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Fast dynamic mesh method and its application on aeroelasticity

G. W.Yang*, G. N. Zheng, X. Y. Nie

Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics of CAS,Beijing,100190,P.R.China

Abstract

A fast dynamic mesh method based on radial basis function (RBF) is developed, which can be suitable of the mesh deformation of any kind of topology. In order to improve the deforming efficiency, firstly, a searching algorithm coupling with a reduced surface point option is used for the choice of control points; then the RBF can be determined by the coordinates and deforming displacements of these control points; then, the deformations of volume mesh are calculated by point-to-point; lastly, the new mesh can be obtained by adding the deformations to the original mesh. To validate the deforming capability, several two- and three-dimensional meshes with rigid rotation are performed. Then, the method is used for the aeroelasticanalysis of the AGARD 445.6 standard model.

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Keywords: Dynamic mesh, RBF, reduced-point option, aeroelasticity

Nomenclature

$u(X)$	displacement
X	surface point location
$\phi(\ )$	radial basis function

* Corresponding author. Tel.:086-10-82544006; fax: 086-10-82544006.
*E-mail address:*gwyang@imech.ac.cn

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$p(\ )$ linear polynomials
α_i interpolation coefficients
A interpolation matrix
M matrix for the solution of coefficients

1. Introduction

Fluid-structure interaction, multi-bodies motion, aerodynamic optimization and multi-disciplinary design optimization need to move CFD mesh based on deforming geometries. The deformed mesh quality, deforming efficiency, and deforming ability are very important for these complex flow simulations. Further, it may be the best if the developed mesh deformation method can be suitable of the mesh deformation of any kind of topology.

In the past decades, the Transfinite Interpolation (TFI) was extensively used for mesh deformation [1-3]. Since TFI is an algebraic method, it has higher efficiency, however, which is only suitable of structured mesh deformation. Supposing the edges of mesh cell as linear spring, Batina [4] proposed a spring analogy for unstructured mesh deformation. For two-dimensional unstructured mesh, Fahart[5] extended its capability by the addition of a torsional spring. Based on the geometrical character of tetrahedron mesh cells, Burg [6] established a three-dimensional torsional spring network model, which is robust for three-dimensional unstructured mesh movement. However, these methods have lower computational efficiency due to the necessary of iterative calculation, and also only suitable for unstructured mesh.

Liu [7] provided a fast dynamic mesh method with Delaunay graph mapping, which is suitable of any topological mesh, however, the Delaunay graph is hard to construct for complex geometrical configuration. Combined with spring analogy, the authors developed a background mesh deformation method [8-9]. Firstly an unstructured background mesh is generated, which is solved with Burg's spring network method and only for the mesh deformation, then the interpolation relation between background mesh and the original CFD mesh can be pre-constructed based on volume weighting. After the deformation of background mesh is obtained, it is easy to determine the CFD mesh deformation with the interpolation relation. The method can be used for any topological mesh movement for complex geometrical configurations.However, its efficiency is still lower.

Recently, a new mesh deformation method based on radial basis function (RBF) interpolation was put forward by Boer [10-11], which only use CFD surface mesh nodes to establish the interpolation coefficients and the deformations of the volume mesh nodes was calculated with the RBF. The method is also independent of mesh topology. However, its efficiency is related with the number of CFD surface mesh points.

In the paper, the minimum number of control points is searched based on a reduced surface point option. Since the RBF interpolation is constructed only with these selected control points, the mesh deformation efficiency can be improved largely. The ARGARD 445.6 aeroelasticstandard modelis then analyzed with the new mesh deformation method.

2. Dynamic mesh method

2.1. RBF interpolation

The solution of Fluid Structure Interaction (FSI) problems need to interpolate the surface data between the displacements of structure and the loads of fluid. As the solutions of structure model with the plate assumption and the aerodynamic loads with linear aerodynamic model, the two-dimensional Infinite Plate Spline (IPS) is extensively adapted. As the aerodynamic loads solved with nonlinear Euler or Navier-Stokes equations, three-dimensional surface interpolation needs to be used. RBF was put forward by Wendland et al [12] for the three-dimensional data interpolations between fluid and structure. The interpolation takes the form

$$u(X) = \sum_{i=1}^{N} \alpha_i \phi(\|X - X_i\|) + p(X) \tag{1}$$

Here, $u(X)$ is the displacement to be evaluated at surface point location of X, $\phi(\|X - X_i\|)$ is the radial basis function which can be taken as different types of functions, X_i is the location at which displacement is known, $p(X)$ is linear polynomials so that translation and rotation are recovered, the coefficients of α_i need to be solved by requiring exact recovery of the known displacement at X_i. Typically, the Euclidean norm is used, so that

$$\|X - X_i\| = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \tag{2}$$

With the known coordinates and displacements of X_i substitute in to X of Eq. (1), N equations can be obtained. Based on total force and moment equilibrium, another four equations can be determined. Then the unknown coefficients of α_i can be solved with any exact solution of algebraic equations, in the paper, LU decomposition is used. Therefore, any other surface point of X substitutes into the RBF, then its displacement can be obtained. Its accuracy and efficiency has been widely testified for the surface data interpolation in the solution of FSI problems.

Recently, the method was extended for dynamic mesh deformation [10-11]. Generally, taken the total surface points and far-field boundary points as assembles ofin Eq. (1), the displacements on the surface points of CFD mesh are known by the CSD solution or the rigid rotation and translation. The RBF can be constructed with the above same method and then the deformations of volume mesh points are calculated by point-to-point. However, the dimensions of RBF algebraic equations solved are very large, its computational consuming increases quickly as the dimension of equation group. Another Eq. (1) needs to be repeated to use at each time step. In order to improve the deforming efficiency, the reduced surface point option has to be studied.

2.2. Reduced surface point option

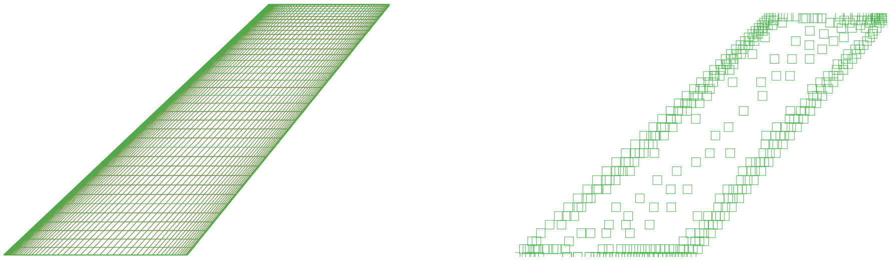
For the CFD mesh deformation, the far-boundary points are generally assumed to be fixed, namely, whose displacements are taken as zero. Several control points can be uniformly selected at far-boundary as control points. How to select the minimum number of surface points needs to be studied in detail. Before the CSD solution, the displacements of CFD surface mesh points are unknown,therefore a criterion of reduced point option needs to be provided. In the paper, the unit deformation in the three coordinate directions are assumed, then the error between exact unit deformation and interpolating deformations at the each surface point can be calculated as

$$e^x = e^y = e^z = 1 - AM_i^{-1}1_i \tag{3}$$

Here, the interpolation coefficients can be determined by $M_i^{-1}1_i$ based on the selected control points. Ais the interpolation matrix obtained with the surface point (x,y,z) into the known RBF function of (1).

The processing of the surface point selection is as follows. First, 4 control points are selected randomly from the CFD surface points; then a RBF interpolation is constructed based on the 4 control points; then the maximum of errors is searched for all of the CFD surface points; then this surface point with maximum error are added to be as new a control point. Repeating the above searching, as the maximum error is less than the given value, we can get the control points needed.

As an example, CFD surface mesh is generated with 61 × 39, namely, total 4758 points on the upper and lower surfaces of a wing as shown in figure (1a). Through the above searching, only 370 control points are obtained as the maximum is less than the error of 1.e-4.



