into Eq.(15). Allocate each load into the finite element notes by this method. Then, the equivalent nodal forces are obtained.

In this paper, the finite element mesh of the wing is quadrilateral, so the former method is not suitable for this situation. The equivalent nodal forces of the finite element model are obtained through two steps: distribute each load to four adjacent nodes of the quadrilateral surrounding the load by the latter method, and put the forces assigned to the same node together for each node.

7. Wing Weight Optimization with the Constraints of Strength and Rigidity

In the initial design, a wing model can be created through the rapid modeling function of the software and the weight estimation module can provide the weight and center of gravity data of the current aircraft wing design. The initial design can be judged through load calculations and static strength analyses. Optimization according to the constraints of strength and stiffness is used to make the result of the weight estimate more reasonable when the safety margin of the wing structure is too large.

The task of wing structure optimization is to adjust the parameters of wing structures to reduce the wing weight and satisfy the constraints of stress, displacement, and size. The optimization problem is stated as follows:

Find $X=\{x_i\}$

Minimize W_{wing}

Subject to

$\sigma_{i\min} \le \sigma_i \le \sigma_{i\max}$

$u_i \le u_{i\max}$

$x_{i\min} \le x_i \le x_{i\max}$

where X includes the parameters of wing structures, including skin thickness, sizes of other structures like spar profile parameters, and rib web thickness, σ_i is the stress, and u_i is the displacement. Now, the strength constraint is the stress less than the allowable stress of the material and more failure modes will be considered in future research. Different aerodynamic load cases are computed and the maximum aerodynamic load case is used in the structure analysis.

The procedure of wing weight optimization according the constraints of strength and rigidity is shown in Fig. 11. This optimization was realized using Workbench and the optimization function is integrated into the system. The optimization is implemented, based on the automatic adjustment illustrated in 4.3.

8. Example

The weight estimation software was developed by the methods described above (Fig.12).

The effectiveness of the weight evaluation method was assessed through an example. Specifically, the wing geometry of the example refers to the wing of an A320.

The wing shape was created and the modeling process is shown in Fig. 13, including setting the wing plane shape and airfoils. The wing shape modeling result is shown in Fig. 14.

The wing structure layout was made based on the wing shape. The wing structure model is shown in Fig. 15 and the initial weight result is shown in Table 2.

The aerodynamic loads were calculated from the results of the aerodynamic analysis (Fig. 17), which is the case of maximum aerodynamic forces in a series of aerodynamic analyses. The inertial loads were calculated according to mass distribution and the results show in Fig. 18.

The wing structure was analyzed with the FE method and the results are shown in the following two figures.

The wing weight was optimized with the constraints of stress and displacement. The stress constraint is the allowable stress of the material, which is 450 MPa here. The optimization results are shown in Table 3. Data in Tables 2 and 3 indicate that the wing weight was reduced. This example result is close to the true A320 wing structure weight, 9150 kg (Ref. [31]).

The accuracy of the weight estimation result depends primarily on two aspects: the parametric modeling is consistent with the actual situation, and the stress and displacement constraints set are reasonable.

