An orthogonal surface-oriented coordinate system has been developed for three-dimensional flows where the computational domain normal to the surface is small. With this restriction the coordinate system requires orthogonality only at the body surface. The coordinate system is as follows: one coordinate measures distance normal to the surface while the other two coordinates are defined by an orthogonal mesh on the surface. One coordinate is formed by the intersection of the body surface and the meridional planes as illustrated in Figure 1 and gives the $\theta = \text{constant}$ lines. The other coordinate $\xi$, which is nondimensionalized with a characteristic length of the body geometry, measures the distance along the body surface when $\theta = 0$. This coordinate system has been utilized in boundary layer flows and for the hypersonic viscous shock-layer problem.

Two methods have been developed for generating the surface coordinates. The first method uses the orthogonal condition in finite-difference form to determine the surface coordinates with the metric coefficients and curvature of the coordinate lines calculated numerically. The second method obtains analytical expressions for the metric coefficients and for the curvature of the coordinate lines. Both methods assume the body surface is defined in terms of a cylindrical coordinate system where $r = r(x, \theta)$. The surface inclinations $\phi_1$ and $\phi_2$ as illustrated in Figure 2 are determined from

$$ \tan \phi_1 = \left( \frac{3r}{3x} \right)_\theta \quad \text{and} \quad r \tan \phi_2 = -\left( \frac{3r}{3x} \right)_x $$

and are known quantities.

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In the numerical method,\textsuperscript{1,2} the orthogonal condition for the surface coordinates results in the relation
\[ dx = \lambda \, d\theta \] (along \( \zeta \) = constant)
where
\[ \lambda = r \tan \phi_1 \tan \phi_2 / (1 + \tan^2 \phi_1) \]
The equation of the surface provides the relation
\[ dr = \tan \phi_1 \, dx - r \tan \phi_2 \, d\theta \]

The surface coordinate \( \zeta \) is determined numerically from the foregoing equations by assuming a value of \( d\theta \) and marching away from \( \theta = 0 \) to determine the values of \( x \) and \( r \). In addition the metric coefficients are determined numerically from
\[ h_\zeta = ds/d\zeta \]
\[ h_\omega = dt/d\omega \]
where
\[ \omega = \theta / 2\pi \]
\[ ds^2 = dx^2 + dr^2 \]
\[ dt^2 = ds^2 + r^2 d\theta^2 \]

The curvature of the coordinate lines is determined from
\[ K_\zeta = \frac{1}{h_\zeta h_\omega} \frac{\partial h_\zeta}{\partial \omega} \] for \( \omega = \) constant
\[ K_\omega = \frac{1}{h_\zeta h_\omega} \frac{\partial h_\omega}{\partial \zeta} \] for \( \zeta = \) constant

with the derivatives replaced with midpoint difference relations.

In the second method\textsuperscript{3}, an analytical expression is developed for \( h_\omega \) as follows:
\[ h_\omega = 2\pi r (1 + \cos^2 \phi_1 \tan^2 \phi_2)^{1/2} \]

A differential equation results for the other metric coefficient as follows:
\[ \frac{1}{h_\zeta} \frac{d h_\zeta}{d\omega} = 2\pi \cos^2 \phi_1 \tan \phi_2 \left( \frac{3\phi_1}{\phi_2} \right) \]

This equation is integrated along \( \xi = \) constant lines on the surface from the initial condition \( h_\zeta = 1 \) at \( \theta = 0 \). The substitution of foregoing equations into the equations for \( K_\zeta \) and \( K_\omega \) give analytical expressions for the curvature of the coordinate lines. In evaluating these relations, the variations of \( x \) and \( \theta \) along the \( \zeta = \) constant coordinate must be known.

A sphere at angle of attack as shown in Figure 3 is used to illustrate the computation of the surface coordinates with both methods. The surface coordinates on the sphere as viewed from the side are illustrated in Figure 4. The \( \xi = \) constant lines result from planes intersecting the sphere with these planes passing through the line which is normal to the plane of symmetry and is located at
\[ x/a = \sqrt{1 - (b/a)^2} \]
\[ y/a = (x/a)^2 / (b/a) \]

The metric coefficients for this coordinate system are given in Figures 5 and 6 with good agreement between the two methods. The curvature of the coordinate lines is given in Figures 7 and 8. It is noteworthy that \( K_\zeta \) is independent of \( \xi \). The differences evidenced in Figure 8 can be partially attributed to the numerical evaluation of \( K_\omega \) being at one-half mesh space locations away from the \( \xi \) indicated.

The numerical method of generating the orthogonal surface coordinates has been applied to ellipsoids, paraboloids and elliptical paraboloids. The coordinates on an ellipsoid are illustrated in Figure 9. The second method or analytical approach has only been developed for the sphere.
Figure 3. Cylindrical Coordinate System for "Sphere at Angle of Attack".

Figure 4. Coordinates on a Sphere (\(\alpha = 30^\circ\))

Figure 5. Variation of Metric Coefficient \(h_{e}\).

Figure 6. Variation of Metric Coefficient \(h_{w}\).
Figure 7. Geodesic Curvature of Lines of Constant θ.

Figure 8. Geodesic Curvature of Lines of Constant θ.

Figure 9. Surface Coordinates on Ellipsoid (b/a = 1/4)

References:

