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Research paper

Grid generation on free-form surface using guide line advancing and surface flattening method

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ABSTRACT

Automatic grid generation on a curved surface is important to more efficient design of free-form structures. However, it is neither a convenient nor an obvious task for engineers to create a discrete grid structure on a complex surface that meets the architectural requirements. Besides, research on the rapid grid generation methodology for free form structural design is still limited. In order to achieve better grid distribution of rods on free-form surface, a grid generation methodology which combines surface flattening technique with guide line method is put forward. The parametric domain of the free-form surface was firstly divided into a number of parts and a discrete free-form surface was accordingly formed by mapping the generated dividing points onto the curved surface. The free-form surface was then flattened based on the principle of identical area. Accordingly, the flattened rectangular lattices were fitted into the 2D surface where grids were formed by using the guide line method. Finally, the 2D grids were mapped onto the 3D surface, and grids were therefore generated on the given surface. A grid shape and rod length quality index was proposed to evaluate the shape of grid cells and rod lengths. The results show that the grid shape quality index and the deviation of rod length of the grid structure are reduced by up to 47% and 34% respectively by using the guide line method with surface flattening when compared to the method without surface flattening.

1. Introductions

In recent years, traditional spatial structural shapes [1–3] including plane, cylindrical surface, spherical surface, and parabolic surface have been widely used around the world. However, these traditional shapes are becoming more difficult to meet people's aesthetic requirements of variation in terms of architectural appearance. At the same time, parametric modeling and scripting techniques in computer aided design have enabled a new level of sophistication in 3D free-form surface, allowing engineers searching for ways to restructure the design process. Structural forms are increasing due to the expression of architectural creativity and the application of modern technology to building design. Complex free-form grid structure is one of the most striking trends in contemporary architecture [4,5]. Free-form surface has the characteristic that is unable to be expressed accurately by means of one or several analytic functions and the curvature of such a surface is in a complex shape, as shown in Fig. 1.

If an appropriate curved surface of such a form is selected and well-positioned supports are added, an efficient flow of forces within will be obtained [6]. This structural form is also more desirable due to the reductions in material usage and increase in service space. However, it is not always obvious and convenient to create an efficient grid structure on a given surface. Fig. 2 illustrates an assembly process of a structure, Wuhan Railway Station (Fig. 2(c)). The architect gave the curved free-form surface (as shown in Fig. 2(a)) in the early concept design stage, however, the structural analysis and assembly required an arrangement of nodes and elements on the curved surface based on experience and was therefore conducted manually with a tedious iteration, as shown in Fig. 2(b). With the increasing application of free-form grid structures, a practical grid generation framework that can generate quick structural grids on a given free-form surface, will be necessary, especially in the early design stage.

Previous research on grid generation methodologies over the free-form surface is still limited. A promising method to create an efficient structural grid on an imposed surface is by topology optimization, a good trial for this method was the research by Peter et al. [7] and Paul and Will [8]. The topology optimization was proved to be efficient for grid generation. However, as pointed by Peter et

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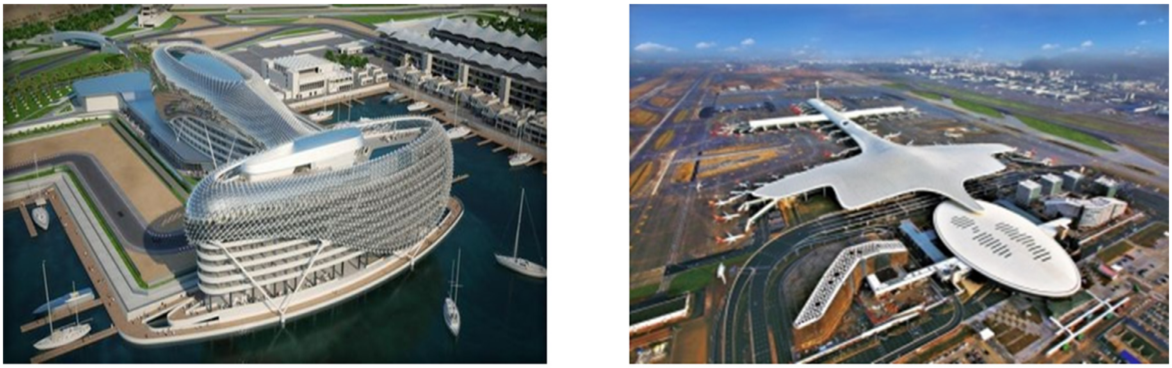

(a) Yas Viceroy Abu Dhabi Hotel (b) Shenzhen Bao'an International Airport

Fig. 1. Free-form grid structures.

