INTERGRID TRANSFORMATION FOR AIRCRAFT AEROELASTIC SIMULATIONS

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Abstract

A transformation methodology is developed for complete aircraft aeroelastic computations. A Structural Dynamics Model based on a generic F16 aircraft has been used to study the intergrid transformation between the structural and fluid grids. A structural model with the fuselage modelled as 1D beam and the wings and the fin modelled as 2D shells is used to obtain the modal response. The Constant Volume Tetrahedron (CVT) is the transformation scheme used for communicating the deformation between the 2D structural components and the corresponding fluid surface components. A modified version of the CVT is used for the transformation between the 1D structural beam and the fuselage. A two level transformation scheme is applied and a hierarchical based blending function is applied at the component interfaces by which the fluid surface grid remains intact.

1 Introduction

The ability to treat realistic aircraft configurations needs to be demonstrated for computational aeroelasticity to realise its potential. One aspect which needs to be considered is the transformation between the fluid and structural grids. There are two aspects to this. First, there is a need to treat aerodynamic and structural surfaces which are offset due to simplifications in the structural model. Secondly, multi-components need to be transformed without introducing holes in the aerodynamic surface.

To illustrate the difficulty of simplified structural geometries, consider modelling a wing by a plate for structural purposes. Applying the well known IPS method [1] the aerodynamic points are projected onto the plate. The spline matrix is then used to transform the projected points and finally the aerodynamic points are recovered by adding the original out-of-plane displacement to the new positions for the projected points. The problem with this approach is with the out-plane treatment, as illustrated in Figure 1 from [3]. A distortion is introduced which increases with the size of the rotation. It was this problem which motivated the development of the BEM based method in [5]. This method copes very naturally with mismatching surfaces. An isoparametric mapping familiar from finite element analysis is not applicable when the surfaces do not coincide.

A second issue identified as important, and also arising from structural simplifications, is when the plate planform does not match that of the wing. This arises when the load bearing wing box is used to define the structural plate. It was shown in [3] that extrapolation beyond the definition of the plate should be linear and using the IPS introduces a spurious camber into the wing which can seriously change the dynamical and static response. The transformed mode shapes used in [6] were constructed with this consideration in mind.

The work presented in Farhat [7] used a detailed FEM model for the F16 which conforms fully to the true geometry used for the aerodynamic grid. This means that the isoparametric mapping is a natural and successful method for the transformation and the complex geometry does not introduce any additional complication. The BEM method in principal can also deal with a complex geometry without complication.

Melville [6] applied predefined mode shapes to deal specifically with a complete aircraft configuration. He noted some errors in the reconstructed geometry, probably arising from the reconstruction via mode shapes. However, the strength and insight of the method is the definition of a hierarchy of components and the use of this to match transformed components, avoiding holes.

An important consideration is that complete aircraft models will involve large CFD and CSD grids. The practicality of the method is therefore crucial. For the example presented in this paper there are 13 thousand fluid points on the aircraft ($n_a = 13000$) and 1700 structural points ($n_s = 1700$).

For the IPS method a matrix defining the transformation must be stored. The number of elements in this matrix is $9 \times n_a \times n_s$, which means around 200 million non-zeros for the example in the next chapter. The BEM method requires even more memory. The isoparametric and Melville methods do not suffer from this overhead.

When the structural and aerodynamic surface grids are defined on the same surface then the use of an isoparametric mapping is entirely satisfactory, as shown in the work of Farhat [7]. However, when the structural model is built from simplified components, as is the normal practice in industry, then a completely satisfactory transformation for large displacements is not available. First, IPS and BEM based methods require large amounts of memory. It is also not clear how to apply the IPS method over the different components without introducing a mismatch between components. The method of Melville copes well with the complex geometry but the accuracy for each component individually was called into question.

There is therefore a need for a cheap and precise transformation method for aircraft geometries. This is the subject of the current paper.

2 Constant Volume Tetrahedron

2.1 Original 2D CVT

The CVT scheme is a transformation technique proposed in [3]. A surface element consisting of the three nearest structural grid points $\mathbf{x}_{s,i}(t)$, $\mathbf{x}_{s,j}(t)$ and $\mathbf{x}_{s,k}(t)$ to a given fluid grid point $\mathbf{x}_{a,l}(t)$ is identified (refer Figure (2)). Once the structural grid points are identified and associated with the fluid grid point the position of $\mathbf{x}_{a,l}$ is given by the expression

$$\mathbf{c} = \alpha\mathbf{a} + \beta\mathbf{b} + \gamma\mathbf{d} \tag{1}$$

where $\mathbf{a} = \mathbf{x}_{s,j} - \mathbf{x}_{s,i}$, $\mathbf{b} = \mathbf{x}_{s,k} - \mathbf{x}_{s,i}$, and $\mathbf{d} = \mathbf{a} \times \mathbf{b}$. From the above the constants α, $\beta$and γ are calculated as

$$\alpha = \frac{|\mathbf{b}|^2(\mathbf{a}.\mathbf{c}) - (\mathbf{a}.\mathbf{b})(\mathbf{b}.\mathbf{c})}{|\mathbf{a}|^2|\mathbf{b}|^2 - (\mathbf{a}.\mathbf{b})(\mathbf{a}.\mathbf{b})} \tag{2}$$

