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A NOVEL RBF DATA TRANSFER METHOD BASED ON PCA GEOMETRIC FEATURE EXTRACTION

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Abstract

Radial basis function（RBF） is an important data transfer method in the multi-field coupling calculation of complicated-shaped aircraft. The physical quantity distribution of complicated-shaped aircraft is usually closely related to the local geometric characteristics and flow characteristics and changes drastically in different regions. How to consider the influence of the actual computational grid geometry and physical quantity anisotropy in the isotropic radial basis function has become the key to further improve its accuracy. In order to solve the problem of insufficient interpolation accuracy caused by the anisotropy of grid geometric features, a new method of radial basis function based on principal component analysis (PCA) is proposed for geometric feature extraction and correction of grid spatial distribution direction. Hypersonic control surface and wing body combination model are used to verify the effect of this method. The results indicate that this method can well improve the effect of global radial basis functions such as TPS and MQ. In addition, the improvement is better for the CSC^2 radial basis function, which can use fewer points to achieve the same accuracy as the global basis functions and realize the balance of data transfer efficiency and accuracy. Therefore, this method has a good engineering application prospect in the complex shape multi-field coupling problem.

Keywords: Multi-physical field coupling; Data transfer; Radial basis function; PCA

1. Introduction

Hypersonic vehicles will be subjected to strong aerodynamic heating when flying at high speed. The temperature rise caused by aerodynamic heating is so high that it will not only affect the working of cabin instruments but also cause the change of structure mechanic property, and then reduce the structure strength, cause aerothermoelastic behaviors and disastrous consequences to hypersonic vehicles [1-3]. The independent and dispersed aerodynamic heating environment, thermal response and thermal stress analysis methods artificially split the complex process of the actual multi-physic field interaction, and are not suitable for situations where there is a serious aerodynamic/thermal/structural multi-field coupling [4-5]. In order to conduct a more detailed design and reliability evaluation of the thermal protection structure, we should make clear the thermal environment of the thermal protection structure and its heat transfer, dissipation, distribution mechanism and the resulting deformation and damage characteristics. Therefore, the coupled fluid-thermal-structure interaction must be considered in numerical simulations [6].

After years of research, many well-proved CFD and CSD solvers have been developed and regularly used in the design cycle. When considering the coupled problem of FSI (Fluid Structure Interaction),we prefer reusing these solvers and coupling them by the partitioned approach. The partitioned approach, so called “loose coupling” solves FSI problems in an iterative way and couples the structure and fluid at each time level by data transfer on the fluid-structure interface. Because of its simplicity and strong applicability, loose coupling method has become the main method to solve the multi-physics coupling problem of the aircraft [7-8]. Since each solver has very different requirements for mesh types (structured grids or unstructured grids, coarse or fine grids, etc.), these meshes will not generally coincide at the fluid-structure interface. How to transfer information between two non-matching meshes in an accurate and simple way has become a bottleneck problem to the fluid-thermal-structure coupling problem.

Commonly used data transfer methods include local methods and global methods. Local methods include weighting method, inverse isoparametric mapping method, constant volume tetrahedral method and boundary element method, etc. [9-11]. A significant disadvantage of the local methods is that it usually requires the connection information between the grid points and is difficult to obtain higher interpolation accuracy [12]. Therefore, the global method is more and more widely used because it does not need additional point connection information [13] and is easy to deal with complex shapes and modular programming [14-16].The radial basis function (RBF) is a typical global interpolation method [17-19]. Adam and Allen et al. [20-21] carried out a series of studies and applied them to the analysis of hypersonic wing aeroelastic problems. Frank, Smith et al. [22-24] conducted a series of tests on various methods and showed that the results obtained by radial basis functions are the most satisfactory. Commonly used radial basis functions include Thin-Plate Splines (TPS), Multiquadric-Biharmonic (MQ) and compactly supported C^2(CSC^2) radial basis functions, etc. However, Wu Zongmin pointed out that the radial basis function is theoretically more suitable for isotropic problems [18] and the spatial distribution of physical quantities such as heat flux and pressure of a complicated-shaped aircraft is anisotropic as it is usually affected by the characteristics of the aircraft shape and the resulting flow field characteristics. At the same time, when the computational grid is artificially generated, its geometric shape and mesh resolution characteristics are also restricted by the local configuration characteristics. Therefore, the spatial structure distribution characteristics of the grid points that require data transfer are also anisotropic. However, when the isotropic radial basis function is used for data transfer, the sharp gradient changes of anisotropic physical quantities cannot be accurately captured, which causes the bottleneck problem of accuracy improvement.

In order to solve the problem of anisotropy of physical quantity distribution and grid point spatial distribution, a non-isotropic radial basis can be used by giving different distances in the x-y-z directions of the radial basis [18]. The correction coefficient is used to eliminate the deviation of anisotropy, so that the gradient of the physical quantity in the entire distribution space is as consistent as possible. In order to eliminate the anisotropy of the spatial distribution and density of grid points caused by the overall size of the aircraft, the author proposed a geometrically normalized radial basis function in the previous research work and achieved a good accuracy improvement effect [25]. Considering the anisotropic characteristics of the physical quantity, we also developed a correction method based on the average statistical characteristic of the gradient of the physical quantity in each direction and got better accuracy improvement [26]. The above methods effectively solved the anisotropy influence of the range and resolution of the grid points, and physical quantities, but cannot eliminate the anisotropy of the directional distribution characteristics of the grid points affected by the geometric shape of the aircraft (For example, the primary and secondary change directions of the grid point distribution caused by the overall sweep of the wing are not consistent with the Euclidean coordinate axis, and the physical quantity distribution is usually consistent with the grid point distribution characteristics). How to extract the geometric directional characteristics of the grid itself and eliminate the influence of its anisotropic distribution has become the key to improving the accuracy of the current complex aircraft based on the radial basis method for data transmission.

