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Curved surface optimization unfolding algorithm research based on composite material component

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ABSTRACT

To some extent, the research level and application level of composite material reflect the science and technology developing level of a country. A novel optimized model is proposed, including the establishment of linear equations, the construction of Hessian matrix, the construction of the gradient vector, and solution of linear equations. The proposed algorithm is used to evaluate unfold two curved surfaces. The results show that the proposed algorithm is stable, has fast convergence speed and high precision. For expansion operation is simple, it can be used in the optimization of complex curved surface.

KEYWORDS

Curved surface optimization; unfold; composite material component; precision.

INTRODUCTION

Composite components have many inimitable performances such as high specific strength, high specific stiffness, designable, heat-resistant, corrosion-resistant, fatigue resistant and good stealthy, so they are being given more and more attention in many fields and being applied more and more widely in many domains including automobile, weapon, electron, aviation, space and so on[1]. To some degree, the research level and application level of composite material reflect the science and technology developing level of a country. Especially in aviation industry, almost every advanced aircraft is closely related to sophisticated material technologies. To meet the improving manufacturing requirement of composite components on aircrafts, it is urgent to apply digital technologies and improve the current manufacturing mode and manufacturing process. Digitalization and integration of designing and manufacturing of composite components should be realized gradually. Flattening of curved surface using finite element method in computer-aided optimum design of structure was proposed by Shimada T[2]. Constraint-satisfying plannar flattening of complex surface was proposed by Parida L[3]. Geodesic curvature preservation in surface fattening through constrained global optimization was proposed by Azariadis P N[4]. Approximate shortest path on a polyhedral surface and its applications was proposed by Kanai T[5]. Knowledge model as an integral way to reuse the knowledge for fixture design process was proposed by Hunter R[6]. Similarity assessment of 3D mechanical components for design reuse was proposed by Chu C H[7]. Constraint reduction based on a lie algebra for kinematic analysis of assembly was proposed by Tanaka F[8]. Improved methods of assembly sequence determination for automatic assembly systems was proposed by Lee H R[9]. Evolutionary path planning for robot assisted part handling in sheet metal bending was proposed by Liao X[10]. A case-based framework for reuse of previous design concepts in conceptual synthesis of mechanisms was proposed by Han Y H[11]. Similarity comparison of mechanical parts to reuse existing designs was proposed by Hong T[12].

The paper is organized as follows. In the next section, the establishment of optimized model is investigated. In Section 3, solution of the optimized model is proposed, including the establishment of linear equations, the construction of Hessian matrix, the construction of the gradient vector, and solution of linear equations. In Section 4, in order to test the performance of proposed algorithm, it is used to evaluate unfold two curved surfaces. Finally, we conclude our paper in section 5.

THE ESTABLISHMENT OF THE OPTIMIZATION MODEL

For convenience, the following symbols are described.

N_v represents the number of vertices, N_e represents the number of edges and N_f represents the number of triangles. $N_{\mathrm{int}v}$ represents the number of inner vertices and V_{int} represents the set of point in the grid. l_i represents the length of each edge after optimization and L_i represents the length of each edge of original grid. v_j^k represents the point which is connected to the j-th inner vertice of the grid, f_j^k represents the face which is connected to the j-th inner vertice of the grid, e_j^k represents the edge which is connected to the j-th inner vertice of the grid, represents the angle which is connected to the j-th inner vertice of the grid, and $e_j^{l(k)}$ represents a neighbor edge of this point. $l_{f_i}^k$ represents the length of the k-th edge, which makes up triangle f_i. $i = 1, 2, \ldots, N_e$, $k = 1, 2, \ldots, m_j$, $k = 1, 2, 3$ and m_j represents the number of edge which is connected to the j-th inner point. In order to make each edge length error minimum between optimized object grid and original curved surface, the object function is shown in (1).

$$E(l) = \sum_{i=1}^{N_e} w_{e_i} (l_i - L_i)^2 \tag{1}$$

$L=(l_1,l_2,\ldots,l_{N_e})^T$ represents a vector, which is composed of each grid edge length. w_{e_i} represents weight factor of each edge and the initial value is

$$w_{e_i}=\frac{1}{L_i^2} \tag{2}$$

The constraints of the model are as follows.