$$\beta = \frac{|\mathbf{a}|^2(\mathbf{b}.\mathbf{c}) - (\mathbf{a}.\mathbf{b})(\mathbf{a}.\mathbf{c})}{|\mathbf{a}|^2|\mathbf{b}|^2 - (\mathbf{a}.\mathbf{b})(\mathbf{a}.\mathbf{b})} \tag{3}$$

$$\gamma = \frac{(\mathbf{c}.\mathbf{d})}{|\mathbf{d}|^2} \tag{4}$$

The position of the fluid grid point $\mathbf{x}_{a,l}$ is denoted by the sum of the in-plane component $\alpha\mathbf{a} + \beta\mathbf{b}$ and out of plane component $\gamma\mathbf{d}$ which is normal to the plane of the structural points. The volume of the tetrahedron is given by

$$V = \frac{(\mathbf{a}.\mathbf{b} \times \mathbf{c})}{4} \tag{5}$$

As the volume of the tetrahedron remains constant the fluid grid position is given by

$$\mathbf{x}_{a,l} = \mathbf{x}_{s,i}(t) + \alpha\mathbf{a}(t) + \beta\mathbf{b}(t) + \gamma(t)\mathbf{d}(t) \tag{6}$$

with α and β fixed at their initial values and γ calculated as

$$\gamma(t) = \frac{|\mathbf{d}(0)|^2}{|\mathbf{d}(t)|^2}\gamma(0). \tag{7}$$

Equation (7) means that the projection of the fluid grid point on the structural element moves linearly with the structural element where the out of plane component is chosen to conserve the volume of the tetrahedron. If the fluid and the structural points are planar then the expression reduces to linear interpolation for the position of the fluid point. Equation (6) can be expressed in a linearised form as follows

$$\delta\mathbf{x}_{a,l} = \mathbf{A}\delta\mathbf{x}_{s,i} + \mathbf{B}\delta\mathbf{x}_{s,j} + \mathbf{C}\delta\mathbf{x}_{s,k} \tag{8}$$

$$\begin{aligned}
\mathbf{A} &= \mathbf{I} - \mathbf{B} - \mathbf{C} \\
\mathbf{B} &= \alpha I - \gamma\mathcal{U}\mathcal{V}(\mathbf{b}) \\
\mathbf{C} &= \beta I + \gamma\mathcal{U}\mathcal{V}(\mathbf{a}) \\
\mathcal{U} &= I - \frac{2}{d^2}\mathcal{D}(\mathbf{d})\mathcal{S}(\mathbf{d})
\end{aligned} \tag{9}$$

$$\mathcal{V}(\mathbf{z}) = \begin{pmatrix} 0 & -z_3 & z_2 \\ z_3 & 0 & -z_1 \\ -z_2 & z_1 & 0 \end{pmatrix} \tag{10}$$

$$\mathcal{D}(\mathbf{z}) = \begin{pmatrix} z_1 & 0 & 0 \\ 0 & z_2 & 0 \\ 0 & 0 & z_3 \end{pmatrix} \tag{11}$$

$$\mathcal{S}(\mathbf{z}) = \begin{pmatrix} z_1 & z_2 & z_3 \\ z_1 & z_2 & z_3 \\ z_1 & z_2 & z_3 \end{pmatrix} \tag{12}$$

To maintain the accuracy of the linearised CVT the linearisation is updated at the latest fluid and surface grid positions i.e. after each update of the structural position during aeroelastic calculations. Hence the values of $\mathbf{a}$, $\mathbf{b}$, and $\mathbf{c}$ are calculated at the latest grid positions.

It was found in [3] that the linearisation error introduced can significantly effect the static and dynamic responses computed. Therefore, the matrices $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ are updated every time the surface is moved so that the linearisation can be considered as being about the latest fluid and structural positions. The values of the transformed deflections have to be interpreted accordingly. This method is found to give geometrically identical results to using the full nonlinear method. The cost of computing the matrices is very small compared to the flow solution itself.

This method has previously been tested for the aeroelastic response of isolated wings. The extension to complete aircraft configurations is considered in the following sections.

2.2 1D Version of the CVT

For structural components modelled as 1 dimensional beams (eg. the fuselage in this work) the CVT transformation does not work without some modification. In the original CVT, to form a tetrahedron 3 structural points forming a triangle are required. For an undeformed 1D beam element this is not possible as the structural points do not form a plane. One possible solution would be to create a structural triangle by adding in a fictitious point close to one of the structural nodes so that the two nodes of the beam element along with the fictitious point forms a triangular element. When the structure deforms the displacement of this fictitious point is calculated as equal to the displacement of the real structural point closest to it i.e. it undergoes only translation without adjusting the relative position to the bending of the fuselage. In the current work the method described above has been used for transformation of the fuselage for Structural Model 3. A fictitious third point for the structural grid was introduced for each 1D beam element. This point had the same x and z coordinates as one of the two points forming the 1D element. The y coordinate of the fictitious point has a unit more than that of the original point. Figure (3) shows the 1D structural element formed by the points $\mathbf{x}_{s,j}$, $\mathbf{x}_{s,i}$ and the fictitious structural point $\mathbf{x}_{s,k}$.