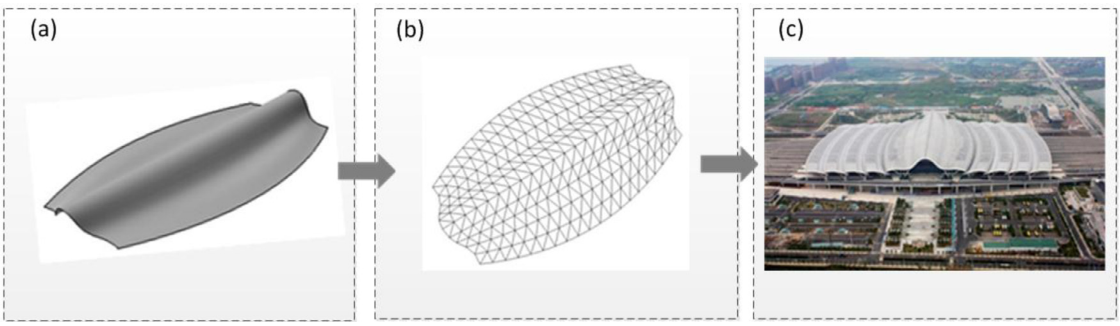

Fig. 2. Structural assembling process of a free-form single layer structure (Wuhan Railway Station, Wuhan City, China).

al. [7], the resulted topology were inapplicable directly, refinement was therefore required.

In order to obtain a usable and optimum grid over a free-form surface considering mechanical performance, research at the University of Cambridge [9] was conducted on the synthesis of optimal grid structures by considering multiple load cases. In another research [10], the main stress trajectories which are the representations of force flows on a free-form surface were used as a grid generation tool. However, the drawback of these two methods is that non-uniform grid with distorted unit cells came into being.

In practice, it is sometimes more important to generate grids on a curved surface that satisfy uniform criteria, where unit cells are with regular shapes and composed of fluent lines. Some research concentrated on the mesh generation over a surface without taking into account their structural performance. Muylle et al. [11] did research on mesh generation for finite element analysis such as presenting a new point creation scheme for generating unstructured, uniform-sized two-dimensional triangular meshes using the delaunay triangulation method. Pottman [12] produced grids manually for Yas Abu Dhabi Hotel roof relying on his experience in engineering. But this method is only appropriate for a specific project and there is a lack of versatility. Shepherd and Richens [6] proposed an interesting subdivision surface method for grid generation. An initial triangular or quadrilateral mesh was firstly imposed to a free-form surface, and then the mesh was subdivided for a number of iterations to fit the original surface. Zheleznyakova [13] proposed a new approach for triangular mesh generation based on the molecular dynamics method. Mesh nodes were considered as interacting particles. The node placement was determined by molecular dynamics simulation. Finally, well-shaped triangles were created after connecting the nodes by delaunay triangulation. Zheleznyakova [14] applied the above method to mesh on NURBS surfaces. The mesh was generated in the parametric domain of the NURBS surface patch using molecular dynamics simulation. Then, the well-shaped triangles were mapped from parametric space to 3D physical space. But the system of the interacting particles had a high sensitivity to the model parameter variation, leading to the problems of unstable solutions and slow convergences.

This paper is therefore innovative by combining surface flattening technique with guide line method to generate grids on a given free-form surface. Surface flattening enables the grid generation on a plane and solves the difficult problem of meshing a complex surface directly. Generating grids on the plane based on guide line method not only shows the connotation of architecture, but also controls the trends of free-form surface grids. Final examples show that this method is able to generate grids with excellent quality and therefore has preferable applicability in the structural concept design stage.

2. Surface representation

This paper expresses free-form surface by using NURBS (Non-uniform rational B-Splines) expression [15]. NURBS has been the industry standard that is used for shape representation, design and data exchange when geometric information is processed by computer. As a result, NURBS is a powerful tool in standard geometric design. NURBS realizes the arbitrary shape of surface by adjusting its control points, knots weights and establishes a one-to-one mapping relation between surface and parametric domain which is convenient for surface flattening and grid generation.

A *p*th-degree NURBS curve is shown in Fig. 3 and is defined by [15]:

$$C(u) = \frac{\sum_{i=0}^{n} N_{i,p}(u) w_i CP_i}{\sum_{i=0}^{n} N_{i,p}(u) w_i} \quad a \le u \le b \tag{1}$$

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