(1) Interior point developable constraint is

$$\forall v_j\in V_{\text{int}},C_{plan}(v_j)=\sum_{k=1}^{m_j}\arccos\left(\frac{\left|e_i^k\right|^2+\left|e_i^{k+1}\right|^2-\left|e_j^{l(k)}\right|^2}{2\cdot\left|e_i^k\right|\cdot\left|e_i^{k+1}\right|}\right)-2\pi=0 \tag{3}$$

$j=1,2,\ldots,N_{\text{int}\,v}$, $e_i^{m_j+1}=e_i^1$.

(2) Grid edge length is

$$L_i>\varepsilon_1>0,\ l_i>\varepsilon_2>0,\ i=1,2,\ldots,N_e \tag{4}$$

(3) The efficient triangle constraint is

$$\forall f_i,l_{f_i}^1>\left|l_{f_i}^2-l_{f_i}^3\right|,l_{f_i}^2>\left|l_{f_i}^3-l_{f_i}^1\right|,l_{f_i}^3>\left|l_{f_i}^1-l_{f_i}^2\right|,i=1,2,\ldots,N_f \tag{5}$$

Lagrange multiplier is used to define penalty function, and add these constraints to the objective function to construct the objective function as follows

$$F(X)=F(l,\lambda)=E(l)+\sum_{j=1}^{N_{\text{int}\,v}}(\lambda_j\cdot C_{plan}(v_j)) \tag{6}$$

Each λ_j is initialized to 1 and $\lambda=(\lambda_1,\lambda_2,\ldots,\lambda_{N_{\text{int}\,v}})^T$.

SOLUTION OF THE OPTIMIZATION MODEL

The establishment of linear equations

The linear equations is composed of Hessian matrix $\nabla F^2(X)$ and gradient vector $\nabla F(X)$, which is shown in (7).

$$\nabla F^2(X)\delta_X=-\nabla F(X) \tag{7}$$

(7) can be expressed as

$$\begin{bmatrix}\mathrm{A}_{N_e\times N_e} & J^t_{N_e\times N_{\text{int}\,v}}\\ J_{N_{\text{int}\,v}\times N_e} & 0\end{bmatrix}\begin{bmatrix}\delta_l\\ \delta_\lambda\end{bmatrix}=\begin{bmatrix}B_1\\ B_2\end{bmatrix} \tag{8}$$

$\mathrm{A}_{N_e \times N_e} = diag(2w_{e_i})$, $J^t_{N_e \times N_{\mathrm{int}\,v}} = \left[\frac{\partial^2 F}{\partial \lambda_j \partial l_i}\right]$, $B_1 = \left[\frac{\partial F}{\partial l_i}\right]$, $B_2 = \left[\frac{\partial F}{\partial \lambda_j}\right]$.

$i = 1, 2, \ldots, N_e$, $j = 1, 2, \ldots, N_{\mathrm{int}\,v}$.

The construction of Hessian matrix

$\alpha_j^1 = \arccos\left(\frac{l_{i1}^2 + l_{i2}^2 - l_{i3}^2}{2l_{i1}l_{i2}}\right)$, $t = \frac{l_{i1}^2 + l_{i2}^2 - l_{i3}^2}{2l_{i1}l_{i2}}$. Calculate partial derivatives for three edge parameters.

$$\frac{\partial \alpha_j^1}{\partial l_{i1}} = -\frac{1}{\sqrt{1-t^2}} \cdot \left(\frac{1}{2l_{i2}} - \frac{l_{i2}}{2l_{i1}^2} + \frac{l_{i3}^2}{2l_{i2}l_{i1}^2}\right) \quad (9)$$

$$\frac{\partial \alpha_j^1}{\partial l_{i2}} = -\frac{1}{\sqrt{1-t^2}} \cdot \left(\frac{1}{2l_{i1}} - \frac{l_{i1}}{2l_{i2}^2} + \frac{l_{i3}^2}{2l_{i1}l_{i2}^2}\right) \quad (10)$$

$$\frac{\partial \alpha_j^1}{\partial l_{i3}} = -\frac{1}{\sqrt{1-t^2}} \cdot \left(-\frac{l_{i3}}{l_{i1}l_{i2}}\right) \quad (11)$$

The three values are accumulated to the elements of matrix X , which is $J(j,i1)$, $J(j,i2)$ and $J(j,i3)$. In the same way, other angle values are dealt similarly to obtain the final j-th row elements of matrix J .