$$\mathbf{x}_{s,k} = \mathbf{x}_{s,i} + \hat{\mathbf{j}} \tag{13}$$

where $\hat{\mathbf{j}}$ is a unit vector in the direction of the y-axis. The triangular element formed is then used in the conventional CVT technique as described in section 2. This technique gives pure translation to the fluid points . No rotation is introduced, consistent with the motion of the points on the beam (refer Figure (4)). Consider the deformation of the node $\mathbf{x}_{s,i}$ which can be written as

$$\mathbf{x}^1_{s,i} = \mathbf{x}^0_{s,i} + \delta\mathbf{x}_{s,i} \tag{14}$$

where the superscript 1 and 0 represent the deformed and undeformed states of the structural nodes. The deformed fictitious node can then be calculated as

$$\mathbf{x}^1_{s,k} = \mathbf{x}^0_{s,k} + \delta\mathbf{x}_{s,i} \tag{15}$$

3 Complete Aircraft Test Case

3.1 The CAD Model

Transformation is tested on the Structural Dynamics Model (SDM) obtained from the Institute of Aerospace Studies-Canada [4]. The SDM model was originally constructed for experimental studies on fin buffet, and the dimensions are similar to a scaled down version of the F16 aircraft. The computational model constructed was scaled up again to realistic aircraft dimensions. The SDM CAD model was supplied in the form of 2D AUTOCAD drawings. A number of stages was involved before a final CAD model was obtained from these 2D drawings. Also geometrical approximations were made by ignoring the engine inlet, the two vertical fin like projections below the back end of the fuselage and the exact shape of the canopy. When carrying out these approximations we have tried to make a demonstration case which is representative of a fighter aircraft to test the transformation methods but which avoids complications during CFD mesh generation.

3.2 The Structural Model

Computational aeroelastic analysis involves two grids i.e. the fluid grid and the structural grid. The fluid grid is constructed over the actual profile of the model whereas the structural grid can be a simplified version of the actual geometry. The structural grid is usually simplified because a reasonably good structural representation can be obtained using 2D shells and beams which are much easier to assemble and computationally cheaper for aeroelastic analysis. The current study is aimed at testing the transformation scheme on a basic aircraft configuration devoid of external stores, control surfaces etc. To test the transformation techniques the structural model has the fuselage modelled as a 1D beam. An FEM grid was constructed for the structural models using PATRAN. The 1D beam was discretized into two node elements and the 2D surfaces into triangular elements. It is important that the 2D surfaces have triangular elements as the CVT scheme uses a triangle on the structural grid and a node on the fluid surface grid to form a tetrahedron for transformation. The FEM grid was preprocessed in PATRAN and analyzed in the FEM solver ABAQUS for the modal frequencies. It is usually the case that the higher vibrational modes are not important for the prediction of the onset of flutter. Usually the third anti-symmetric mode is the most significant mode. The first 4 modes of vibration were retained here to demonstrate the transformation scheme. These modes include the first and second fuselage bending modes and the first symmetric and anti-symmetric bending modes for the wings. It should be stressed that the current work is not based on prediction of onset of flutter or simulation of flutter but on developing an effective technique for the transformation between the structural and fluid grids to enable such a simulation to be carried out in future. The material properties used here for the structural response are arbitrary and fulfill the need of providing realistic mode shapes although these are not exact frequencies as reported by Melville [6]. The values used for the structural model are given in Table (1) . Figure (5) shows the modal deformation of the structural model on which the transformation was carried out.

3.3 The CFD Grid

The grid generation software ICEM-HEXA was used to generate a multiblock structured grid for the flow simulation. An O-grid blocking strategy is applied around the aircraft with the fuselage as the core and the blockings over the wings and tail plane formed by collapsing radial lines around the component. The proposed transformation technique was tested on a fluid surface grid of 12200 points extracted from a coarse volume grid of 650000 points.

4 Transformation for Complete Aircraft

A version of the CVT is required which can do the transformation for a complete aircraft with the minimum of manual intervention and which preserves the surface mesh, particularly at junctions between components. The insight for the method is provided by the paper of Melville [6] which treats the aircraft components in a hierarchy.

The first stage of the method is to partition the fluid and structural points into levels associated with components. The primary component is the fuselage since all the other parts of the aircraft are connected to it. The fluid and structural grid points on the fuselage are therefore designated as being of level 1. Next, the wings, tail planes and fin are connected to the fuselage and the fluid and structural grid points on these components and the fuselage are designated level 2. The idea of the hierarchy is that level 2 points have a primary motion due to the fact that they are connected to the fuselage and a secondary motion due to their own elasticity. Extra components attached to the wing, such as fuel tanks and stores would be designated level 3, with their primary motion being due to the fact that they are attached to the wing.

At this stage a number of subsets of points has been defined for the fluid and structural grids, with one subset for each level. Denote the set of aerodynamic points in level m as $\mathcal{A}^m$ and the structural points as $\mathcal{S}^m$. The lowest level (2 in this case) contains all of the points in the respective grids and level $m-1$ is a subset of level m.

