The Investigation of Fluid and Structure Data Exchange Methods in Aeroelasticity

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Abstract:

Data exchange to couple the fluid and structure is essential to solve aeroelastic problems. In this paper, the triangle area weight method has been introduced to transfer the force from fluid mesh points to structure mesh nodes, and then the Constant-Volume Tetrahedron Method modified by triangle area weight method and/or the Infinite-Spline Interpolation Method have been used to transfer the displacement from structure mesh nodes to fluid mesh points. It has been proved that the modified Constant-Volume Tetrahedron Method is more suitable for dealing with the singularity points and outer boundary points. The advantages and disadvantages in different applications have been described by comparing the Infinite-Spline Interpolation Method and the Constant-Volume Tetrahedron Method.

Key Words: Data exchange, triangle area weighted method, Constant-Volume Tetrahedron Method, Infinite Plate Spline Interpolation Method

Introduction

Data exchange to couple the fluid and structure is essential to solve aeroelastic problems. In this paper, the triangle area weight method has been introduced to transfer the force from fluid mesh points to structure mesh nodes, and then the Constant-Volume Tetrahedron Method[1] modified by triangle area weight method and/or the Infinite-Spline Interpolation Method[2] have been used to transfer the displacement from structure mesh nodes to fluid mesh points. It has been proved that the modified Constant-Volume Tetrahedron Method is more suitable for dealing with the singularity points and outer boundary points. The advantages and disadvantages in different applications have been described by comparing the Infinite-Spline Interpolation Method and the Constant-Volume Tetrahedron Method.

1 Force translation between Fluid-Structure Interface

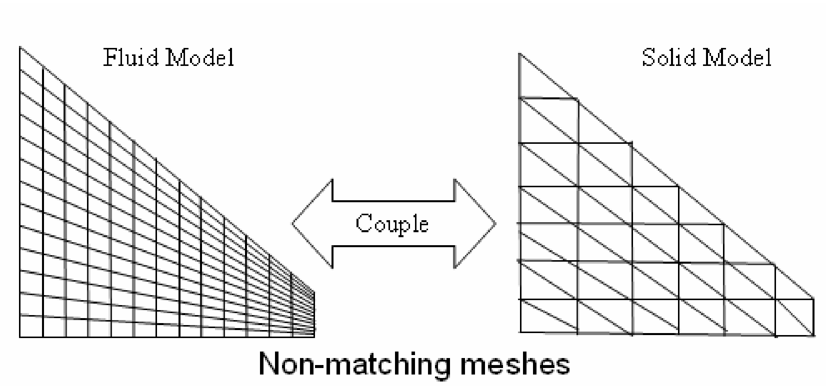


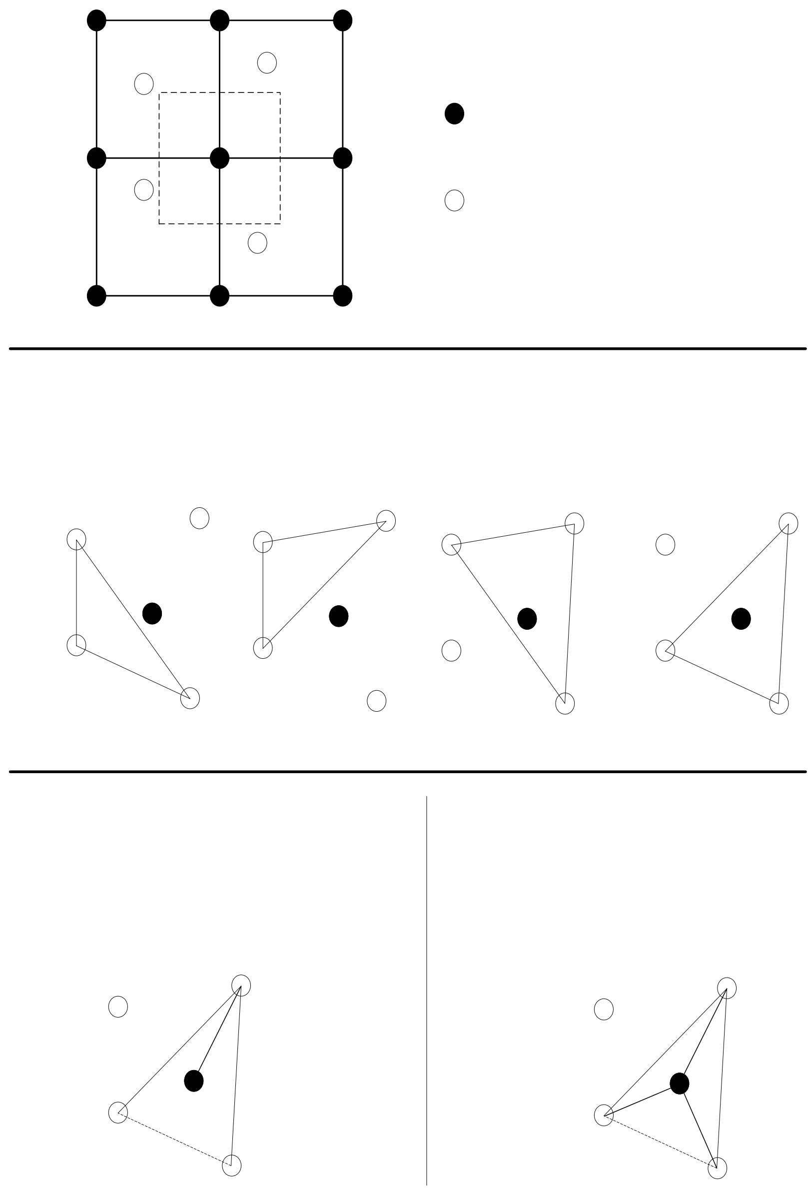
Figure 1 Fluid-Structure Non-matching meshes