As the Principal Component Analysis (PCA) can be used to extract the geometric features of a large number of scattered points of data, and to obtain data points in the new coordinate system that can characterize the major and minor axes of the geometric feature changes, a new method of radial basis function interpolation based on PCA was proposed to realize the anisotropy correction of grid points geometric characteristics. A hypersonic control surface and wing body combination were used to verify the feasibility and effect of this method on the CSC^2, TPS and MQ radial basis functions. At the same time, the improved interpolation accuracy of the three methods is compared and analyzed.

2. Improved RBF interpolation model based on PCA

2.1 Basic principles of RBF

The papers should be prepared, if possible, using the format like this document. Given function ϕ: $R_+ \to R$ in d-dimensional Euclidean space. For n different points $\{x_i, g_i | \text{i=1,2,3,...,n}\} \in R^d \otimes R$, the scalar values at these fixed points are $\{g_1, g_2.g_3,..., g_n\}$, According to these points, a function needs to be determined:

$$g(\boldsymbol{x}) = \sum_{i=1}^{n} c_i \phi\left(\|\boldsymbol{x} - \boldsymbol{x}_i\|_2\right) \tag{1}$$

to satisfy interpolation condition:

$$g(\boldsymbol{x}_k) = \sum_{i=1}^{n} c_i \phi\left(\|\boldsymbol{x}_k - \boldsymbol{x}_i\|_2\right) \tag{2}$$

Where $g(\boldsymbol{x}_k)$ is the attribute value of point $\boldsymbol{x}_k$ which is an arbitrary point in the space, $\phi\left(\|\boldsymbol{x}_k - \boldsymbol{x}_i\|_2\right)$ is a general form of some kind of RBF adopted, $\boldsymbol{x}_i$ is the location of the supporting centre for the RBF labeled with index i. The coefficient c_i is the weight of each point. $\|\boldsymbol{x} - \boldsymbol{x}_i\|_2$ is the Euclidean distance between two points(second order norm). It can be writen as:

$$r = \|\boldsymbol{x} - \boldsymbol{x}_i\| = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \tag{3}$$

From Eq.(1), $g(\boldsymbol{x})$ is a function space constituted by n different basic functions and the coefficient c_i can be determined by solving Eq.(2).

The RBF can be divided into global radial basis functions and compactly supported radial basis functions based on the influence range of the base function. The former refers to the RBF basic function can influence the whole domain, such as TPS , MQ and other basic functions, while the latter refers to the influence is within a fixed radius range such as Wendland C^2 compactly supported function[27]. In this work, these three RBF functions are selected as the basic functions because of their satisfactory performance for data transfer in multi-physical coupling [22-24] and their specific mathematical forms are as follows:

Table 1 Three radial basis functions

Function	Formula
TPS	$\phi(r) = r^2 \log r$
MQ	$\phi(r) = \left(c^2 + r^2\right)^{1/2}$
C^2	$(1\text{-}R)_+^4(4R+1)$

Where r is shown in Eq.(3), and $\mathrm{R} = \frac{\|r - r_i\|}{d}$ with d denoting the supporting radius of RBF.

2.2 RBF based on PCA geometric feature extraction

The thermo-aeroelastic analysis of hypersonic vehicle wing is a typical multi-field coupling calculation problem. As shown in Figure 1, the distribution of wing heat flux and grid distribution under real flight condition and calculation condition are anisotropic.

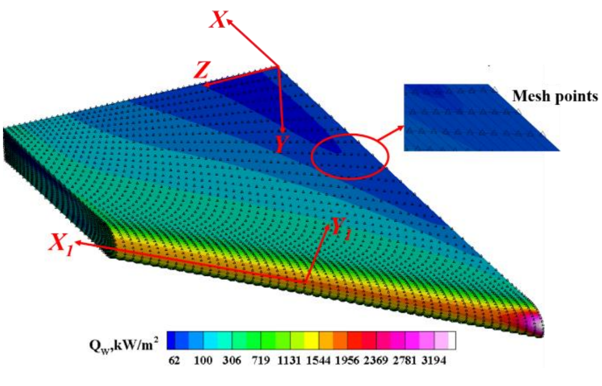


Figure 1 - Heat flux distribution of the wing leading edge and the grid points distribution

Affected by the flow characteristics of the wing, the leading edge of the wing is the area where the heat flux changes the most, and the change is gentler away from the leading edge. Therefore, the heat flux gradient differs greatly in the x-y-z three directions (commonly used calculation coordinate system), which leads to the anisotropic distribution of physical quantities. At the same time, we also noticed that the physical quantity distribution is actually not directly related to x, y, and z directions, but is more directly related to geometric features such as the wing sweep direction X1 and the sweep vertical direction Y1 of the aircraft and is striped in the latter direction. Apart from that, the geometric distribution directional characteristics of the grid points are actually directly affected by the sweep of the wing surface and the curvature of the leading edge and are closely related to the heat flux distribution. The variance of the grid points in the swept direction is larger while the heat flux gradient changes smaller. On the contrary, the variance is smaller in the vertical direction of the sweep direction and the heat flux gradient changes more. The usual xyz coordinate system is established on the basis of the fuselage. In this coordinate system, the radial basis change calculated according to formula (3) cannot represent the true direction of the physical quantity change. We need to obtain the maximum and minimum changes of the grid points structure according to the geometric characteristics, and carry out the construction of the anisotropic radial basis interpolation model in the coordinate system that can best describe changes of the grid and physical quantities.