The first stage for the CVT as described above is to associate each fluid point with three structural points. This is done in practice by defining a triangularisation of the structural grid and then searching for the nearest centroid to each aerodynamic point. This mapping can be done over the structural points in each level as well, defining level one and two mappings. In the current case the level one mapping has all points in the fluid grid driven only by points on the fuselage. The level two mapping is equivalent to the original CVT method applied to all grid points without restriction. The transformation of a wing bending mode is shown in Figure (6) using successively the first and second level mappings. The first level mapping leads to the fluid grid motion following the fuselage, with the wings being moved in a rigid fashion. The second level mapping introduces the wing bending as well, with the motion of the fuselage being identical to that arising from the first level mapping.

A problem with the level two mapping arises at junctions between components. This is illustrated in Figure (7). A second problem arises where the fin is attached to the fuselage, as shown in Figure (8). For the level two mapping the nodes off the fuselage are being driven by a different transformation from those actually on the junction, which are driven by the fuselage. This leads to a small but disastrous distortion of the grid in the junction regions. Using the level one mapping treats all points in a consistent way and maintains the grid quality in the junction regions as a result. However, the level one mapping misses all effects introduced by the elasticity of the non-fuselage components, since these structural components are not used to drive the fluid surface grid. A new method is therefore needed to correctly transform the complete deformation while avoiding the problems at junctions.

The basis for the method is derived from the observation that the level one and two transformed mode shapes on level two components in regions close to the fuselage are almost identical. This follows from the observation of Melville [6] that the fuselage drives the wing motions and this effect is dominant close to the wing root as opposed to any wing alone elastic effects. The method therefore blends the level one and two transformed fluid points, giving priority to the level one transformation as we approach the fuselage (in general the level m transformation is given priority as the level m component is approached). This means that in the junction region the fluid grid is transformed from the fuselage structural model rather than the wing.

Denote the transformed deflection for a fluid point $\mathbf{x}_{a,l}$ using the mth level mapping as $\delta\mathbf{x}^m_{a,l}$. The blending used to give the final transformed displacement is given as

$$\delta\mathbf{x}_{a,l} = \Sigma^n_{m=1} w_{m,l}\delta\mathbf{x}^m_a. \tag{16}$$

The weights for the blending $w_{m,1}$ must add to one. To define the values of the weights for level m we need to consider the distance from the components associated with that level. Define the nearest distance of the point $\mathbf{x}_{a,l}$ to all of the points in level m by $d_{m,l}$. It is a simple matter to calculate $d_{m,l}$ by searching over the fluid points defined in level m for the nearest point. If $\mathbf{x}_{a,l}$ actually belongs to level m then $d_{m,l} = 0$. Then, the weights for blending the two levels of transformation in the current test case are computed from

$$w_{1,l} = e^{-10 d_{m,l}} \tag{17}$$

and

$$w_{2,l} = 1 - w_{1,l}. \tag{18}$$

For points on the fuselage the entire weight will be put on the fuselage driven transformation, for points close to the fuselage most weight will be given to the fuselage driven transformation and otherwise most weight is given to the level two component driven transformation. The exponential function was found to be suitable for the current test case but some experimentation with functions for other cases may be required. The comparison between the transformed fourth mode using the blended transformation and the level two transformation is shown in Figure (9) indicating that there is little difference between the two. However, looking to the junction region, the blended transformation has avoided the folded grid as required. Also, the fin now remains cleanly attached to the fuselage as opposed to the level two transformation. Since the cost of computing the original CVT transformation is small, the cost of applying the new multi-level scheme is also small. On cost grounds there is an objection to using the exponential function in the weighting but the weights are calculated as part of a preprocessing step so this is insignificant.

5 Results

The two level transformation was applied on the the Structural Models described in the previous section and the transformed mode shapes were checked for any irregularities in the surface grid smoothness that may cause problems during the time marching aeroelastic calculations. There was no undesirable roughness in the transformed aircraft surface grid found. The two level transformation results for the first four modes are shown in Figure (10).

6 Conclusion

A successful transformation methodology for a complete aircraft configuration was developed and applied. A two level weighting methodology was developed and successfully applied with the CVT transformation technique to give transformed fluid surface grids without any damage to the grids at component interfaces. A number of cases were studied (fuselage modelled as a 2D plate for example), the results for which are not presented in this publication, for the effect of fuselage twist on the transformation and the ability of the weighting scheme to handle this. The transformation method worked satisfactorily for all the test cases.

References

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[2] Goura, G.S.L., Badcock, K.J., Woodgate, M.A. and Richards, B.E., Implicit Method for the Time Marching Analysis of Flutter, Aeronautical Journal, volume 105, number 1046, April, 2001.