The aerodynamic data from solver are of aerodynamic nodal points, but the force data of structural nodes are required in the structural deformation calculation; moreover, the fluid mesh is not matching[3] with the structural mesh, so it is necessary to translate the discrete force from the fluid mesh to structural mesh. To realize the force translation, the triangle area weighted method has been used in the research.

Generally, the fluid mesh is denser than structural mesh, and non-matched each other. The triangle area weighted method used in the research is as shown in figure 1.

First, a proper triangle consisting of three structural points as shown in figure 2 is required to be chosen for each fluid mesh point, so the work was done in the following steps[4]:

1. Set up the fluid points (CFD Grid points) for conducting data exchange and find out the relevant structural points (CSD nodes) , see step 1 in figure 2;
2. For a given CFD grid point (i , j), select a number of structural nodes closest to the CFD grid point (in figure 2, N=4, generally N is a positive integral number in the range of >3   <30). In the structural nodes of Ns, a triangle can be formed within three arbitrary points, so the total numbers of triangles were calculated by $N\times(N-1)\times(N-2)/6$, but the minimum area limit *Amin* is required in the triangle set-up. If the triangle area A is less than the limit ($A<A_{min}$), this triangle element should be kicked out. Supposing *N*s of the triangle elements can be kicked out (Nkick), see the step 2 in figure 2;



Step 1

i - 1

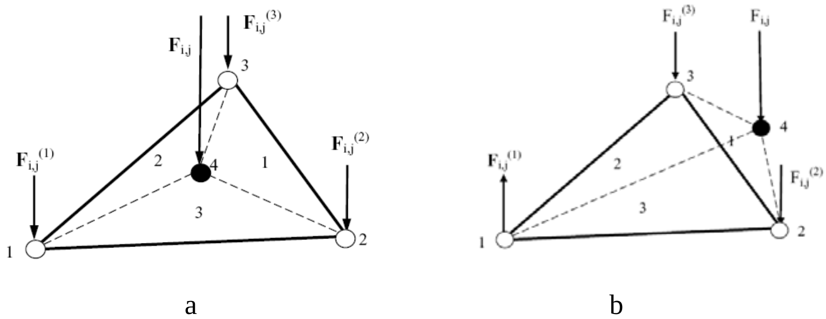
j - 1

1

j

Fig.2 the triangle element formed by CFD Grid points and structural mesh modes

3



j +1

Fig. 3 Triangle area weighted method

Step 2

3. For each triangle structure, the distances d_k^m from its three points respectively to the CFD Grid point (i, j) can be obtained by

$$d_k^m = \sqrt{\left((x_s)_k^m - x_a\right)^2 + \left((y_s)_k^m - y_a\right)^2 + \left((z_s)_k^m - z_a\right)^2} \quad k = 1,2,3 \ ; m = 1,2,\cdots N \qquad 1$$

where

m is the serial number of a triangle, k is the serial number of point of triangle m.

The max distance d_k^m of them should be taken as the triangle characteristic value, i.e. $d_{\max}^m = \max\left(d_1^m, d_2^m, d_3^m\right)$. For CFD Grid point (i, j), there will be a number of N×(N-1)×(N-2)/6-Nkick characteristic distance, the min distance $d_{\min}$ of them should be chosen, then the triangle corresponding to the characteristic distance is the structural mesh node triangle, see step 3 in fig. 2.

As shown in step 4 fig. 2, the aerodynamic grid point and three structural mesh nodes can form four triangle elements, panel A2 is composed of structural mesh node 3 and 4, also A3 and A4 are similar in definition. Then, taking A as the structural triangle element, keeping with its three serial vertex numbers (2, 3, 4) and coordinate, the areas of S, S1, S2 and S3 of panels A, A2, A3 and A4 can be calculated. Then weight value w_1, w_2, w_3 can be obtained by

$$w_1 = S_1/S \qquad w_2 = S_2/S \qquad w_3 = S_3/S \qquad 2$$

Each aerodynamic grid point has three corresponding area weight values. These values will be used in the aerodynamic exchanges and displacement transfer between the aerodynamic grid point and structural mesh node. In addition, in the four area calculation with this method, the sequence, namely array direction (clockwise/counterclockwise) of the three vertexes of a triangle must be always consistent with each other, so as to keep the unification of value calculation and force transfer in case that the aerodynamic grid points fall out of the triangle structure. As shown in fig. 3, the fig.3(a) indicates that the aerodynamic grid points projection fall inside of the structural triangle element, the w_1, w_2, w_3 are positive value, sum is 1. Fig. 3(b) shows that the aerodynamic grid points projection fall out of the structural triangle element, the negative weight value occurs, but their sum is 1.