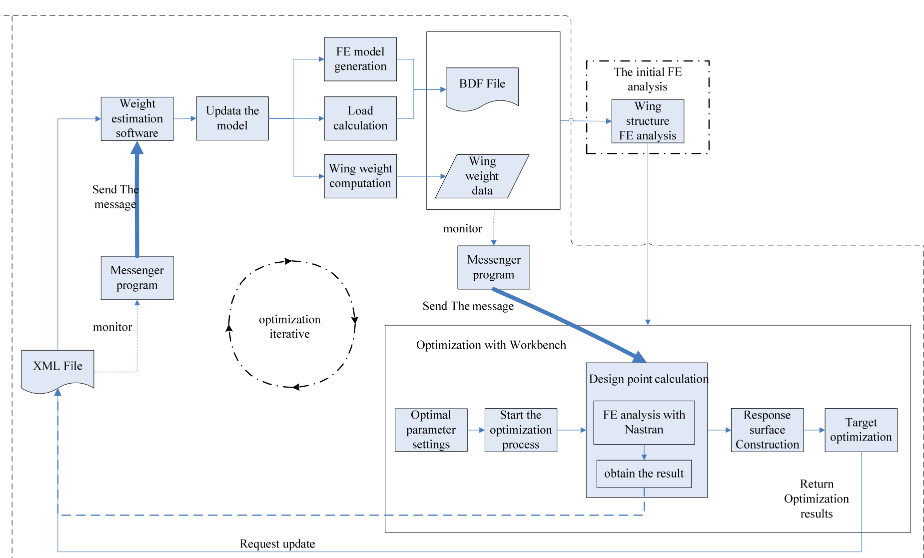

Fig. 11. Procedure of wing structure optimization

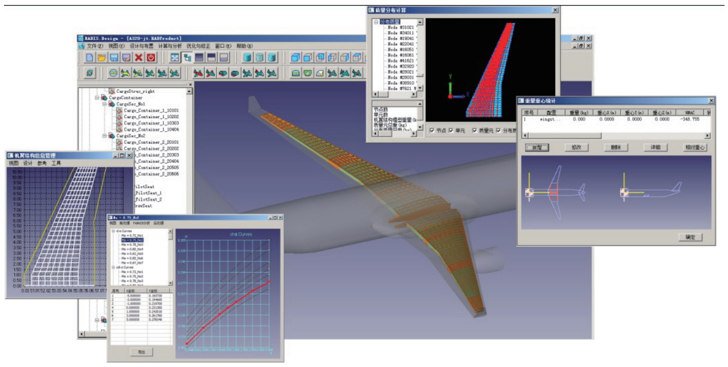

Fig. 12. Software interface

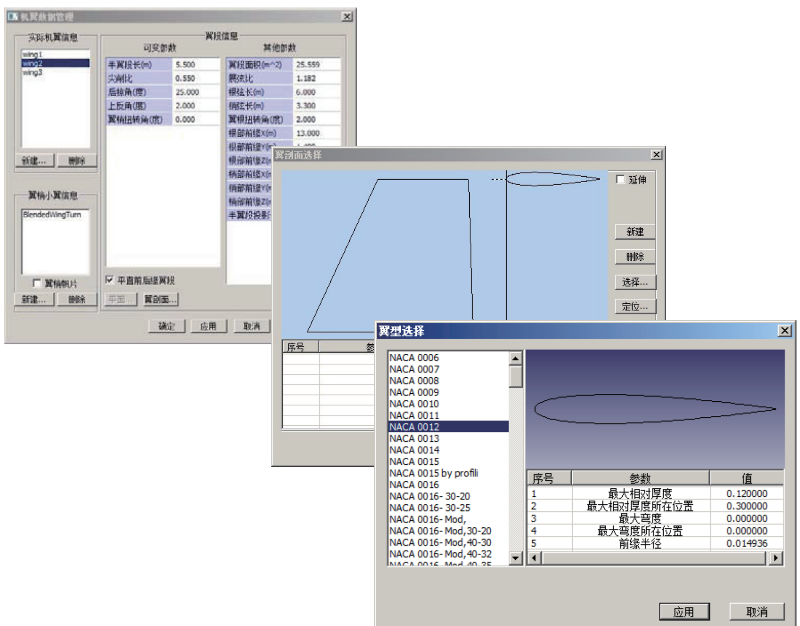

Fig. 13. Wing parametric modeling

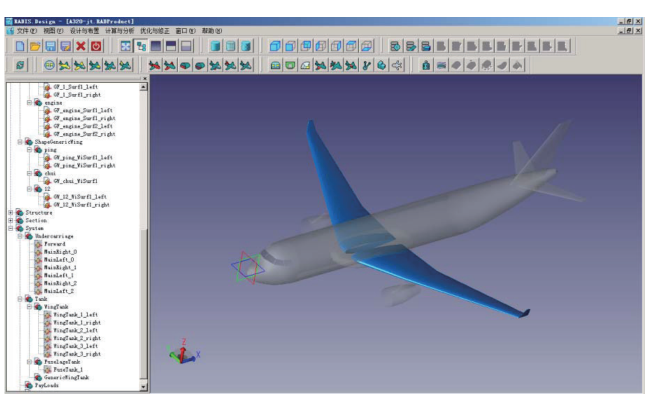

Fig. 14. Wing shape modeling result

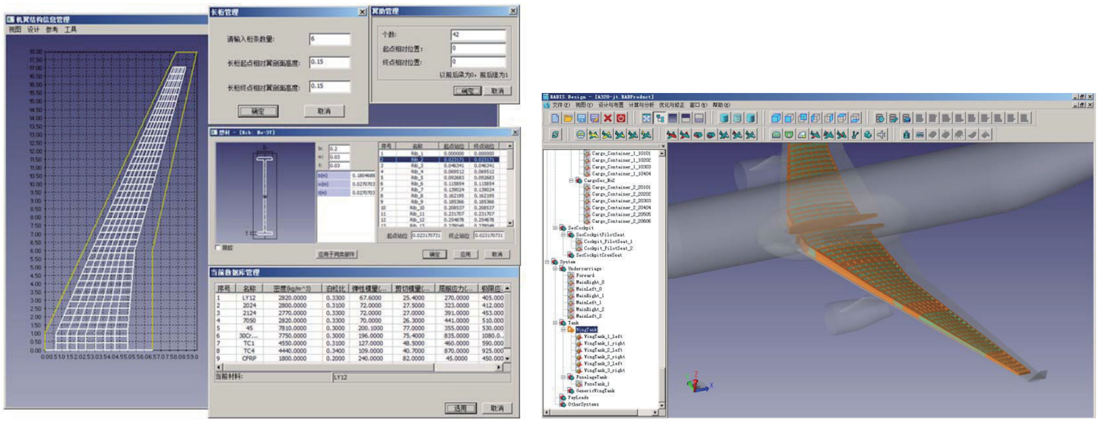