In the analysis of the geometric directional characteristics of discrete points, PCA is an important algorithm. In the three-dimensional space, PCA finally obtains the orthogonal axis system by analyzing the correlation between each data dimension. The first direction of the new axis system is the direction with the largest data distribution variance, and the second direction is the second [28]. Although the original purpose of PCA is to reduce the data dimension, if all eigenvalue components are retained during the analysis process, the coordinate rotation transformation can be realized. Therefore, after a large number of discrete points are processed by PCA, grid points will be rearranged in a new coordinate system, which represents three uncorrelated and orthogonal main directions of geometric feature changes of the original grid points. Therefore, the anisotropy caused by the geometric directional characteristics of the existing grid points to be interpolated can be eliminated. In addition, with the combination of geometric scale normalization and physical quantity gradient correction method, we can achieve higher data transmission accuracy. Based on this idea, the new data transfer method proposed in this article is as follows:

(1) In the first step, we extract mesh node coordinates to form a matrix, that is $\mathbf{X}=[\mathbf{X}_1\ \ \mathbf{X}_2\ \ \mathbf{X}_3]$, where $\mathbf{X}_1$、$\mathbf{X}_2$、$\mathbf{X}_3$ are coordinate vectors in three axis directions. Then the covariance matrix $Cov(\mathbf{X})$ of $\mathbf{X}$ is presented as follows:

$$Cov(\mathbf{X})=\begin{pmatrix} \mathrm{cov}(\mathbf{X}_1,\mathbf{X}_1) & \mathrm{cov}(\mathbf{X}_1,\mathbf{X}_2) & \mathrm{cov}(\mathbf{X}_1,\mathbf{X}_3) \\ \mathrm{cov}(\mathbf{X}_2,\mathbf{X}_1) & \mathrm{cov}(\mathbf{X}_2,\mathbf{X}_2) & \mathrm{cov}(\mathbf{X}_2,\mathbf{X}_3) \\ \mathrm{cov}(\mathbf{X}_3,\mathbf{X}_1) & \mathrm{cov}(\mathbf{X}_3,\mathbf{X}_2) & \mathrm{cov}(\mathbf{X}_3,\mathbf{X}_3) \end{pmatrix} \tag{4}$$

Calculating the eigenvector matrix $\mathbf{A}(\mathbf{X})$ of $Cov(\mathbf{X})$ and then transformaing the original node matrix $\mathbf{X}$ by (6):

$$\mathbf{X}^{'}=\mathbf{A}(\mathbf{X})*\mathbf{X} \tag{5}$$

Where $\mathbf{X}^{'}$ is new mesh nodes matrix.

(2) The geometric normalization method [25] is adopted to eliminate the anisotropy of the grid distribution range caused by the overall sizes of the aircraft:

$$\left(\mathbf{X}_i^{'}\right)_{new}=\frac{\mathbf{X}_i^{'}-\left(\mathbf{X}_i^{'}\right)_{\min}}{\left(\mathbf{X}_i^{'}\right)_{\max}-\left(\mathbf{X}_i^{'}\right)_{\min}} \tag{6}$$

Finally, calculating the distance at the new node matrix $\left(\mathbf{X}_i^{'}\right)_{new}$:

$$\begin{aligned} r_{new}&=\sqrt{(\left(\mathrm{x}^{'}\right)_{new}-\left(\mathrm{x}_i^{'}\right)_{new})^2+(\left(y^{'}\right)_{new}-\left(y_i^{'}\right)_{new})^2+(\left(z^{'}\right)_{new}-\left(z_i^{'}\right)_{new})^2} \\ &=\sqrt{\alpha_1(x-x_i)^2+\alpha_2(y-y_i)^2+\alpha_3(z-z_i)^2} \end{aligned} \tag{7}$$

Compared with Eq. (3) it can be found:

$$\begin{aligned} \alpha_1&=\mathbf{A}(\mathbf{X})/\left(\mathbf{X}_1^{'}\right)_{\max}-\left(\mathbf{X}_1^{'}\right)_{\min} \\ \alpha_2&=\mathbf{A}(\mathbf{X})/\left(\mathbf{X}_2^{'}\right)_{\max}-\left(\mathbf{X}_2^{'}\right)_{\min} \\ \alpha_3&=\mathbf{A}(\mathbf{X})/\left(\mathbf{X}_3^{'}\right)_{\max}-\left(\mathbf{X}_3^{'}\right)_{\min} \end{aligned} \tag{8}$$

(3)In the new coordinate system, the physical quantity gradient correction is completed based on the literature [26] method, and the influence of the physical quantity gradient correction is eliminated.

2.3 Simple test case of improved RBF method

The three-dimensional semi-cylindrical model of the leading edge of the wing is used as a simple test case to illustrate the method in this paper. The x-y-z coordinate axis is the most commonly used coordinate system established by the aircraft overall geometry feature. The value of heat flux on this model is given by：

$$q = 200 * \cos(2 * pi * 0.2 * y) * e^{\wedge(-(y-5)^2/4)} \tag{9}$$

The heat flux is transferred from the fluid domain to the structural domain, and the surface mesh distribution of the two is shown in the figure below：

