Title:
Research on the IGA Based Multi-hole Wall Plate Structure's Design Technology

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Introduction:
Due to the difference of the geometry representation methods in CAD and FEM, severe data transferring problems thereby emerge, including the frequent need of model fixing, mesh subdivision and loss of certain geometric features [2]. Isogeometric analysis (IGA) has offered a prospect of integrating CAD and CAE more closely [4], while the existing CAD models derived from commercial software usually need extra efforts to be made suitable for IGA, which hinders the industry level practice for this budding technology framework. But in certain particular design scenarios, the targeted products have basic shape features in common so if we want to use IGA in real work for them, we can generate models specially IGA oriented, especially when such products stress the design efficiency strongly wherein IGA can play a critical role to shorten the overall design & analysis time [5]. In aerospace industries, multi-hole wall plate structures are prevailing due to their frequent use as external housings. In the general design stage, these structures are predominantly utilized for the main body construction, while repeated modeling and analysis work exists for different sector's requirements always endure constant changes and the changed intentions cannot avoid being reflected in the basic structures. Hence, we developed a series of methods to realize the IGA-based technique roadmap for the design of multi-hole wall plate structures for aerospace products. Parametric modeling interface is used to input the important design information and the structure's geometry is segmented into more elementary parts during the modeling, which will undergo special process to make them IGA suitable. Thus, the IGA-based design process can be obtained, which simplifies the design work, especially eliminates data transferring bottlenecks so shortens the product development timespan and improves field efficiency.

NURBS Basic Functions:
Trivariate NURBS
The trivariate NURBS is the basis for the elementary geometries' construction. A NURBS volume of degree p in the u direction, degree q in the v direction and degree r in the w direction, respectively, is a trivariate vector-based piecewise rational function according of the form

$$\mathbf{S}(u,v,w)=\frac{\sum_{i=0}^{n}\sum_{j=0}^{m}\sum_{k=0}^{l}N_{i,p}(u)N_{j,q}(v)N_{k,r}(w)\omega_{i,j,k}\mathbf{P}_{i,j,k}}{\sum_{i=0}^{n}\sum_{j=0}^{m}\sum_{k=0}^{l}N_{i,p}(u)N_{j,q}(v)N_{k,r}(w)\omega_{i,j,k}} \tag{2.1}$$

The $\mathbf{P}_{i,j,k}$ form a tridirectional control net, the $\omega_{i,j,k}$ are the weights, and the $N_{i,p}(u)$, $N_{j,q}(v)$ and $N_{k,r}(w)$ are the nonrational B-spline basis functions defined on the knot vectors U, V and W. The definition of U is given in Eqn. (2.2), where $\alpha = n+p+1$, and the same for V and W without further elaboration.

$$U = \left\{ \underbrace{0,\ldots,0}_{p+1}, u_{p+1},\ldots,u_{\alpha-p-1}, \underbrace{1,\ldots,1}_{p+1} \right\} \tag{2.2}$$

Cylindrical intersecting line fitting
The multi-hole wall plate structure has many circular holes that must be processed properly, which will affect the geometry segmentation for generating conforming elements used in IGA [1]. The mathematical nature of the hole's contour curve is an intersecting curve composed of two mutually perpendicular cylinders intersecting with intersecting axes. Definition for such curves is given in Eqn. (2.3), where R_1, R_2 are the radii of the two cylinders respectively.

$$\begin{cases} x = x(\varphi) = R_2 \cos(\varphi) \\ y = y(\varphi) = \pm\sqrt{R_1^{\,2} - R_2^{\,2}\cos^2(\varphi)} \qquad \varphi \in [0, 2\pi] \\ z = z(\varphi) = R_2 \sin(\varphi) \end{cases} \tag{2.3}$$

In this paper, we fit the intersecting line in four parts, each part fitting a quarter of the intersecting curve, based on the global curve interpolation method with end derivatives specified [6]. A cubic NURBS curve is used to interpolate at the intersecting curve's data points $Q_k, k = 0,\cdots,n$, which are sampled uniformly on the parameter curve, assuming that D_0 and D_n are the first derivative vectors at the start point and end point of the curve. Knot vector is obtained whereby using chord length method. To simplify the implementation, we set $n = 4$ and all control point weights be 1. The result of the cylindrical intersecting curve fitting can be obtained by solving Eqn. (2.4) below.