Fig. 15. Wing structure modeling

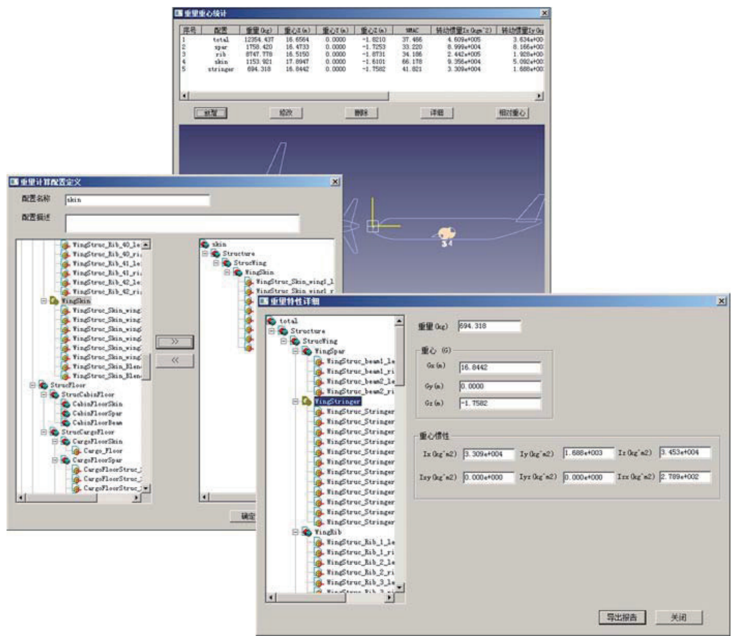

Fig. 16. Wing structure weight calculation

Table 2. Initial wing structure weight

Wing structure	weight/kg	Center of gravity x/m	y/m	z/m
Spar	1758.4	16.47	0	-1.72
Stringer	694.3	16.84	0	-1.75
Rib	8747.8	16.51	0	-1.87
Skin	1153.9	17.89	0	-1.61
Total	12354.4	16.66	0	-1.82