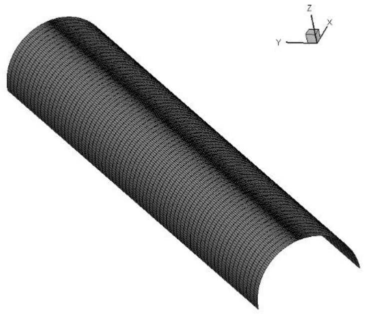


Figure 2 - Fluid domain mesh

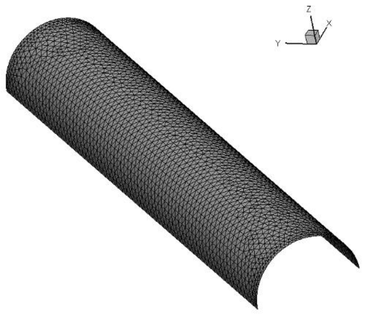
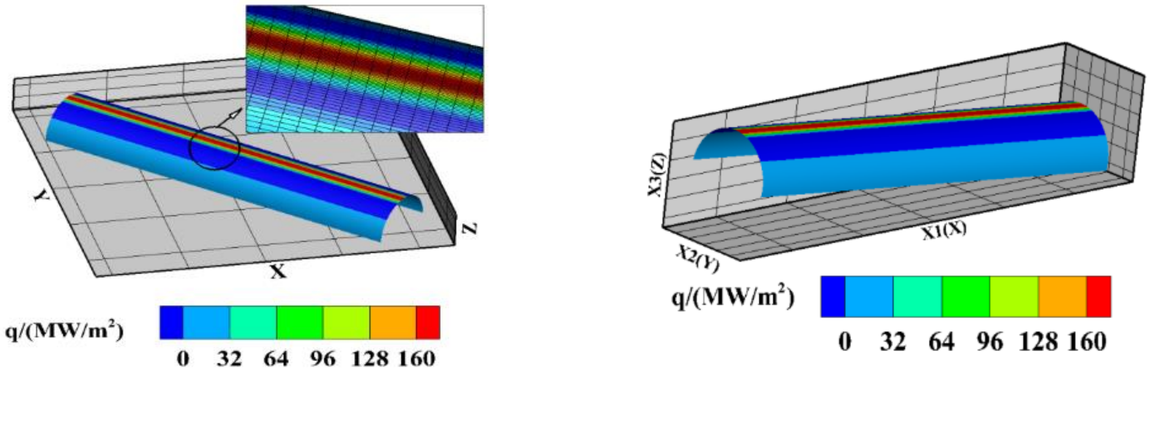


Figure 3 - Solid domain mesh

Figure 4 shows the heat flux distribution contour calculated by Eq. (9). Using the original RBF interpolation method will lead to a large interpolation error, because most of the selected points and radial basis distance calculation can’t represent the heat flux change very good. However, it can be found from Figure 4 (a)that the change in heat flux is not directly related with x-y-z directions. On the contrary, it changes strongly along the X1 and X2 directions. If the X1 direction is set as the x-axis in formula 3, and the X2 direction is set as the y-axis, then the use of Eq.(3) will inevitably reduce the interpolation error. While we can also find that X1 and X2 are the directions of geometry feature changes of grid points, so we can realize the grid points’ rotation by PCA. Figure 4(b) gives out the transformed coordinates by PCA.

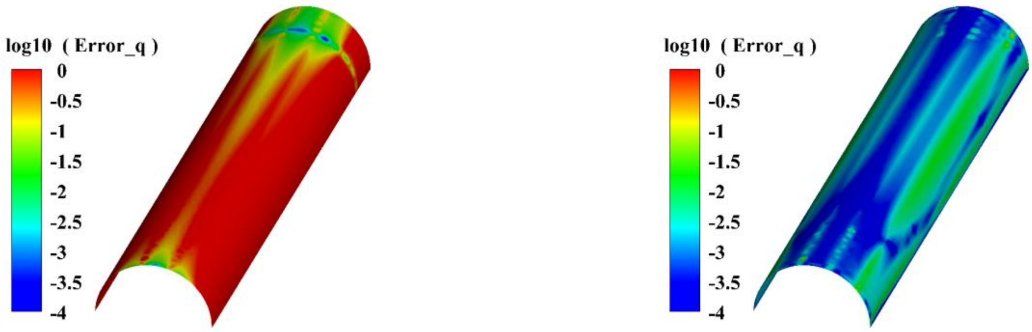


(a) Original coordinates

(b) PCA transformed coordinates

Figure 4 - Original coordinates and PCA transformed coordinates

Figure 5 shows the heat flux error contour obtained when the original RBF method and the improved RBF method proposed by this paper are used for interpolation. It can be seen from the figure that the error of the original RBF method is obviously much larger than that of the improved RBF method, especially in the middle area of the model. From Figure 5(a), it can be found that the error distribution obtained by the original method is basically around -2.5, while the error distribution obtained by the improved RBF method is basically around -3.5.



(a) Classic RBF (b) Improved RBF

Figure 5 - Interpolation error in solid domain

3. Verification Based on Complicated configuration cases

In this section, two hypersonic vehicle test cases will be used to test the robustness, accuracy and efficiency of the improved RBF data transfer method based on PCA. Multi-physics coupling phenomena including aerodynamic heat, displacement, and temperature fields often occur in hypersonic vehicles. Generally speaking, because the heat flux transfer needs to ensure the conservation of heat flux, the interpolation of heat flux is a most difficult point in the data transfer of hypersonic aircraft. Hence, this paper selects the heat flux interpolation of the hypersonic vehicle control surface and wing body model as verification cases for the improved RBF method. In previous work [24], TPS, MQ and CSC^2 are the most commonly used basis functions in data transfer. This part will analyze the influence of these basis functions on data transmission before and after improvement.

3.1 Control surface of hypersonic vehicle

Since the control surface of hypersonic aircraft has obvious coupling phenomenon during flight, this section selects this configuration as a test case for evaluation. Figure 6(a) shows the structural mesh of the fluid domain, which contains 4073 surface nodes. The unstructured mesh of the solid domain is shown in Figure 6(b), which contains 5317 surface nodes.

(a) Fluid domain mesh (b) Solid domain mesh

Figure 6 - Mesh of the hypersonic vehicle control surface

To simplify the accuracy assessment, heat flux distribution on the surface is given by Eq.(10). By this equation, we can easily calculate the ‘real’ heat flux value. If we have obtained the heat flux by interpolation, we can evaluate the error between the ‘real’ and interpolation obtained value directly. Even though the heat flux distribution is given by equation, it can typically represent the heat flux distribution characteristics under real flight conditions. As shown in Figure 7, the region with a larger heat flux gradient in this model is at the leading edge of the control surface and the heat flux is striped along the vertical direction of the leading-edge sweep.

$$q = 1.4 - \sqrt{\frac{x - 1.732y}{2.72}} \left(MW / m^2 \right) \tag{10}$$

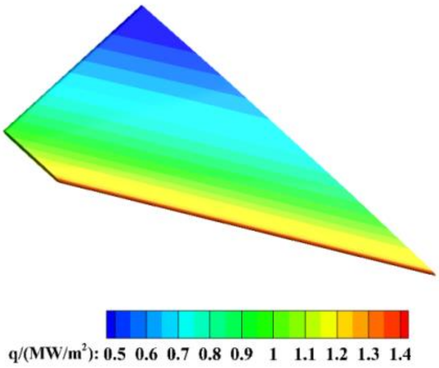
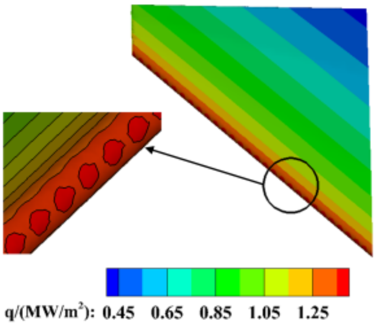


Figure 7 - Surface heat flux contour of fluid domain mesh

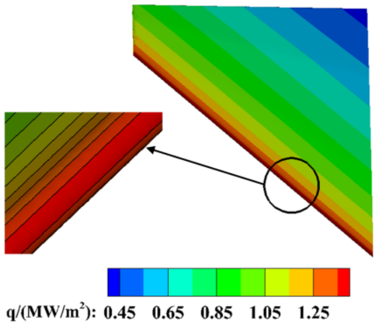
In this example, the true value of the surface heat flux in the fluid domain and the solid domain is calculated by Eq. (10). Therefore, when the data is transferred from the fluid domain to the solid domain, the heat flux error on the solid surface can be calculated by equation (11). As mentioned above, TPS interpolation method, MQ interpolation method and compactly supported base interpolation method will be used for data transfer.

$$q_{error} = \left| \frac{q_{real} - q_{interpolation}}{q_{real}} \right| \tag{11}$$

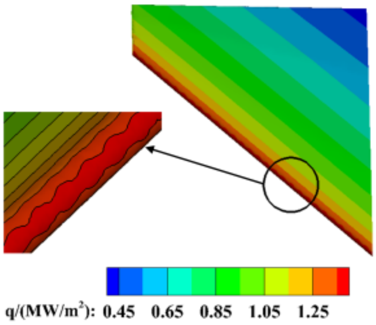
Figure 8 shows the heat flux distribution contour obtained by six different interpolation methods. From the figure, it can be found that the heat flux distribution obtained by interpolation is generally accurate regardless of the method, except for areas where the heat flux changes drastically at the leading edge of the control surface. For the heat flux distribution contour obtained by the three original RBF interpolation methods, irregular ripples will appear on the leading edge of the control surface, especially for the original MQ interpolation method. On one hand, the reason for this phenomenon is that the heat flux changes more drastically in the y and z directions and slowly in the x direction, so use isotropic radial basis function is inappropriate. On the other hand, x-y-z isn't the sharp change direction of heat flux, the heat flux changes along the vertical direction of the wing sweep and stays constant along the sweep direction. Moreover, the geometric shape of the mesh, such as the resolution difference of the grid in different directions, is also larger at the leading edge, resulting in a denser distribution of mesh nodes along the z-direction compared to the x-direction. Therefore, in the interpolation process, the selected nodes at a fixed radius can't truly reflect the characteristics of heat flux changes. On the contrary, the improved RBF method can increase the weight of nodes with similar physical quantities to eliminate this phenomenon.