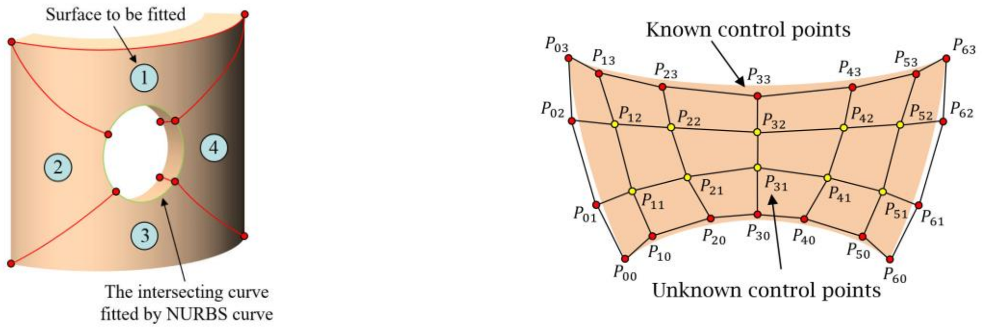
$$\begin{cases} \mathbf{Q}_k = \mathbf{C}(\bar{u}_k) = \sum_{i=0}^{n+2} N_{i,p}(\bar{u}_k)\mathbf{P}_i \\ -\mathbf{P}_0 + \mathbf{P}_1 = \dfrac{u_4}{3}\mathbf{D}_0 \\ -\mathbf{P}_{n+1} + \mathbf{P}_{n+2} = \dfrac{1-u_{n+2}}{3}\mathbf{D}_n \end{cases} \tag{2.4}$$

Surface fitting
After successfully fitting the intersecting curve, the trimmed outer surface of the cylinder, taking the surface 1 as an example, needs to be fitted, as shown in Fig. 1(a).

In this paper, based on the global surface interpolation method, equations for surface interpolation are given below.

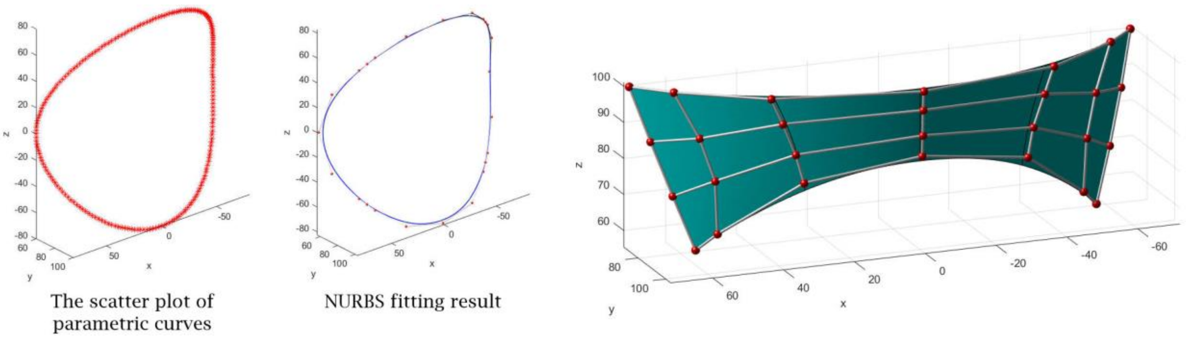
$$\mathbf{Q}_{k,l} = \frac{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}\ \bar{u}_k\ N_{j,q}\ \bar{v}_l\ w_{i,j}\mathbf{P}_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}\ \bar{u}_k\ N_{j,q}\ \bar{v}_l\ w_{i,j}} \tag{2.5}$$

The essence of solving Eqn. (2.5) is to perform two successive curve interpolation operations, in which control points located at the boundaries have been already obtained. Fitting results are presented in Fig. 2.



(a) (b)

Fig. 1: Wall plate with a round hole: (a) curves and surfaces to be fitted, (b) schematic diagram of surface fitting, with red dots representing known control points and yellow ones are unknown.



(a) (b)

Fig. 2: Fitting results: (a) intersecting curve, (b) surface 1 in Fig. 1(a).

<u>Parametric Modeling Method:</u>

Multi-hole wall plates are generally regularly wrapped around the outer surface of the aerospace product to help the product withstand external loads, such as bending or torsion. In addition, conforming elements are often used in the meshing stage of IGA, facilitating the stiffness matrix assembly of computation. Since the arrangement pattern of the wall plates is in accordance with the characteristics of the conforming elements, it is reasonable and effective to conduct parametric design and mechanical analysis based on the conforming elements.

The parametric modeling process of multi-hole wall plates is briefly described, and the process is clearly shown in Fig. 3.

1. Parameters input: users input overall dimensions of the product, and the location as well as size of the holes, respectively, according to the design requirements.
2. NURBS volume modeling: same as NURBS volumes, wall plates without holes and the ribs are hexahedral in topology, easy to be directly modeled. Segmentation is proposed on the wall plates with square or round holes in order to obtain hexahedral patches. After fitting the partitioned curves and surfaces, we can build the NURBS volume model based on the open-source framework NLIGA [3].
3. Assembly: all the NURBS volume models are assembled. Conforming operations need to be performed to form conforming elements, which is conducive to the convergence of calculation results in the process of isogeometric analysis, including degree elevation, knot insertion and patch alignment.

4. Analysis: material properties and boundary conditions are set for the mechanical analysis of the model.

All models are stored into a one-dimensional array, which facilitates the temporary addition or removal of holes and quick modeling. Wall plate models without holes and ribs are stored first in light of overall dimensions. Certain wall plate models, subsequently, will be replaced by the ones with square or round holes if the hole features are acquired, which enables quick modification and re-modeling, as shown in Fig. 4.