(a) (b)

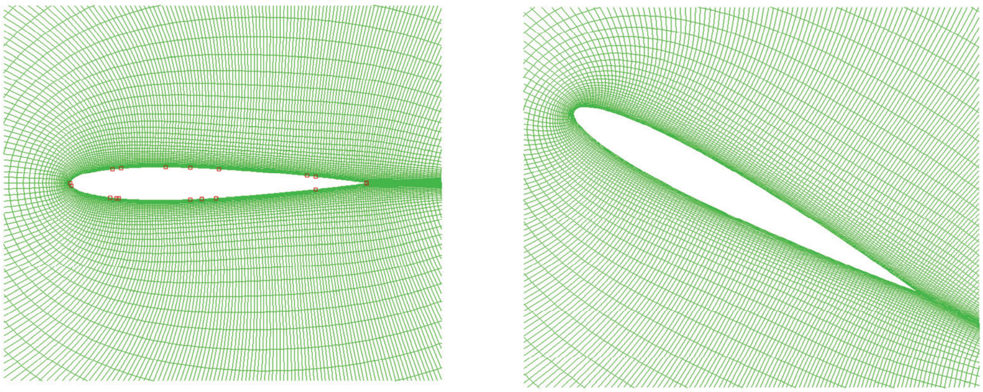
Fig. 1 CFD surface mesh and control selected by RBF

2.3. Dynamic mesh deformation

Through the above searching, the CFD surface control points and their corresponding displacements are known. The control points at CFD far-boundaries are distributed with several points. In the paper, only 5 points are selected uniformly at each far-boundary surface, whose displacements are set to be zero. The total control points and their displacements are substituted into Eq.(1). Then RBF coefficients can be solved by any solution method of algebraic equations such as LU decomposition. After RBF is solved, the displacement of any volume mesh point can be determined.

To validate the deformation method, 4 cases of mesh deformation from simple to complex configurations are calculated.

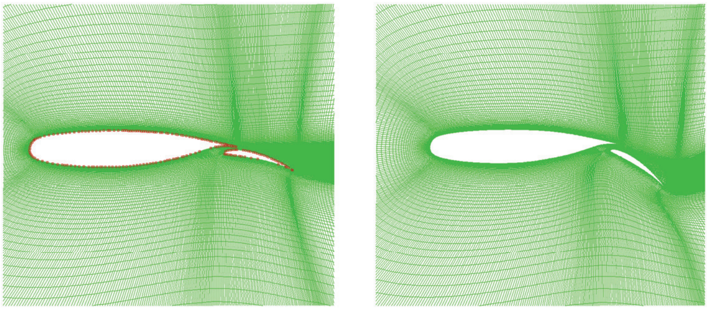
Fig.2 (a) shows the structured mesh for the NACA0012 airfoil and the surface control points selected. We assume that the airfoil rotates 30^0 based on the quarter chord-wise position. The mesh after deformation shown in Fig.2 (b) indicates that the mesh quality is good as the original mesh.



(a) (b)

Fig.2 Mesh deformation for NACA0012 airfoil with 300 rotation

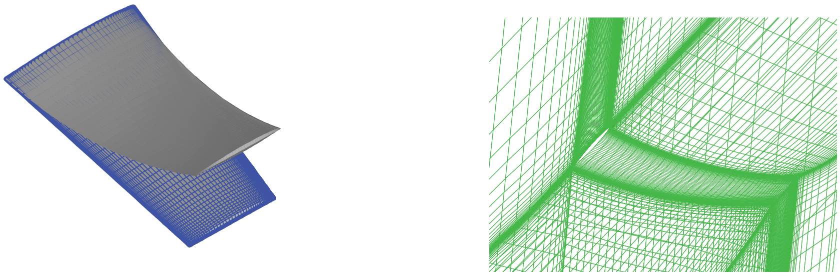
Fig. 3(a) shows the multi-block structured mesh for the NLR7301 two-element airfoil and the control points selected. The flap is assumed to rotate 20^0 with its leading-edge. The dynamic mesh shown in Fig. 3(b) also indicates that the mesh quality is conserved.



(a) (b)

Fig.3 Mesh deformation for two-element airfoil with 20^0 deflection of flap

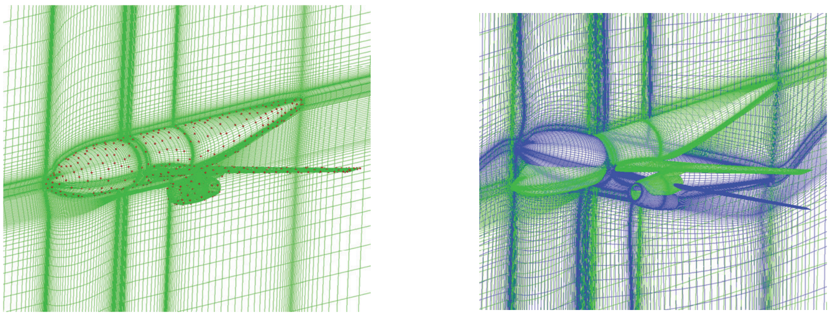
Fig. 4(a) shows the swept wing of Fig. (1) with 20% deformation of span length at the wing tip. Fig. 4(b) gives the mesh comparison before and after the deformation, which indicates the mesh quality can be conserved.