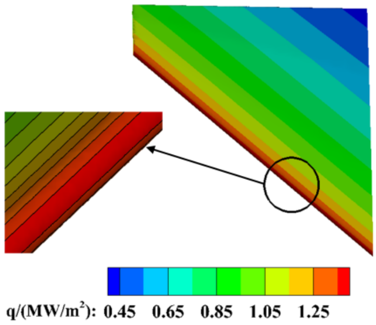
(a) Classic MQ



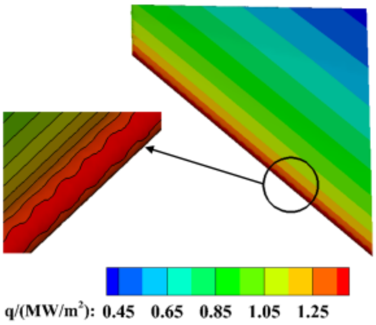
(b) Improved MQ



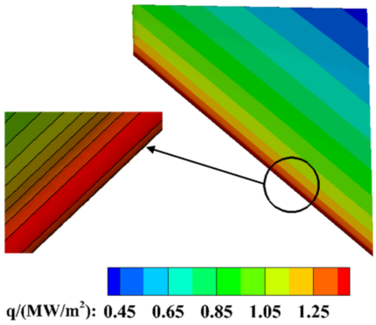
(c) Classic TPS



(d) Improved TPS



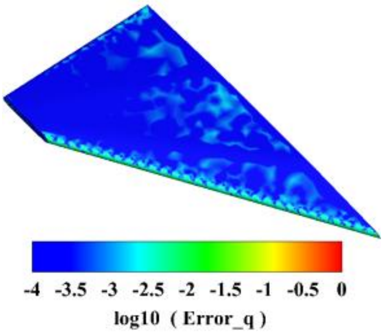
(e) Classic CSC^2



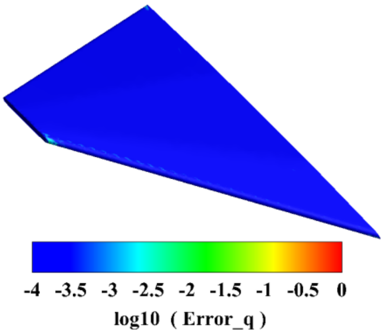
(f) Improved CSC^2

Figure 8 - Heat flux contours of solid domain mesh

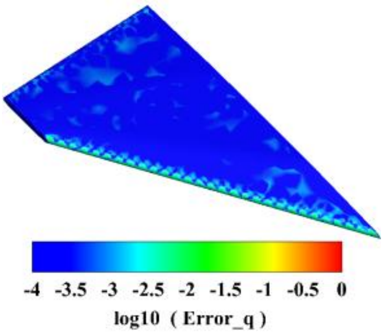
Figure 9 compares the heat flux error (logarithm to the base 10) distribution contour obtained by the six interpolation methods. Obviously, when the traditional RBF data transfer method is used, the heat flux error is distributed along the leading edge larger, while the error in other parts is smaller. As shown in Figure 8(a)(c)(e), the error of the leading edge is basically around -2. The difference is that Figure 8(b)(d)(f) shows that the interpolation error of both the leading edge of the control surface and the upper and lower surfaces is approximately -4.



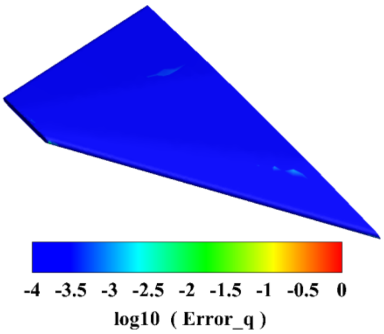
(a) Classic MQ



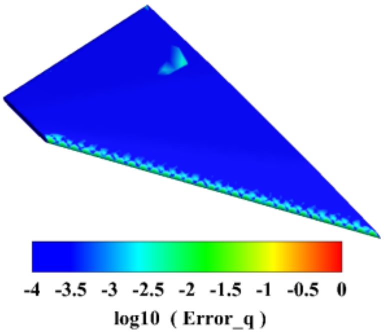
(b) Improved MQ



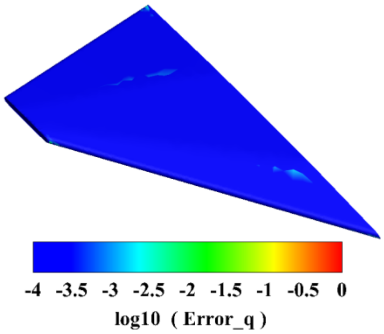
(c) Classic TPS



(d) Improved TPS



(e) Classic CSC2



(f) Improved CSC2

Figure 9 - Surface heat flux error contours

Figure 10 compares the maximum error and average error curves obtained by the original RBF interpolation method and the improved RBF interpolation method. From these two figures, it can be found that the improved RBF method is obviously better than the original RBF method. The average error of the original three RBF methods is basically around -3.5, while the average error of the improved three RBF interpolation methods is around -5, which is a drop of nearly two orders of magnitude in comparison. In addition, compared with the method based on physical quantity gradient correction in literature [26], the average error and maximum error distribution of this method are -4.81 and -1.79. Obviously, the error of the method in this paper is lower than that in literature [26].

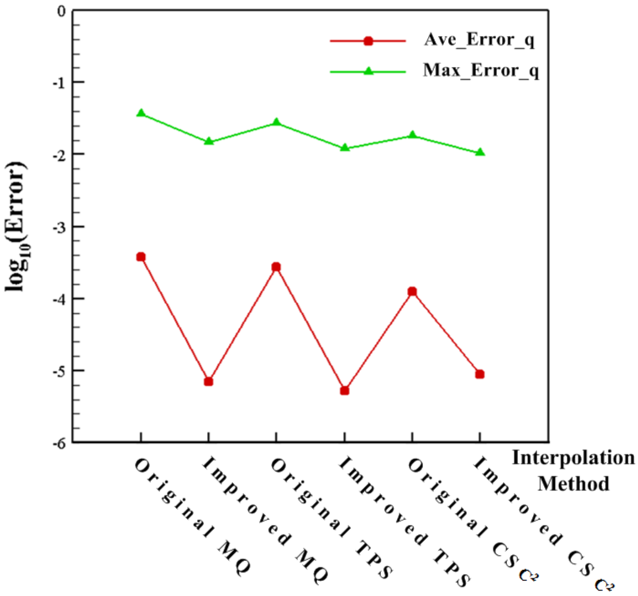


Figure 10 - Average error and Maximum error of six interpolation methods

3.2 Wing-body combination configuration

In this section, a wing-body combination configuration is used to test the interpolation efficiency of the improved TPS, MQ, CSC2 basis function and its practicality in the actual complex shape. As shown in Figure 11, the complex shape example is similar to X-37. The surface mesh generated in the fluid domain has 13216 nodes and the mesh generated in the solid domain has 5704 nodes. Using the flow field grid in Figure 11(a) to calculate the surface heat flux distribution shown in Figure 12, the calculated flow condition is Ma=8.84, $\alpha = 0^{\circ}$, $T_{wall} = 300k$. From Figure 12, it is obvious that the heat flux has a large gradient at the nose and the leading edge of the wings.