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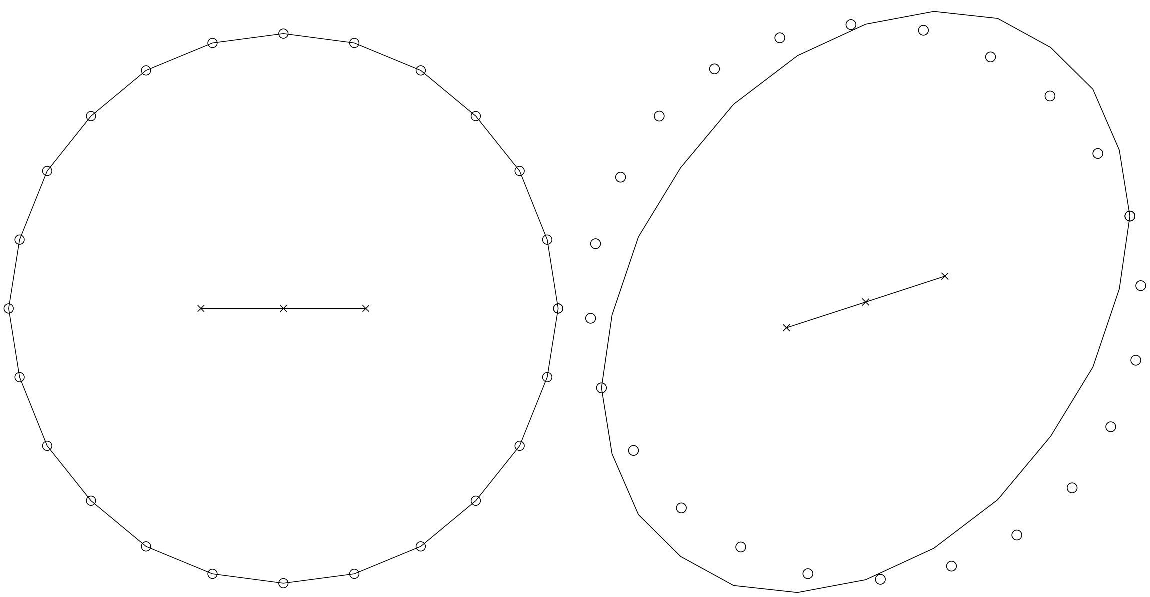
Member	Dimension	Thickness or Radius (m)	Material Density(kg/m^3)	Elasticity Modulus(Pa)
Wing	2D Plate	0.1	700	5×10^{10}
Vertical Fin	2D Plate	0.1	700	5×10^{10}
Tail Plane	2D Plate	0.1	700	5×10^{10}
Fuselage	1D Beam	0.3	250	2×10^{11}

Table 1: Material and Dimensional Properties of the Components



(a) Initial

(b) 0.1π

Figure 1: Rigidly rotated circle. Solid lines are the recovered fluid points by IPS [3]

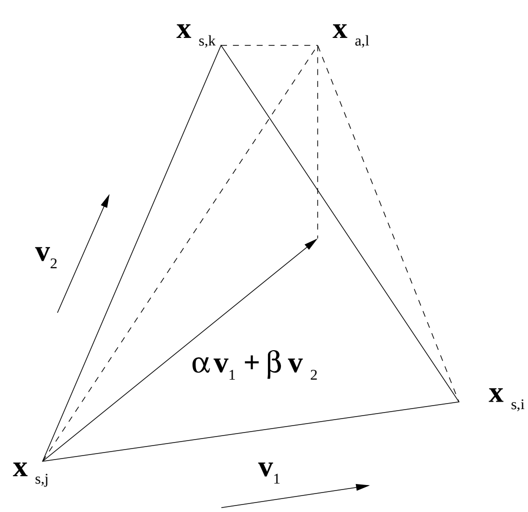


Figure 2: The Constant Volume Tetrahedron (from [3])