Supposing the discrete force at aerodynamic grid point (i, j) to be $\boldsymbol{F}_{i,j}$ based on the above-stated weight value, it will be a distributive and placed at three structural mesh nodes as given in equation (3).

$$\boldsymbol{F}_{i,j}^{(1)} = \boldsymbol{F}_{i,j} \cdot w_1 \ ; \ \boldsymbol{F}_{i,j}^{(2)} = \boldsymbol{F}_{i,j} \cdot w_2 \ ; \ \boldsymbol{F}_{i,j}^{(3)} = \boldsymbol{F}_{i,j} \cdot w_3 \qquad 3$$

With the area weight method of triangle element stated in this paper, the problem in force transfer of aerodynamic grid points to structural mesh nodes can be solved, the transferred force will be neither any loss nor additional force moments so it is a method with higher accuracy.

2. Fluid—structure displacement transfer

After the force of aerodynamic grid points transferred to structural mesh nodes with the area weight method of triangle element, the structure deformation have to be calculated. The structure deformation can be described by the displacement of structural mesh nodes. In order to transfer the structural mesh node displacement to aerodynamic grid points, the infinite plate spline interpolation and constant-volume Tetrahedron method are used in the paper, but the traditional constant-volume Tetrahedron method has been modified in the research so as to be more desirable in dealing with the displacement transfer over fluid—structure boundary surface. Moreover, the applicability and advantages were shown by comparison between the two methods.

2.1 Infinite plate spline(IPS)[2]

On the assumption that, when a flat-plate under the function of given distributive loads, the vertical-to-the-plate-surface displacement (to $z=0$ plane distance) should meet the equation (4):

$$w_j(x_j, y_j) = \sum_{i=1}^{N} F_i r_{ij}^{\ 2} \ln\left(r_{ij}^{\ 2}\right) + a_0 + a_1 x_j + a_2 y_j \qquad (j = 1,2,3,......N) \qquad 4$$

where

$r_{ij}^{\ 2} = (x_i - x_j)^2 + (y_i - y_j)^2$ N point numbers;

a_0, a_1, a_2 the coefficients to be decided;

when point N known, an infinitive curve surface can be developed, in other words, when the relations between a coordinate (x_i, y_i) of N and its distance from $z=0$ plane can meet equation (4), a group composed of N equations with N+3 unknown numbers, the absent three equations can be reinforced by the balance equations of forces and moments:

$$\sum_{i=1}^{N} F_i = \sum_{i=1}^{N} x_i F_i = \sum_{i=1}^{N} y_i F_i = 0 \qquad 5$$

the matrix form of the equations is:

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ \cdots \\ w_N \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_{11}\ln r_{11}^2 & r_{12}\ln r_{12}^2 & \cdots & r_{1N}\ln r_{1N}^2 & 1 & x_1 & y_1 \\ r_{21}\ln r_{21}^2 & r_{22}\ln r_{22}^2 & \cdots & r_{2N}\ln r_{2N}^2 & 1 & x_2 & y_2 \\ r_{31}\ln r_{31}^2 & r_{32}\ln r_{32}^2 & \cdots & r_{3N}\ln r_{4N}^2 & 1 & x_3 & y_3 \\ r_{41}\ln r_{41}^2 & r_{42}\ln r_{42}^2 & \cdots & r_{4N}\ln r_{4N}^2 & 1 & x_4 & y_4 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ r_{N1}\ln r_{N1}^2 & r_{N2}\ln r_{N2}^2 & \cdots & r_{NN}\ln r_{NN}^2 & 1 & x_N & y_N \\ 1 & 1 & \cdots & 1 & 0 & 0 & 0 \\ x_1 & x_2 & \cdots & x_N & 0 & 0 & 0 \\ y_1 & y_2 & \cdots & y_N & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ \cdots \\ F_N \\ a_0 \\ a_1 \\ a_2 \end{bmatrix} \qquad 6$$

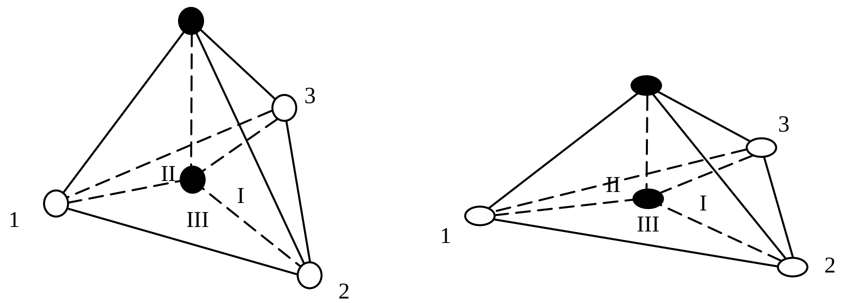
By solving this linear equations the pending coefficient obtained $F_1, F_2 \ldots F_N, a_0, a_1, a_2$ .By doing this, the surface which contain N structure mesh nodes can be confirmed, the displacement vertical to the plate surface can obtained by the following equation:

$$w(x, y) = \sum_{i=1}^{N} F_i r^2 \ln(r^2) + a_0 + a_1 x + a_2 y \qquad 7$$

(x, y) is an arbitrary aerodynamic grid point but not N structure mesh nodes, $w(x, y)$ is the displacement vertical to the plate, $r^2 = (x - x_i)^2 + (y - y_i)^2$.