(a) Fluid domain mesh (b) Solid domain mesh

Figure 11 - Mesh of the Wing-body combination aircraft configuration

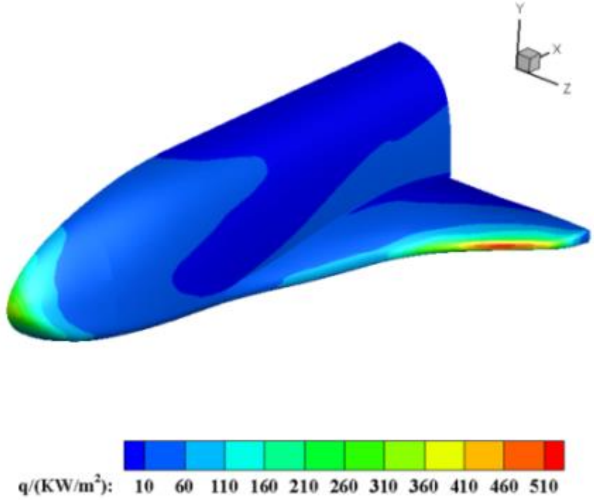
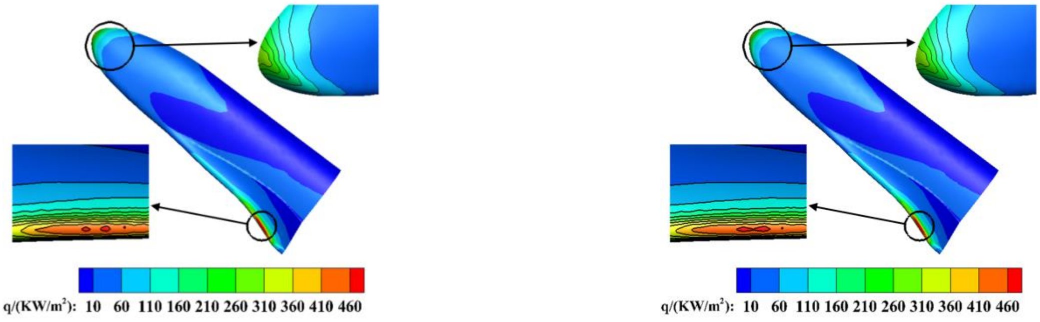
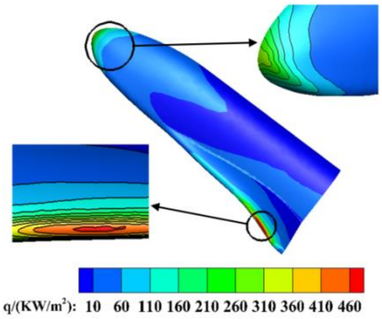


Figure 12 - Numerical simulation heat flux of fluid domain mesh

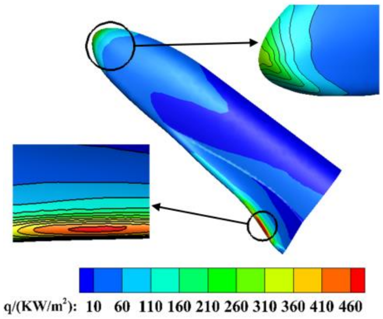
Figure 13 shows the heat flux distribution contour interpolated from the fluid domain to the solid domain. As shown in the figure, the six interpolation methods used in this article can more accurately capture the heat flux distribution on the surface of the aircraft. However, compared with the improved interpolation method, the original interpolation method cannot accurately capture the heat flux at the leading edge of the wing. From the heat flux contours in Figure 13(a)(c), it can be found that the heat flux distribution at the leading edge is relatively rough. Figure 13(e) shows that the contours of the original CSC^2 basis function at the leading edge are relatively smooth, but the contours at the nose and the middle of the fuselage of the aircraft are relatively rough. In contrast, Figure 13(f) shows that the improved CSC^2 basis function interpolation method can eliminate the irregular ripples at the nose and mid-section of the aircraft. As mentioned above, in areas such as the leading edge of the wing and the nose of the aircraft, the heat flux gradient is large, so the large anisotropy of the physical quantity gradient results in large errors in the original isotropic interpolation method. The results in Figure 13 show that the improved RBF method can consider the influence of various anisotropic factors, and can select more appropriate points to be interpolated in the uniform space to complete the interpolation and improve the accuracy.