The construction of the gradient vector

$-\nabla F(X)$ is decomposed into vector B_1 and vector B_2. Each element of B_1 is initialized to 1.

$$\frac{\partial E}{\partial l_i} = 2w_{e_i}(l_i - L_i) \quad (12)$$

$-\frac{\partial E}{\partial l_i}$ is accumulated to the i-th element b_{1i} of vector B_1. Then calculate the derivation of $\sum_{j=1}^{N_{\mathrm{int}\,v}} (\lambda_j \cdot C_{plan}(v_j))$ on l_i. If $j_1 > 0$, v_1 is inner point, there is α_1 in the constraint condition and calculate

$$u = \frac{\partial \alpha_1}{\partial l_i} = -\frac{1}{\sqrt{1-t^2}} \cdot \left(\frac{1}{2l_{i2}} - \frac{l_{i2}}{2l_{i1}^2} + \frac{l_{i3}^2}{2l_{i2}l_{i1}^2}\right)$$

$t=\frac{l_i^2+l_{i1}^2-l_{i2}^2}{2l_il_{i1}}$, then $-\lambda_{j2}\cdot u$ is accumulated to the i-th element b_{1i} of vector B_1. If $j_3>0$, v_3 is inner point, there is α_3 in the constraint condition and calculate

$$u=\frac{\partial\alpha_3}{\partial l_i}=-\frac{1}{\sqrt{1-t^2}}\cdot\left(-\frac{l_i}{l_{i1}l_{i2}}\right)$$

$t=\frac{l_{i1}^2+l_{i2}^2-l_i^2}{2l_{i1}l_{i2}}$, then $-\lambda_{j3}\cdot u$ is accumulated to the i-th element b_{1i} of vector B_1. If $j_2>0$, v_2 is inner point, there is α_2 in the constraint condition and calculate

$$u=\frac{\partial\alpha_2}{\partial l_i}=-\frac{1}{\sqrt{1-t^2}}\cdot\left(\frac{1}{2l_{i1}}-\frac{l_{i1}}{2l_i^2}+\frac{l_{i2}^2}{2l_{i1}l_i^2}\right)$$

$t=\frac{l_i^2+l_{i1}^2-l_{i2}^2}{2l_il_{i1}}$, then $-\lambda_{j2}\cdot u$ is accumulated to the i-th element b_{1i} of vector B_1. Carry out the same solution process to each edge of grid, derivation of edge length can be obtained, thus B_1 is obtained.

$$b_{2,j}=-C_{plan}(v_j)=-\left(\sum_{k=1}^{m_j}\arccos\left(\frac{\left|e_i^k\right|^2+\left|e_i^{k+1}\right|^2-\left|e_j^{l(k)}\right|^2}{2\cdot\left|e_i^k\right|\cdot\left|e_i^{k+1}\right|}\right)-2\pi\right) \quad \textbf{(13)}$$

$j=1,2,\ldots,N_{\text{int}v}$. $b_{2,j}$ is the j-th element of vector B_2.

Solution of linear equations

$$\mathrm{A}\delta_l+J^T\delta_\lambda=B_1 \quad \textbf{(14)}$$

$$J\delta_l=B_2 \quad \textbf{(15)}$$

$$J\mathrm{A}^{-1}J^T\delta_\lambda=J\mathrm{A}^{-1}B_1-J\delta_l \quad \textbf{(16)}$$

$\mathrm{A}^{-1}=diag(\frac{1}{2w_{e_i}})$, $J\mathrm{A}^{-1}J^T\delta_\lambda=J\mathrm{A}^{-1}B_1-B_2$. After solution of δ_λ, δ_l is obtained.