2.2 Constant-Volume Tetrahedron Method(CVT)

The Constant-Volume Tetrahedron (CVT) Method was first referred by *Goura*[1]. This method is a local interpolation method and not correlative with structure mode. It's basic principle is described as following. Three structure mesh nodes and a aerodynamic grid points formed a tetrahedron in space. The tetrahedron volume and aerodynamic grid points projected point related position can be confirmed. When the structure mesh nodes moved to a new place, the aerodynamic grid points and structure mesh nodes makeup a new tetrahedron, and the new tetrahedron volume was equal to the former tetrahedron volume which the structure mesh nodes did not move, at the same time, the projected point related position was not changed. The advantage of this method is that this method is only related to local information (in other words, need not compute and save matrix).



(a) (b)

Figure 4 CVT method principle

Before the structure moved, for every aerodynamic grid point (x_4, y_4, z_4), three vertex of triangle which was found by using the triangle area weight method were listed as (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3), named as 1, 2, 3. We use (x, y, z) to describe the projected point in the 123 plane, see Figure 4. The weight w_1, w_2, w_3 of the projected points in 123 plane can be obtained by using the triangle area weight method.

$$\begin{cases} x = w_1 x_1 + w_2 x_2 + w_3 x_3 \\ y = w_1 y_1 + w_2 y_2 + w_3 y_3 \\ z = w_1 z_1 + w_2 z_2 + w_3 z_3 \end{cases} \qquad 8$$

Where $w_1 + w_2 + w_3 = 1$, the normal vector of the 123 plane is $\boldsymbol{n}(l, m, n)$:

$$\begin{vmatrix} \boldsymbol{i} & \boldsymbol{j} & \boldsymbol{k} \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \end{vmatrix} = l\boldsymbol{i} + m\boldsymbol{j} + n\boldsymbol{k} \qquad 9$$

the relationship of the aerodynamic grid point and projected point is:

$$\begin{cases} x_4 = x + vl \\ y_4 = y + vm \\ z_4 = z + vn \end{cases} \qquad 10$$

where v can control the displacement between the aerodynamic grid point and the projected point, the directional volume of tetrahedron which was formed by aerodynamic grid point and triangle was described as:

$$V = (1/6) \cdot \left(l(x_4 - x_1) + m(y_4 - y_1) + n(z_4 - z_1)\right) \qquad 11$$

After transmutation, the coordinate of point 1, 2, 3 of the structure triangle and aerodynamic grid point, the projected points are (x_1', y_1', z_1'), (x_2', y_2', z_2'), (x_3', y_3', z_3'), (x_4', y_4', z_4'), (x', y', z'). The relatively location of the projected point in the 123 plane does not change, in other words, the weight w_1, w_2, w_3 do not change, and then the coordinates of the aerodynamic grid point after transmutation are:

$$\begin{cases} x_4' = x' + v' l' = w_1 x_1' + w_2 x_2' + w_3 x_3' + v' l' \\ y_4' = y' + v' m' = w_1 y_1' + w_2 y_2' + w_3 y_3' + v' m' \\ z_4' = z' + v' n' = w_1 z_1' + w_2 z_2' + w_3 z_3' + v' n' \end{cases} \qquad 12$$

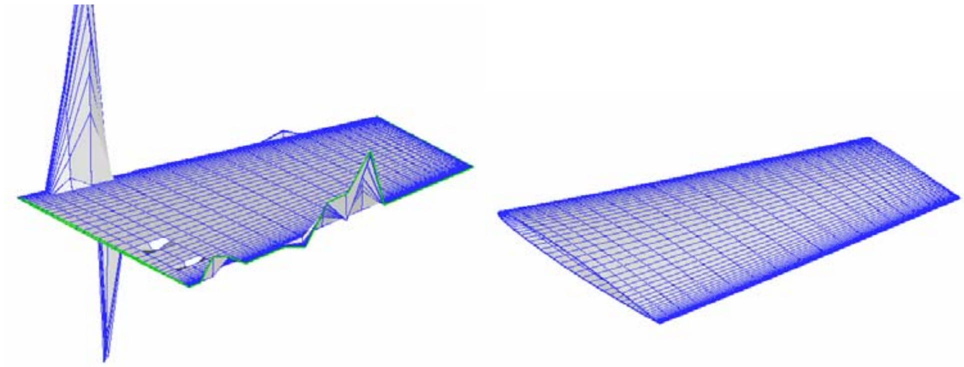
where the definition of l', m', n' are the same as l, m, n, these are the normal vector of 1\`2\`3\` plane, the definition of v' are the same as v. After transmutation the new tetrahedron volume is given by

$$V_{new} = \frac{1}{6}\left(l'(x'_4 - x'_1) + m'(y'_4 - y'_1) + n'(z'_4 - z'_1)\right) \qquad 13$$

Take formula (12) into formula (13), and let the old volume equal to the new one $V_{new} = V$, by doing this the unknown v' can be obtained. Take v' into formula (12) can obtain the coordinate of aerodynamic grid point 4\` (x_4', y_4', z_4') after transmutation.