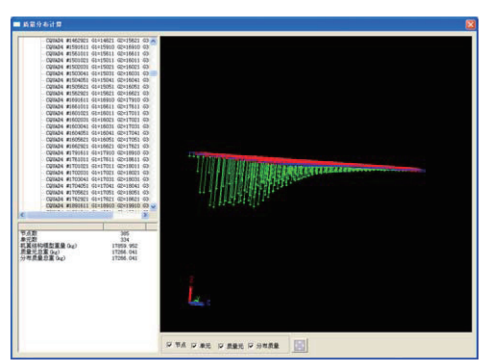

Fig. 17. Aerodynamic loads

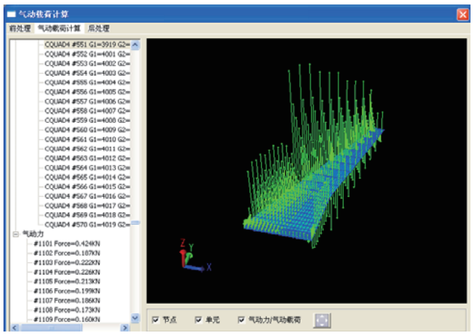

Fig. 18. Inertial loads

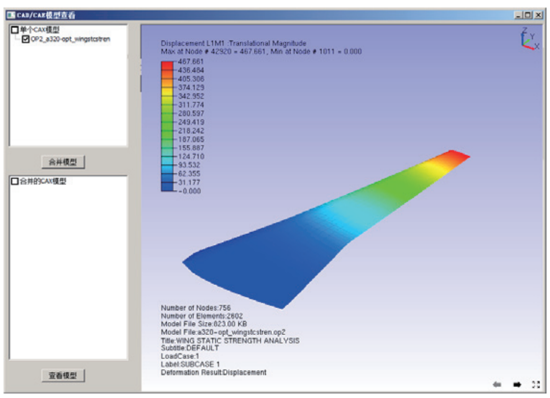

Fig. 19. The displacement distribution of wing

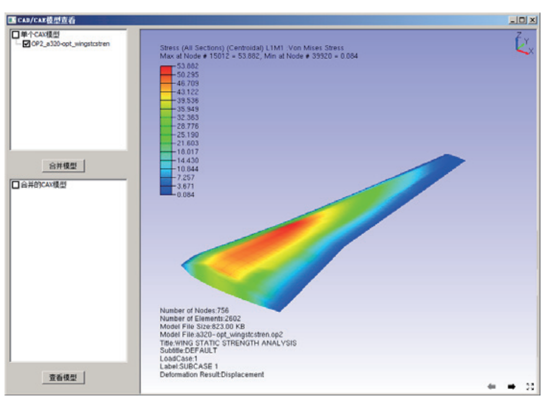

Fig. 20. The stress distribution of wing

Table 3. Wing weight estimation result

Wing structure	weight/kg	Center of gravity		
		x/m	*y*/m	*z*/m
Spar	1161.4	16.47	0	-1.72
Stringer	418.8	16.84	0	-1.75
Rib	6224.7	16.51	0	-1.87
Skin	1240.9	17.89	0	-1.61
Total	9045.8	16.71	0	-1.82

9. Conclusions

1) According to weight estimation requirements for speed and accuracy, a wing weight evaluation method considering the structural straight and rigidity is proposed in this paper. The feasibility and practicability of the method are demonstrated by an example.

2) A weight estimation software tool was developed with this method. The software possesses functions of wing shape parametric modeling and rapid wing structure layout facing the wing weight estimation, finite element model automatic generation, automatic load calculation, and weight characteristic calculations based on the model.

3) The software can simplify the tedious and repetitive aspects with its automated processing of modeling, weight computation, load calculation, and structure analysis, especially its automated adjustment and data update when a design is changed. This will help users to pay more attention to the aircraft design itself. This software could become a convenient tool in weight estimation during aircraft conceptual design.

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