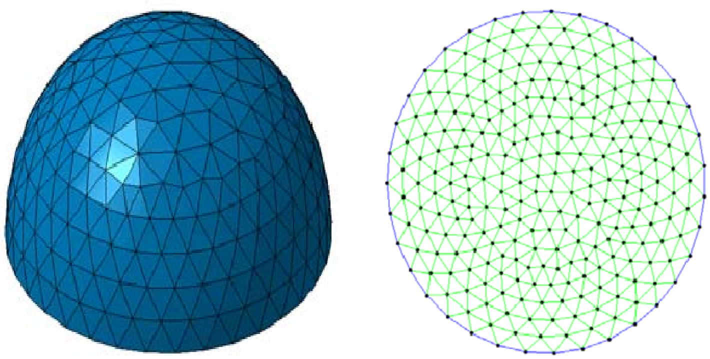
$$\delta_l=\mathrm{A}^{-1}B_1-\mathrm{A}^{-1}J^T\delta_\lambda$$

EXPERIMENT AND ANALYSIS

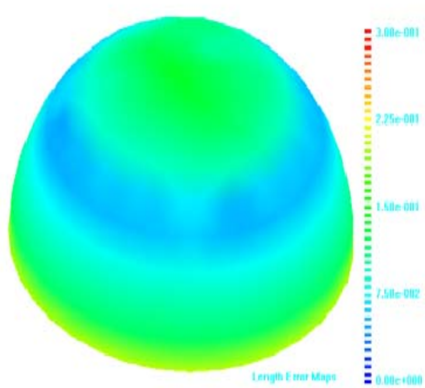
In order to test the performance of proposed algorithm, two examples which can not be unfolded is used. Figure 1 is the first example, which can not be unfold and Figure 2 is the second example. (a) represents spatial three dimension grid, (b) represents the unfold result and (c) represents relative error of length. It can be seen from TABLE 1, compared with angle based flattening, optimized variables and constraint of the proposed algorithm is less than angle based flattening. It also adopts the matrix partition technology, so the optimization of time is less than angle based flattening method. Algorithm is stable and has fast convergence speed, high precision and expansion operation is simple, which can be used in the optimization of complex curved surface.

TABLE 1 : Comparison of unfold result with other unfold algorithms

Algorithm	Hemisphere				Rotary face			
	Time(s)	Mean edge error	Mean angle error	Mean area error	Time(s)	Mean edge error	Mean angle error	Mean area error
Proposed algorithm	4.953	0.10363	0.13358	0.086280	18.641	0.061427	0.091516	0.081499
Angle Based	16.73	0.41287	0.03190	1.059640	30.516	0.233598	0.082218	0.479834
Spring particle	18.1	0.1035	0.16687	0.105628	88.406	0.061999	0.090150	0.086936

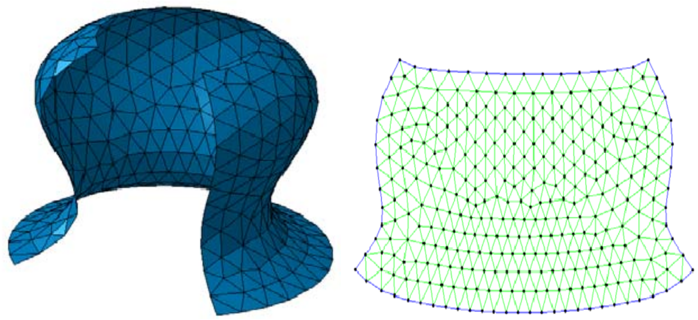


(a) spatial three dimension grid (b) unfold result

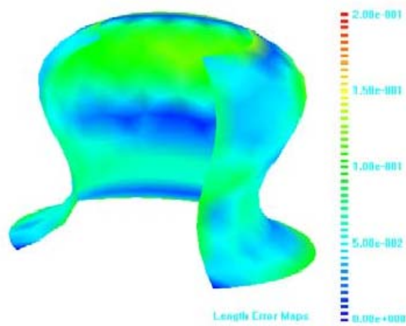


(b) relative error of length

Figure 1 : Unfold result of hemisphere



(a) spatial three dimension grid (b) unfold result



(c) relative error of length

Figure 2 : Unfold result of rotary face

CONCLUSION

Composite components have many inimitable performances such as high specific strength, high specific stiffness, heat-resistant, corrosion-resistant, fatigue resistant and good stealthy. A novel optimized model is proposed, including the establishment of linear equations, the construction of Hessian matrix, the construction of the gradient vector, and solution of linear equations. The proposed algorithm is used to evaluate unfold two curved surfaces. The results show that the proposed algorithm is stable, has fast convergence speed and high precision.

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