The new position of every aerodynamic grid point can be obtained by CVT method. By doing this the displacement can be translate from structure mesh points to aerodynamic grid points.

The improvement of the CVT method is that we take the product of weight and the coordinates of structure triangle to describe the aerodynamic grid points, but not the classic method. This improvement can make the computation easier, and need not calculate the linear equations. And also, the triangle area weight method can deal with the outer boundary points, so the improved CVT method can deal with the outer boundary points and need not deal with it specially. By introduce the minimum area control, the triangle area weight method can prevent the appearance of singularity points (the three vertexes of structure triangle nearly on one line) in the displacement translation process, and make sure the aerodynamic grid smooth after translation. In figure 5, the effect of minimum area control to CVT method is shown. In Figure 5(a), the minimum area control was not introduced, the singularity points appeared, and the aerodynamic grid was not smooth. In figure 5(b), the minimum area control was introduced, and the aerodynamic grid was very smooth.

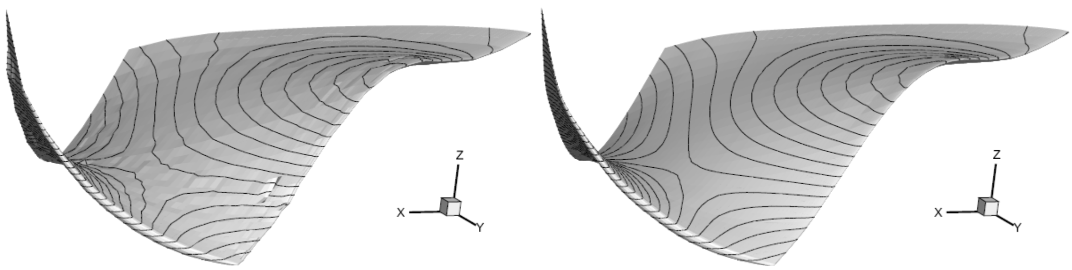


(a)The minimum area control was not introduced.   (b)The minimum area control was introduced

Figure 5 The effect of the minimum area control in CVT method

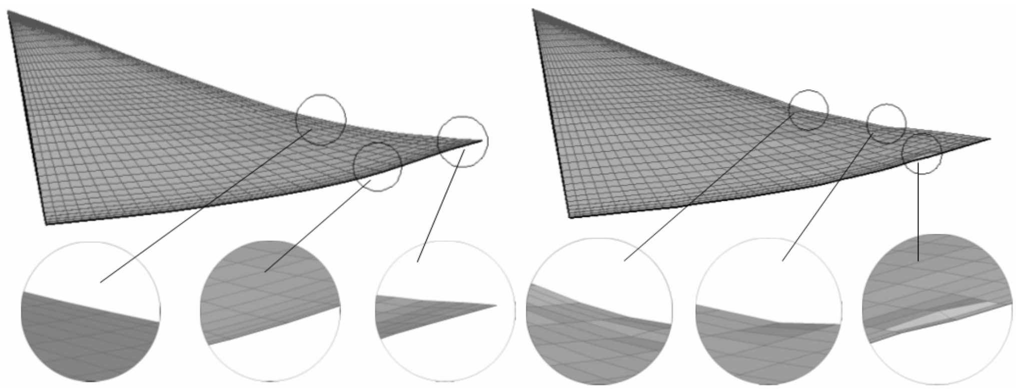
2.3 The comparison of IPS and CVT

Both IPS and CVT method have advantage and disadvantage. The IPS method is a two dimensional method, it can only calculate the displacement of certain direction, so when dealing with large displacement problem the aerodynamic grid may distortion. But the CVT method is a three dimensional method, it can describe the displacement more actual. The CVT method is a local interpolation method and need not calculate and save matrix. The aerodynamic grid was not smooth if the CVT method has been used to translate displacement when the structure mesh was very sparse, but if the IPS method has been used the aerodynamic grid was smooth. Figure 6 shown the different grid quality when the different structure mesh density was used. Figure 6(a) shown that the structure mesh was 10×10, and the aerodynamic grid was very coarse, but when the structure grid was up to 80×80 as shown in figure 6(b), the aerodynamic grid became smooth enough. Figure 7 shown the different interpolation effect between IPS and CVT methods, when the structure mesh was very sparse. If the IPS method has been used, the aerodynamic grid was smooth as shown in figure 7(a), but if the CVT method has been used, the aerodynamic grid was coarse as shown in figure 7(b). The advantages and disadvantages in different applications have been listed in sheet 1.



(a) structure mesh with 10×10 elements   (b) structure mesh with 80×80 elements

Figure 6 The different CVT effect when different structural mesh density was used.



(a) the aerodynamic grid when the IPS method was used   (b) the aerodynamic grid when the CVT method was used

Figure 7 The different interpolation effect between CVT and IPS when the structural mesh was sparse

Sheet 1 The comparison between IPS and CVT method

IPS	2D method	Small displacement	Both dense and sparse structural mesh	Save matrix	Sparse structural mesh and small displacement
CVT	3D method	Both	Dense structural mesh	Need not save	Dense structural mesh

3 Conclusion

In this paper, the triangle area weight method was a high precision method to translate force. To solve the outer boundary points, the author have introduced negative weight, by doing this the outer boundary points need not dispose specially. The author has also introduced minimum area control in the triangle area weight method, and this technology has prevented the singular points occurrence. The Infinite Plate Spline method and Constant Volume Tetrahedron method have been introduced particularly. The classic CVT method has been improved by triangle area weight method. The improved CVT method can deal with the data exchange more easily, and it need not deal with the outer boundary points specially, and it can prevent the singular points appearance, this technology make the aerodynamic grid smooth. In this paper, the author has compared the CVT method and IPS method, the different usage has been described. The Infinite Plate Spline method would be selected first when the structure mesh density was sparse and the displacement is small, and the CVT method would be selected when the structure mesh density was dense.