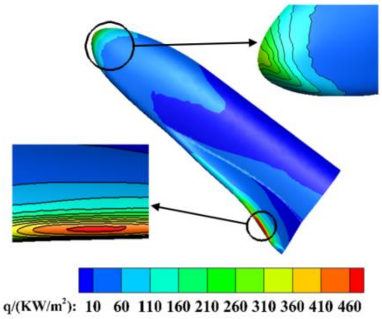
(a) Classic MQ (b) Improved MQ



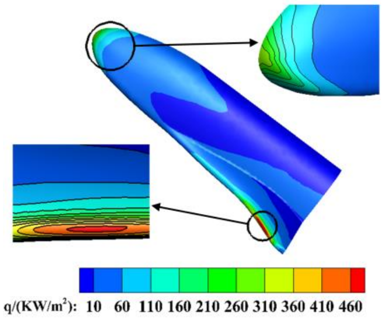
(c) Classic TPS



(d) Improved TPS



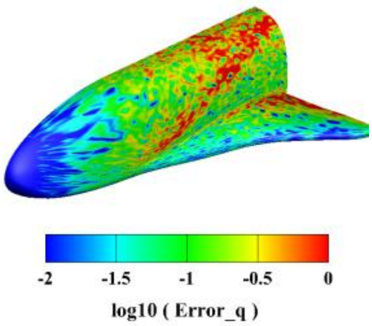
(e) Classic CSC^2



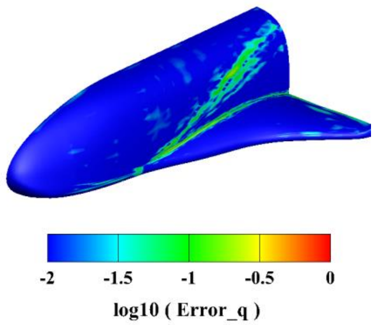
(f) Improved CSC^2

Figure 13 - Surface heat flux contours of solid domain mesh

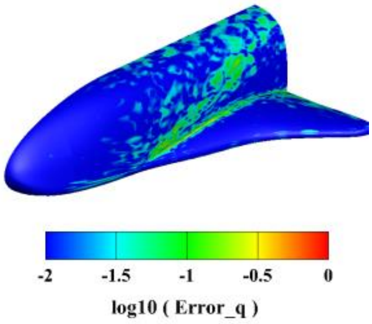
Figure 14 compares the errors of the original interpolation method and the improved interpolation method. Since there is no real heat flux distribution contour in the solid domain, in order to compare the errors of each interpolation method, this paper uses the same method to interpolate the heat flux in the solid domain back to the fluid domain. The error calculation formula is consistent with the formula in the previous section, where $q_{interpolation}$ is the data obtained by two interpolations, first transfer from the fluid domain to the solid domain, and then from the solid back to the fluid domain, and q_{real} is the original heat flux distribution. From Figure 14(a), it can be found that the heat flux error at the middle section of the aircraft fuselage is relatively large, but the interpolation results obtained by the improved MQ method show that the error at the middle section is greatly reduced, basically from -0.5 to -1.5. It can be seen from the figure that the interpolation effect of the CSC^2 basis function is very good, but the error at the nose is large, but when the improved compactly supported basis function method is used, the error at the nose can be eliminated well. Generally speaking, local RBF methods such as CSC^2 basis functions select fewer nodes than global RBF functions such as TPS, so this type of interpolation method is faster but not accurate. However, from the comparison of Figure 14(d) and Figure 14(f), the interpolation effect of the improved CSC^2 basis function is close to that of the improved TPS interpolation, indicating that the improved compactly supported basis function in this paper takes less time to implement a better interpolation effect.



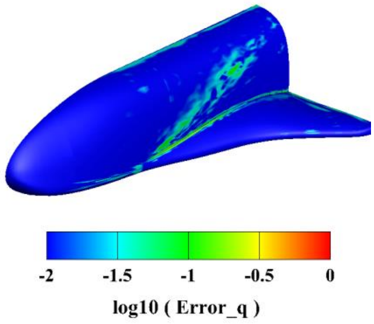
(a) Classic MQ



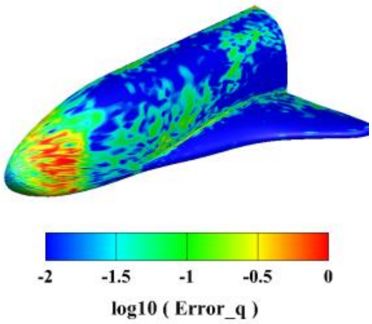
(b) Improved MQ



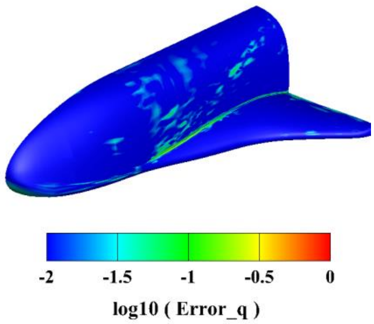
(c) Classic TPS



(d) Improved TPS



(e) CSC^2



(f) Improved CSC^2

Figure 14 – Surface heat flux error contours of fluid domain mesh

Figure 15 compares the maximum error and average error of the original RBF interpolation method and the improved interpolation method. It can be found from the red curve that the improved method is obviously better than the original method, especially for the improved MQ method and the improved CSC^2 basis function. The average error is much lower than the original method. The same phenomenon can be found in the green maximum error curve. The results show that the interpolation effect of the improved interpolation method is better than the original method in the process of data transfer of complex configuration. In addition, compared with the method based on physical quantity gradient correction in the literature [26], the method in this paper is lower than the maximum error in the literature.

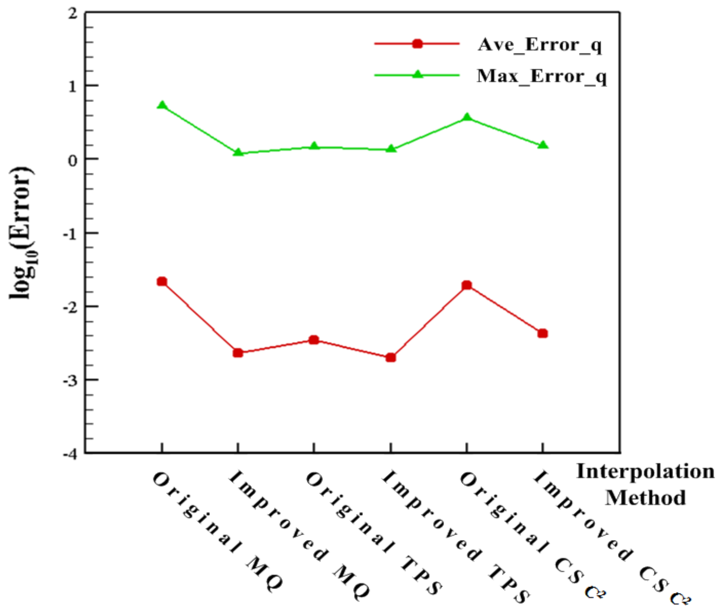


Figure 15 - Average error and Maximum error of six interpolation methods

4. Conclusion

An RBF data transfer method based on PCA geometric feature extraction was proposed and verified in this paper. Based on the previous geometric scale normalization method and gradient correction method, PCA was introduced into this method to eliminate the influence of the anisotropy of the geometric spatial structure of the grid. The improved RBF method was verified by the hypersonic control surface configuration and the wing-body combination configuration. The results show that the improved TPS, MQ, and CSC^2 basis function methods can effectively eliminate the oscillations in the interpolation caused by the large gradient of physical quantities at the local area such as leading edge and reduce the interpolation error by about two orders of magnitude. In addition, compared with the global RBF method, the improved CSC^2 basis function method can use fewer points which mean less time costs to achieve similar interpolation effects. Therefore, this method can be applied to multi-physics data transfer and has a good engineering prospect.

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6. Copyright Statement

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