(a) (b)

Fig. 4 Mesh deformation of a swept wing with spanwise bending

Fig. 5(a) shows the multi-block mesh of a complex aircraft with wing/body/nacelle. We assume the aircraft rotates 30^0 around quarter axisalong longitudinal direction. Fig.5(b) shows the comparison before and after mesh deformation.



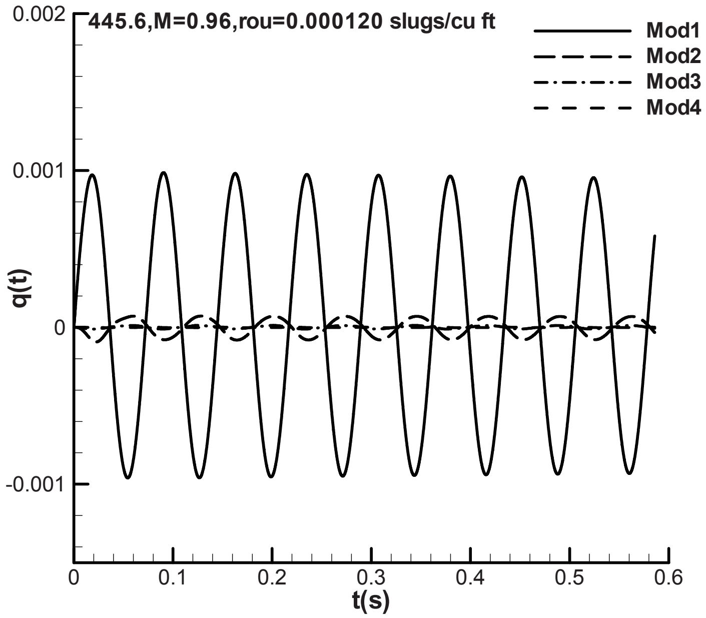
(a) (b)

Fig. 5 Mesh deformation for a wing/body/nacelle configuration with rigid rotation

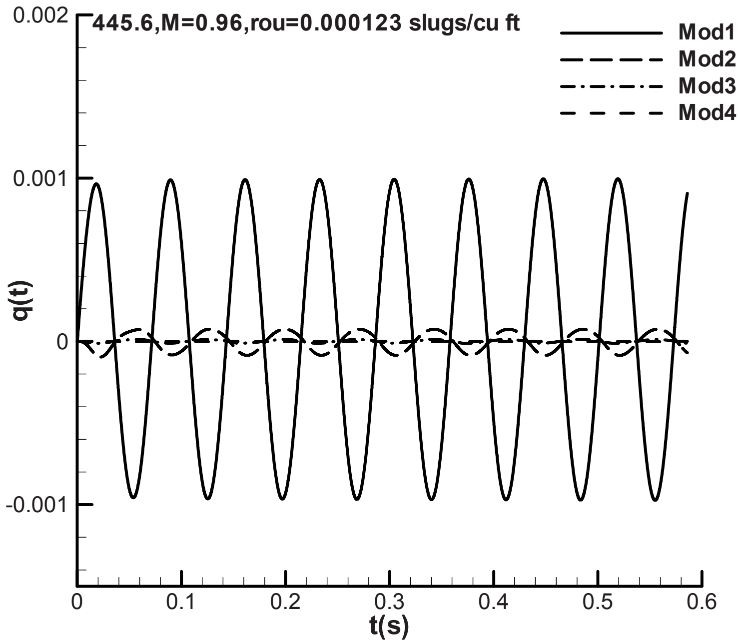
Though the above 5 examples of mesh deformation, it indicates that the developed method can conserve the higher mesh quality and possess higher efficiency. The method can be used for aeroelasticanalyses and optimization design.