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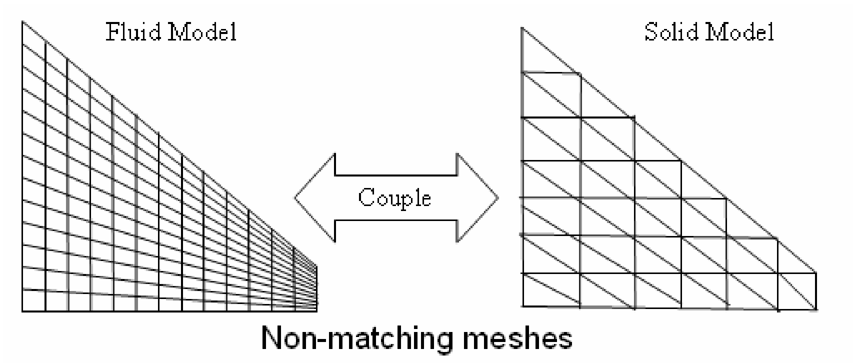
[1] [2]

1

[3]

1



1

2 [4]

CFD Grid points CSD nodes 2

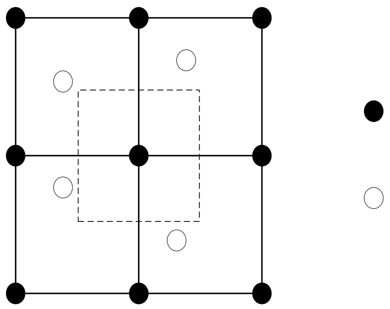
Step 1

(i, j) N N=4 N 3 30

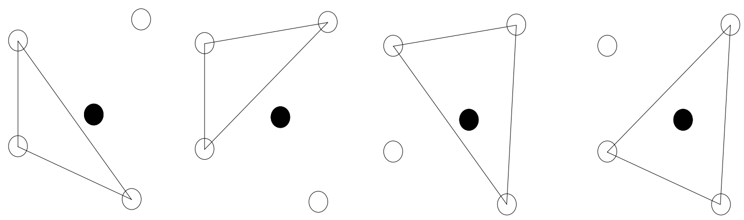
N N×(N-1)×(N-2)/6

Amin A<Amin Nkick

2 Step 2



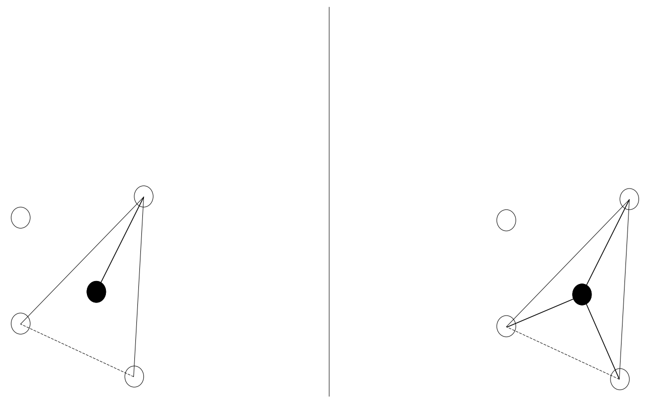
Step 1



i - 1

j - 1

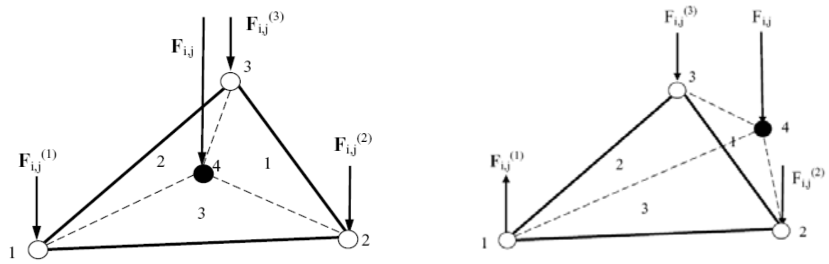
1



j

2

3



j +1

a

b

3

Step 2

(i, j) d_k^m

$$d_k^m = \sqrt{\left((x_s)_k^m - x_a\right)^2 + \left((y_s)_k^m - y_a\right)^2 + \left((z_s)_k^m - z_a\right)^2} \quad k = 1,2,3\ ;\ m = 1,2,\cdots N \qquad 1$$

m k m k d_{max}^m

$d_{max}^m = \max\left(d_1^m, d_2^m, d_3^m\right)$ (i, j) N×(N-1)×(N-2)/6-Nkick

d_{min} 2 Step 3

2 Step 4 4 A2 3 4
A3 A4 A 2 3 4

A A2 A3 A4 S S1 S2 S3 w_1, w_2, w_3

$$w_1 = S_1/S \qquad w_2 = S_2/S \qquad w_3 = S_3/S \qquad 2$$

/
3 3(a)

w_1, w_2, w_3 1 1 3(b)