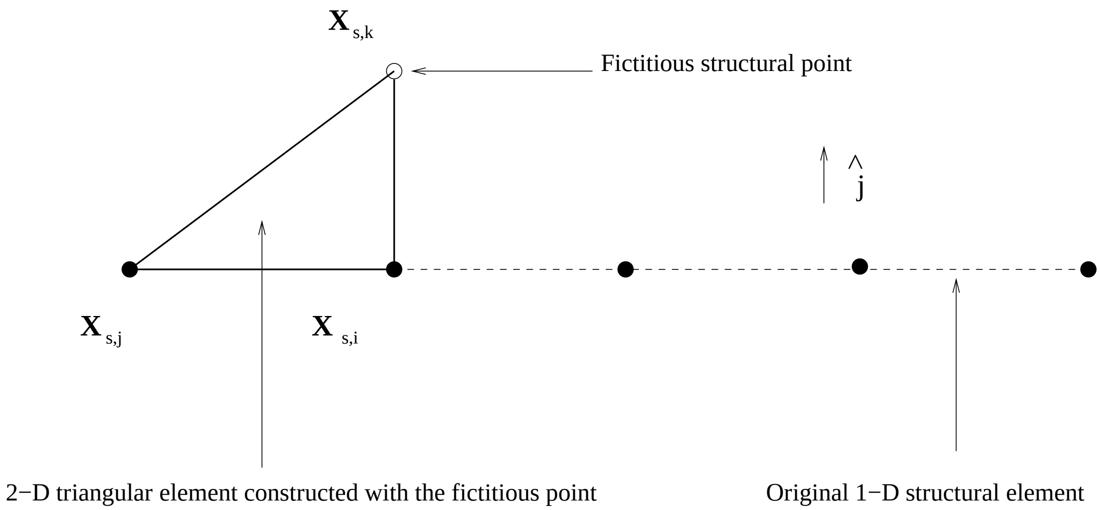


Figure 3: The 1D CVT fictitious point

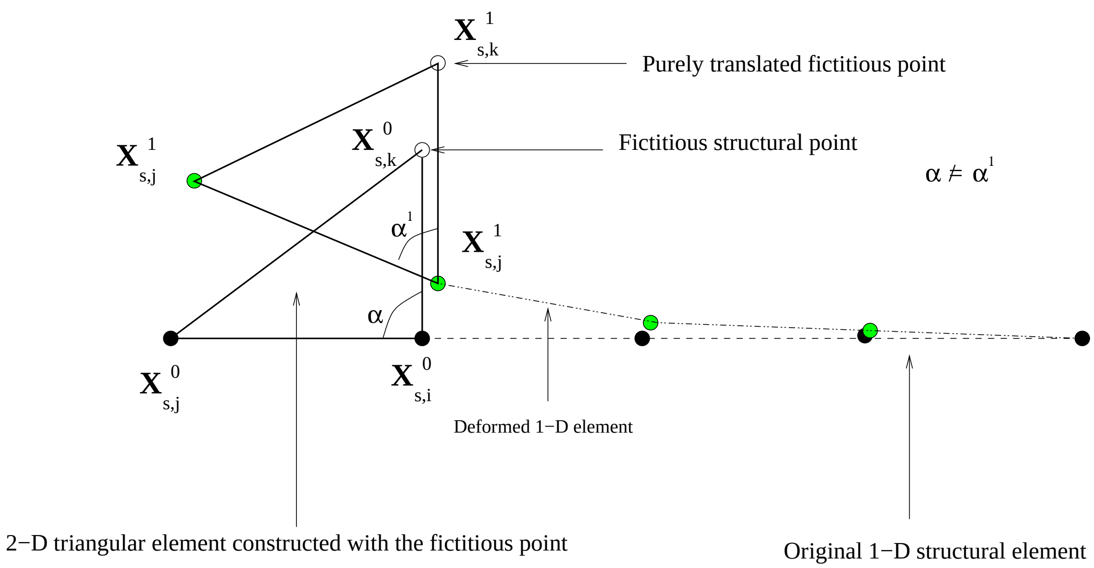
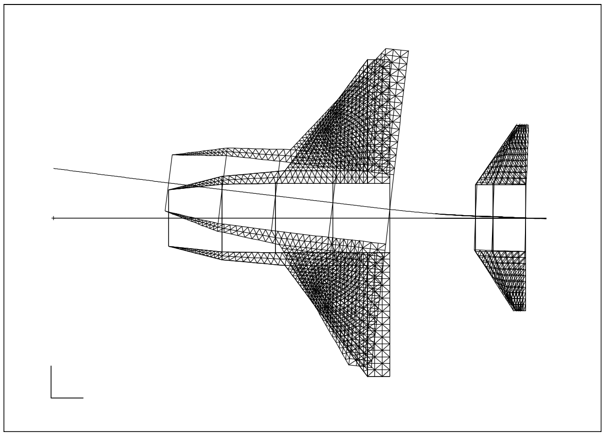
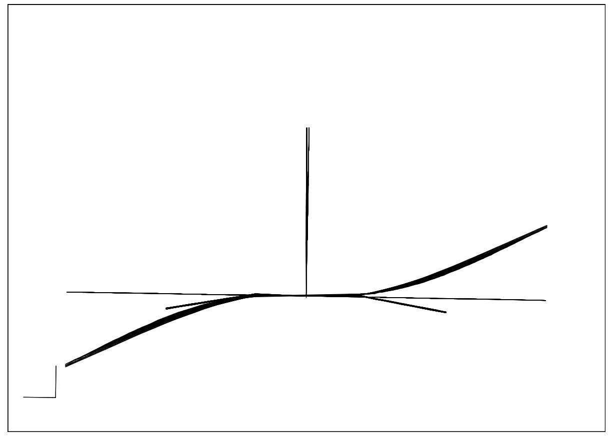


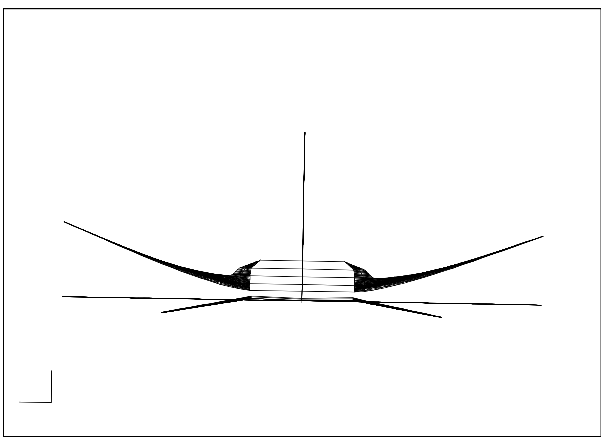
Figure 4: Translation of the 1D CVT element