3. Aeroelastic Analyses

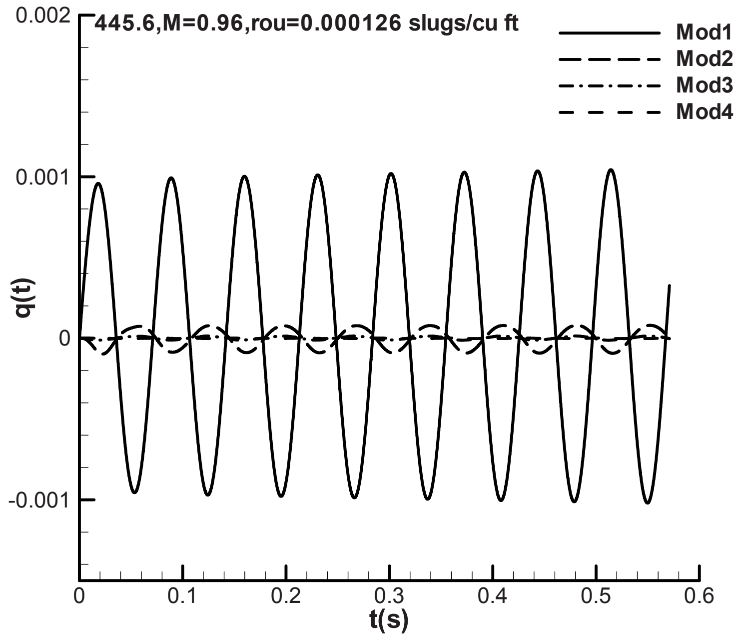
The weakened model of transonic aeroelastic wing of AGARD445.6 [13] is considered. The wing shape and mesh are shown in Fig.1 and Fig.4. Fig.6 (a-c) shows only the time histories of generalized displacement of the first four structural modes at Mach number of 0.96 with different air densities. The comparison of the generalized displacement of first mode is shown in Fig. 6(d). The experimental flutter air density is 0.000123slugs/ft3, the calculated results agree with experiments very well. It indicates the mesh deformation method can be suitable of aeroelastic analyses.



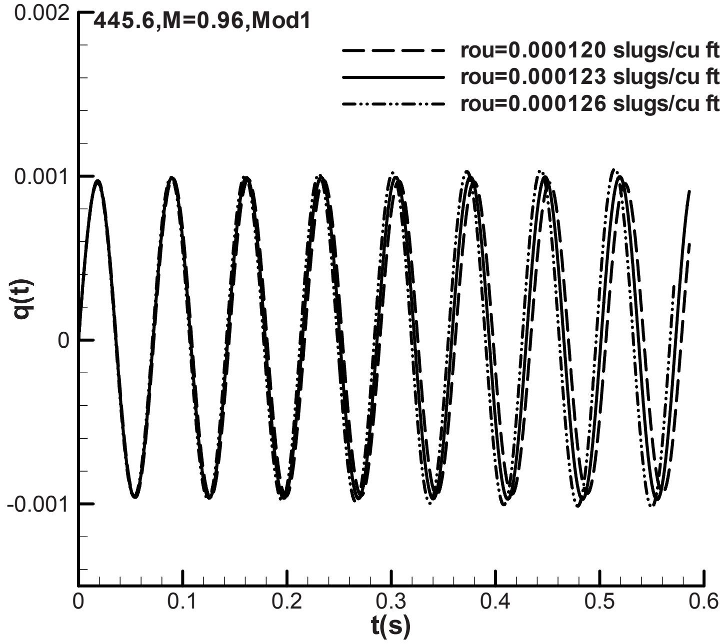
(a)


445.6,M=0.96,rou=0.000123 slugs/cu ft
Mod1
Mod2
Mod3
Mod4
q(t)
t(s)
0.002
0.001
0
-0.001
0
0.1
0.2
0.3
0.4
0.5
0.6

(b)


445.6,M=0.96,rou=0.000126 slugs/cu ft
Mod1
Mod2
Mod3
Mod4
q(t)
t(s)
0.002
0.001
0
-0.001
0
0.1
0.2
0.3
0.4
0.5
0.6

(c)



(d)

Fig.6 Time histories of generilised displacement at M=0.96

4. Conclusion

A mesh deformation method based on RBF and reduced point option has been developed in the paper, which can conserve higher mesh quality and has higher computational efficiency. The method is suitable of the mesh deformation of any mesh topology. It indicates preliminary that the developed method can be used for the aeroelastic analyses and optimization design.

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