1 1

(i, j) $\boldsymbol{F}_{i,j}$ 3

$$\boldsymbol{F}_{i,j}^{(1)} = \boldsymbol{F}_{i,j} \cdot w_1 \ ;\ \boldsymbol{F}_{i,j}^{(2)} = \boldsymbol{F}_{i,j} \cdot w_2 \ ;\ \boldsymbol{F}_{i,j}^{(3)} = \boldsymbol{F}_{i,j} \cdot w_3 \qquad 3$$

2

2.1 (IPS)[2]

$z = 0$

$$w_j\left(x_j, y_j\right) = \sum_{i=1}^{N} F_i r_{ij}^{\ 2} \ln\left(r_{ij}^{\ 2}\right) + a_0 + a_1 x_j + a_2 y_j \qquad \left(j = 1,2,3,\ldots\ldots N\right) \qquad 4$$

$r_{ij}^{\ 2} = \left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2$ N a_0, a_1, a_2 N

N $\left(x_i, y_i\right)$ $z=0$ 4 N+3

N

$$\sum_{i=1}^{N} F_i = \sum_{i=1}^{N} x_i F_i = \sum_{i=1}^{N} y_i F_i = 0 \qquad 5$$

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ \ldots \\ w_N \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_{11}\ln r_{11}^2 & r_{12}\ln r_{12}^2 & \ldots & r_{1N}\ln r_{1N}^2 & 1 & x_1 & y_1 \\ r_{21}\ln r_{21}^2 & r_{22}\ln r_{22}^2 & \ldots & r_{2N}\ln r_{2N}^2 & 1 & x_2 & y_2 \\ r_{31}\ln r_{31}^2 & r_{32}\ln r_{32}^2 & \ldots & r_{3N}\ln r_{4N}^2 & 1 & x_3 & y_3 \\ r_{41}\ln r_{41}^2 & r_{42}\ln r_{42}^2 & \ldots & r_{4N}\ln r_{4N}^2 & 1 & x_4 & y_4 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ r_{N1}\ln r_{N1}^2 & r_{N2}\ln r_{N2}^2 & \ldots & r_{NN}\ln r_{NN}^2 & 1 & x_N & y_N \\ 1 & 1 & \ldots & 1 & 0 & 0 & 0 \\ x_1 & x_2 & \ldots & x_N & 0 & 0 & 0 \\ y_1 & y_2 & \ldots & y_N & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ \ldots \\ F_N \\ a_0 \\ a_1 \\ a_2 \end{bmatrix} \qquad 6$$

$F_1, F_2 \ldots F_N, a_0, a_1, a_2$ N

N

$$w(x,y) = \sum_{i=1}^{N} F_i r^2 \ln\left(r^2\right) + a_0 + a_1 x + a_2 y \qquad 7$$

(x,y) N $w(x,y)$

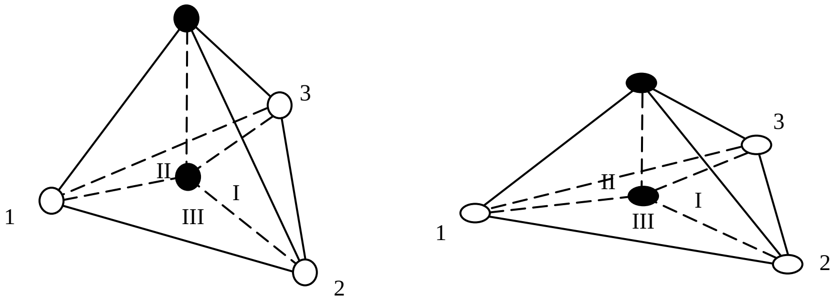
$r^2 = \left(x - x_i\right)^2 + \left(y - y_i\right)^2$

2.2 (CVT)

Goura[1]

( )

( )



(a) (b)

4 CVT

$\left(x_4, y_4, z_4\right)$ $\left(x_1, y_1, z_1\right)$

$\left(x_2, y_2, z_2\right)$ $\left(x_3, y_3, z_3\right)$ 1 2 3 $\left(x, y, z\right)$ 123

4 123 w_1, w_2, w_3

$$\begin{cases} x = w_1 x_1 + w_2 x_2 + w_3 x_3 \\ y = w_1 y_1 + w_2 y_2 + w_3 y_3 \\ z = w_1 z_1 + w_2 z_2 + w_3 z_3 \end{cases} \quad 8$$

$w_1 + w_2 + w_3 = 1$ 123 $\boldsymbol{n}\left(l, m, n\right)$

$$\begin{vmatrix} \boldsymbol{i} & \boldsymbol{j} & \boldsymbol{k} \\ x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \end{vmatrix} = l\boldsymbol{i} + m\boldsymbol{j} + n\boldsymbol{k} \quad 9$$

$$\begin{cases} x_4 = x + vl \\ y_4 = y + vm \\ z_4 = z + vn \end{cases} \quad 10$$

v

$$V = \left(1/6\right) \cdot \left(l\left(x_4 - x_1\right) + m\left(y_4 - y_1\right) + n\left(z_4 - z_1\right)\right) \quad 11$$