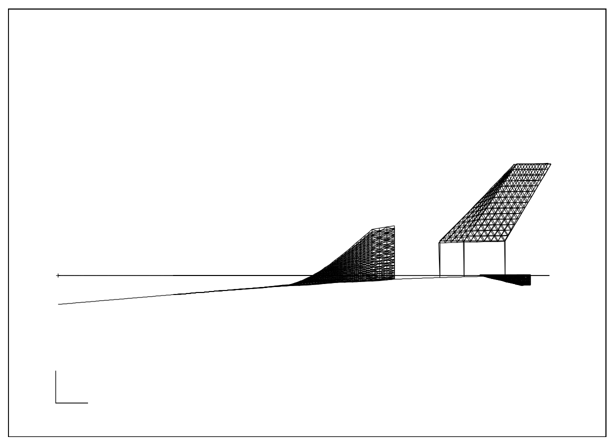
(a) Fuselage Lateral Bending



(b) Wing Antisymmetric

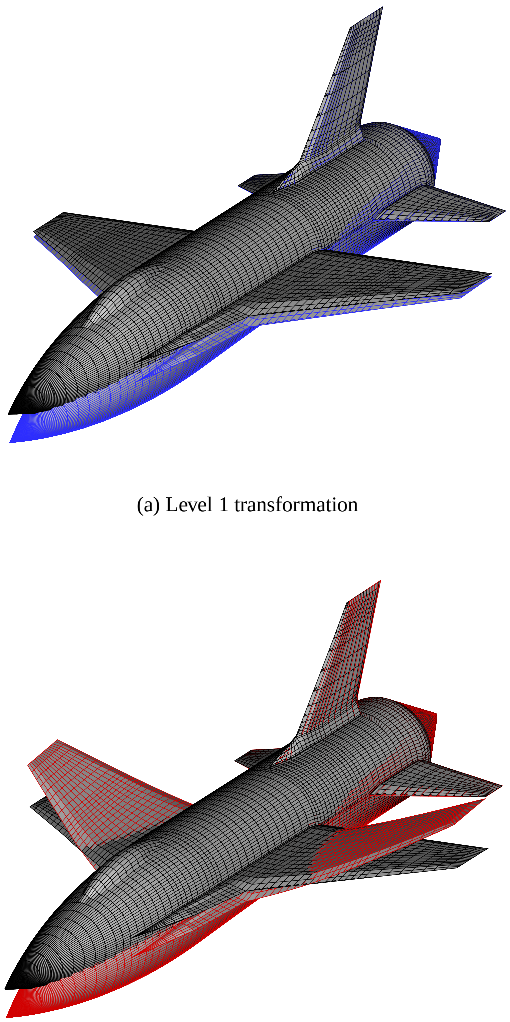


(c) Wing Symmetric



(d) Fuselage Vertical Bending

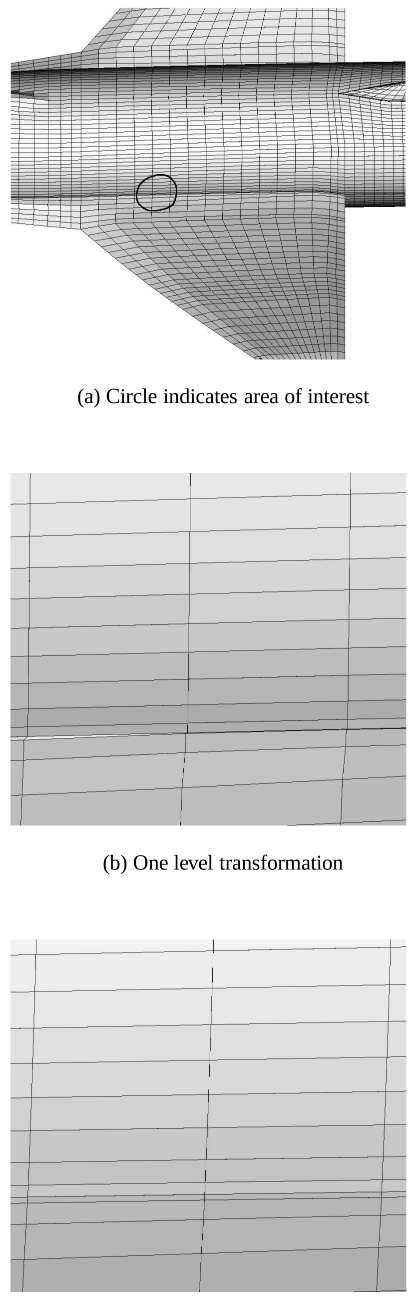
Figure 5: Natural mode shapes of the structural model