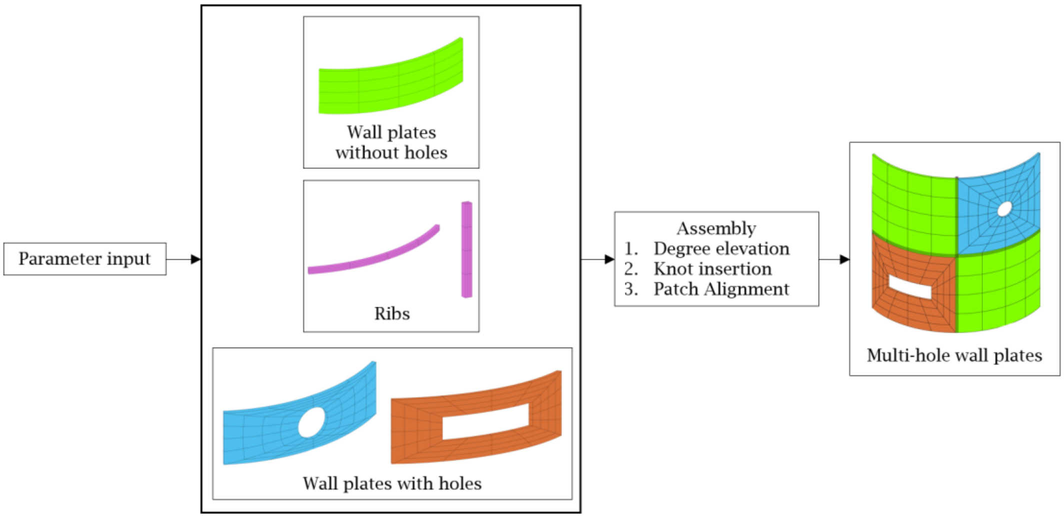


Fig. 3: Parametric design process of multi-hole wall plates.

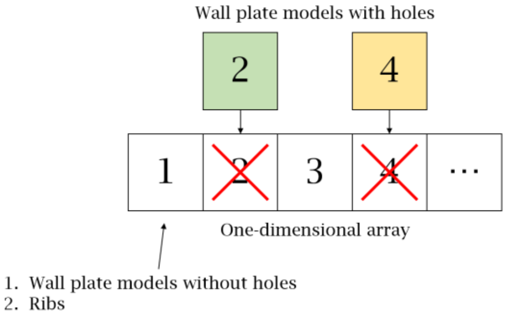


Fig. 4: The method for model information storage, where the green square represents the wall plate with square holes, and the yellow one represents the wall plate with round holes.

Case Study:

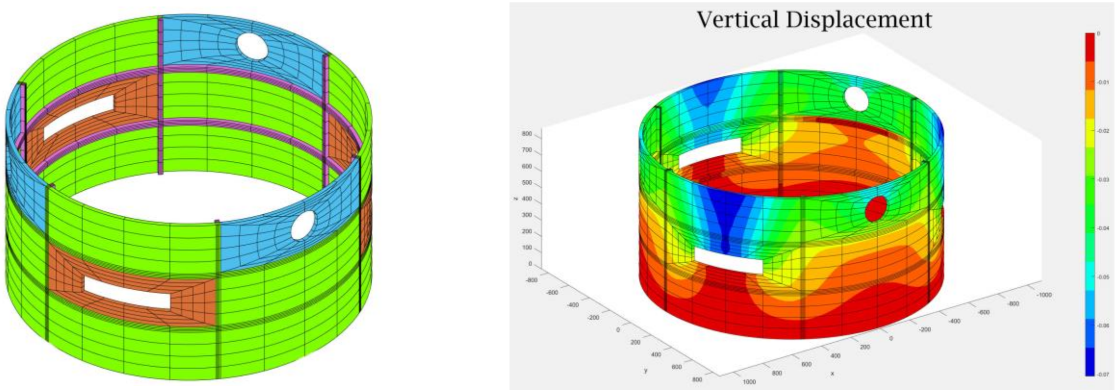
According to the above parametric modeling method, a multi-hole wall plate model is built, which is around the outer surface of the cylindrical aerospace equipment. The parameters are specified below:

1. the outer diameter R , height H , wall thickness t .
2. number of axial ribs n_a , number of circumferential ribs n_c .
3. length a and width b of the square holes

4. the radius r_h of the round holes

(Assume that the ribs are uniformly arranged and the holes are located at the center of wall plates.)

Based on the assumption of elastic material and isogeometric analysis method, a vertical downward force F is applied to the top of the model. The modeling results as well as the analysis results are shown in Fig. 5.



(a) (b)

Fig. 5: Parametric modeling case study: (a) modeling result (b) analysis result.

Conclusions:

This paper put forwards an IGA-based design approach for multi-hole wall plate structures, which presents the conception of integrating modeling & analysis in one single software environment. The case study proves the effectiveness and practicality of the method. Moreover, the paper shows that although using IGA as a basic pattern for product design still needs more efforts even breakthroughs in geometry modeling theory, it can exert prowess in circumstances where the product's shape features are comparatively stable and regular, which will provide practical experiences for the implementation of CAD/CAE integrating software.

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