1 2 3 $\left(x_1', y_1', z_1'\right)$ $\left(x_2', y_2', z_2'\right)$

$\left(x_3', y_3', z_3'\right)$ $\left(x_4', y_4', z_4'\right)$ $\left(x', y', z'\right)$ 123

w_1, w_2, w_3

$$\begin{cases} x_4' = x' + v'l' = w_1 x_1' + w_2 x_2' + w_3 x_3' + v'l' \\ y_4' = y' + v'm' = w_1 y_1' + w_2 y_2' + w_3 y_3' + v'm' \\ z_4' = z' + v'n' = w_1 z_1' + w_2 z_2' + w_3 z_3' + v'n' \end{cases} \quad 12$$

l', m', n' l, m, n 1`2`3` v' v

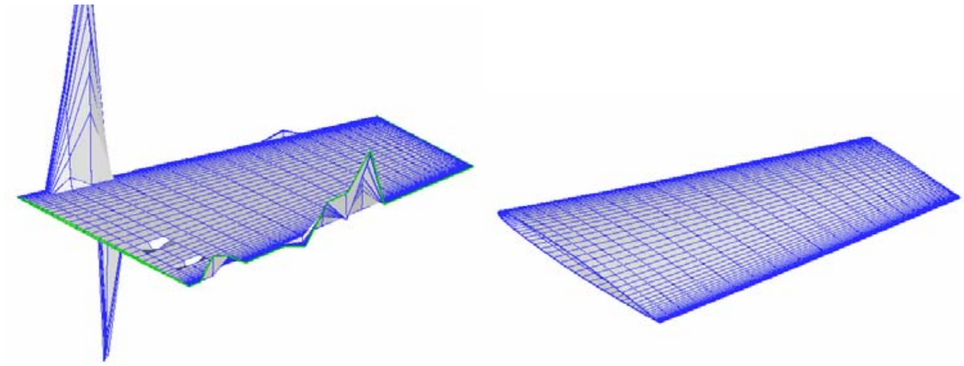
$$V_{new} = \frac{1}{6}\left(l'\left(x'_4 - x'_1\right) + m'\left(y'_4 - y'_1\right) + n'\left(z'_4 - z'_1\right)\right) \quad 13$$

(12) (13) $V_{new} = V$ v' v' 12

4` $\left(x_4', y_4', z_4'\right)$

5 5 a

5 b



a b

5

2.3 IPS CVT

IPS CVT

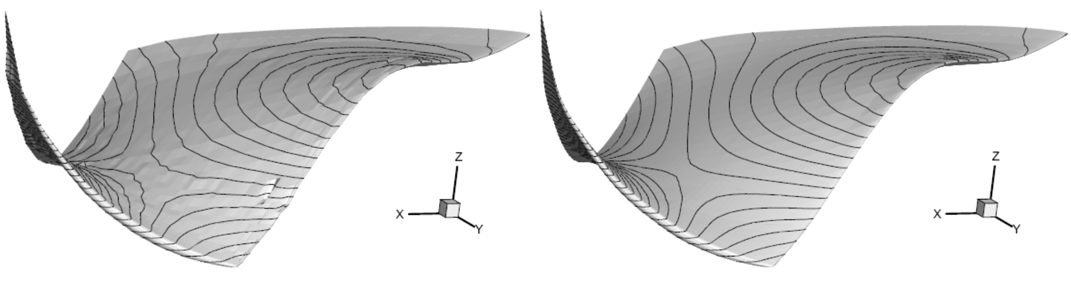
6 CVT

6 a 10×10 80×80

6 b 7 IPS CVT

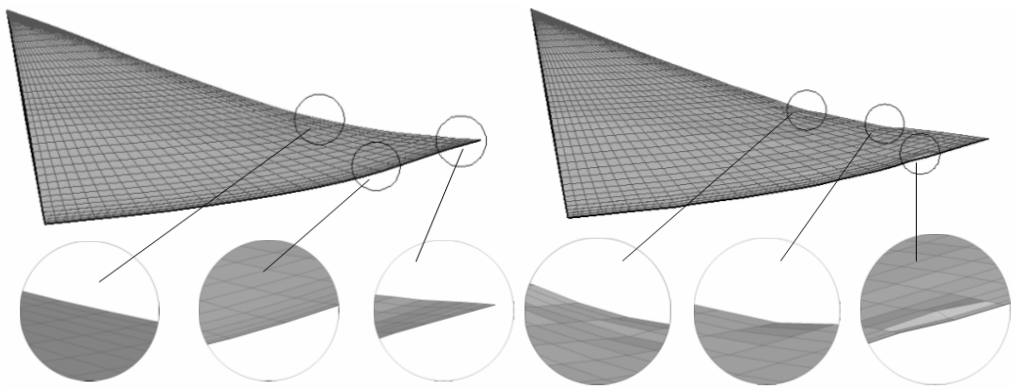
7 a IPS 7 b CVT 1

IPS CVT



a 10×10 b 80×80

6 CVT



a IPS　　　　b CVT

7　　　IPS　　CVT

1 IPS　CVT

IPS					
CVT					

3

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