(a) Level 1 transformation

(b) Level 2 blended transformation

Figure 6: Transformation for the 4th mode

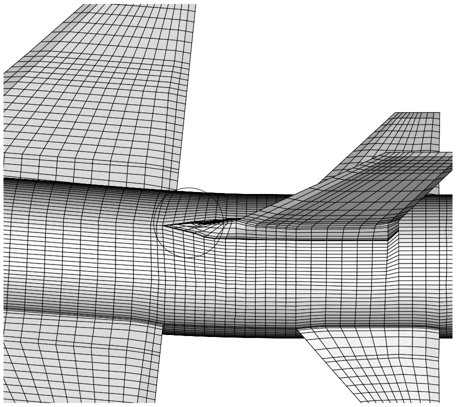


(a) Circle indicates area of interest

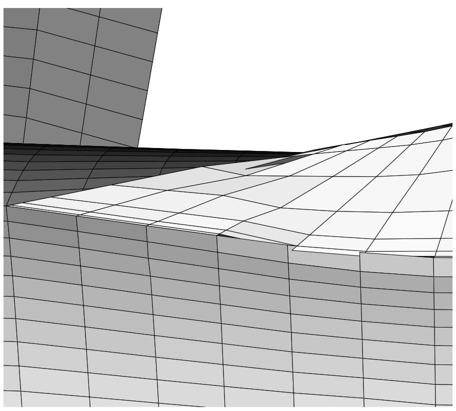
(b) One level transformation

(c) Two level blended transformation

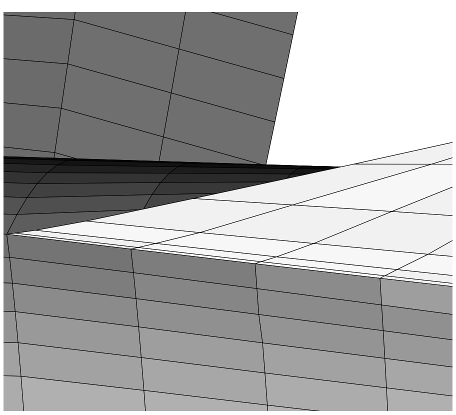
Figure 7: Fuselage wing interface close-ups



(a) Circle indicates area of interest

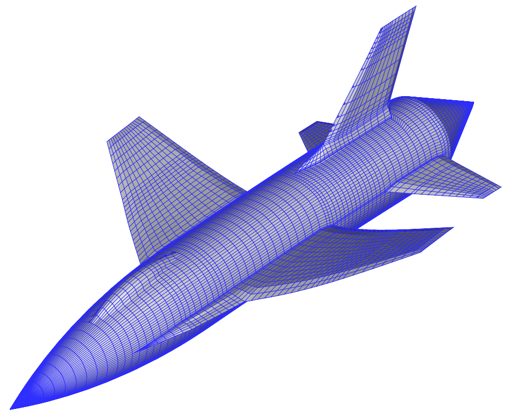


(b) One level transformation

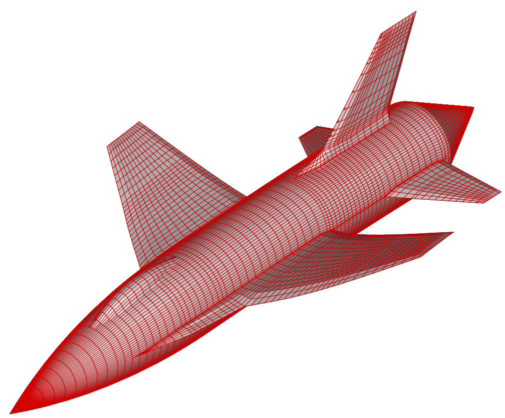


(c) Two level blended transformation

Figure 8: Fuselage vertical fin interface close-ups

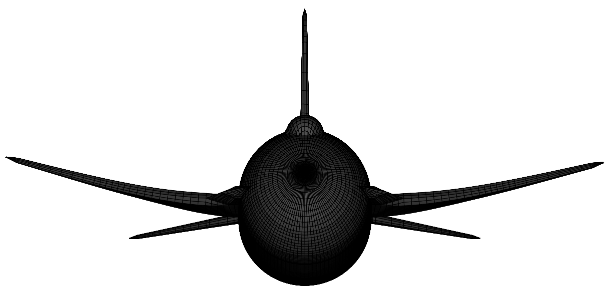


(a) Level 2 transformation without blending at the interface

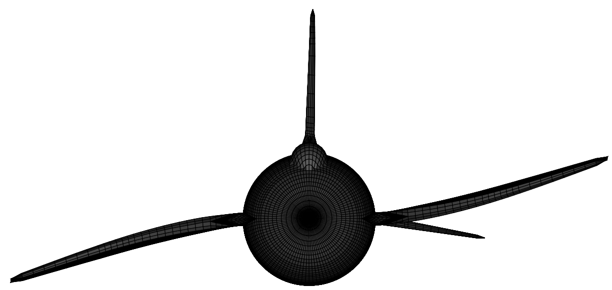


(b) Level 2 transformation with blending at the interface

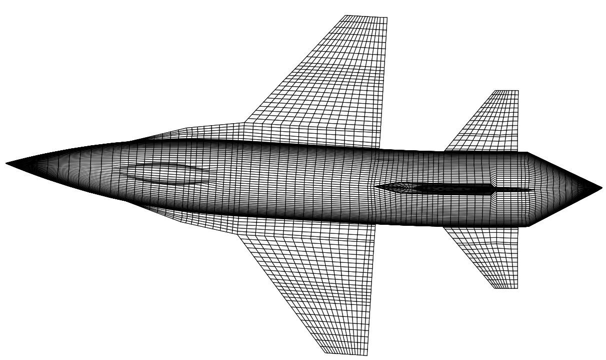
Figure 9: Blended and unblended level 2 transformations for the 4th mode



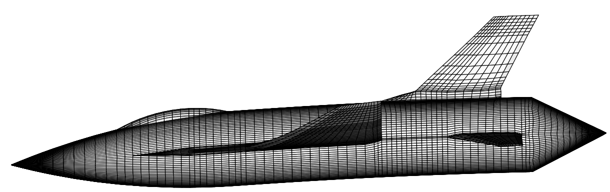
(a) Wing Symmetric



(b) Wing Antisymmetric



(c) Fuselage Lateral Bending



(d) Fuselage Vertical Bending

Figure 10: Transformed mode shapes of the structural model