AE/ME 339 Computational Fluid Dynamics (CFD)

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Grid Generation (Chapter 5)

The basic idea behind grid generation is the creation of the transformation laws between the physical space and the computational space.

These laws are known as the *metrics* of the transformation.

We have already performed a simple grid generation without realizing it for the flow over a heated wall when we used the τ, ξ, η coordinates for the numerical scheme. This was simply a transformation from one rectangular domain to another rectangular domain.

Grid Generation (Chapter 5)

Quality of the CFD solution is strongly dependent on the quality of the grid.
Why is grid generation necessary? Figure 5.1(next slide) can be used to explain.
Note that the standard finite difference methods require a uniformly spaced rectangular grid.
If a rectangular grid is used, few grid points fall on the surface.
Flow close to the surface being very important in terms of **forces**, **heat transfer**, etc., a rectangular grid will give poor results in such regions.
Also uniform grid spacing often does not yield accurate solutions.

Typically, the grid will be closely spaced in boundary layers.

Rectangular grid on curved boundary.
Few grid points lie on the boundary

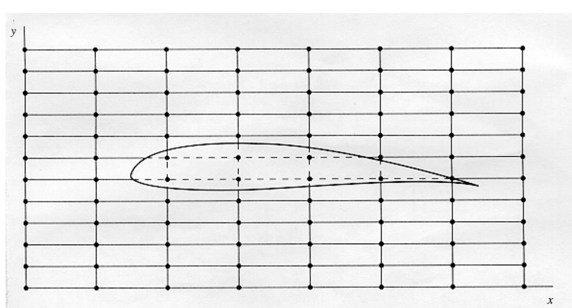

FIG. 5.1
An airfoil in a purely rectangular grid.

Figure shows a physical flow domain that surrounds the body and the corresponding rectangular flow domain.
Note that if the airfoil is cut and the surface straightened out, it would form the ξ-axis.
Similarly, the outer boundary would become the top boundary of the computational domain.
The left and right boundaries of the computational domain would represent the cut surface.
Note the locations of points a, b, and c in the two figures.

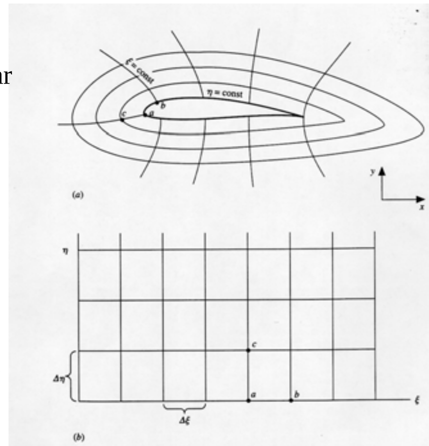

FIG. 5.2
Schematic of a boundary-fitted coordinate system. (*a*) Physical plane; (*b*) computational plane.

Note:
in the physical space the cells are not rectangular and the grid is not uniformly spaced.
There is a one-to-one correspondence between the physical space and the computational space. Each point in the computational space represents a point in the physical space.

The procedure is as follows:
1. Establish the necessary transformation relations between the physical space and the computational space
2. Transform the governing equations and the boundary conditions into the computational space.
3. Solve the equations in the computational space using the uniformly spaced rectangular grid.
4. Perform a reverse transformation to represent the flow properties in the physical space.

General Transformation Relations

Consider a two-dimensional unsteady flow with independent variables t, x, y.

The variables in the computational domain are represented by τ, ξ, η, and The relations between the two sets of variables can be represented as follows.

$$\tau = \tau(t) \ldots\ldots\ldots\ldots(5.1c)$$

$$\xi = \xi(x, y, t) \ldots\ldots\ldots\ldots(5.1a)$$

$$\eta = \eta(x, y, t) \ldots\ldots\ldots\ldots(5.1b)$$

The derivatives appearing in the governing equations must be transformed using the chain rule of differentiation.

$$\left(\frac{\partial}{\partial x}\right)_{y,t} = \left(\frac{\partial}{\partial \xi}\right)_{\eta,\tau}\left(\frac{\partial \xi}{\partial x}\right)_{y,t} + \left(\frac{\partial}{\partial \eta}\right)_{\xi,\tau}\left(\frac{\partial \eta}{\partial x}\right)_{y,t} + \left(\frac{\partial}{\partial \tau}\right)_{\xi,\eta}\left(\frac{\partial \tau}{\partial x}\right)_{y,t}$$

The subscripts are used to emphasize significance of the partial derivatives and they will not be included in the equations that follow.

$$\left(\frac{\partial}{\partial x}\right)=\left(\frac{\partial}{\partial \xi}\right)\left(\frac{\partial \xi}{\partial x}\right)+\left(\frac{\partial}{\partial \eta}\right)\left(\frac{\partial \eta}{\partial x}\right) \qquad (5.2)$$

$$\left(\frac{\partial}{\partial y}\right)=\left(\frac{\partial}{\partial \xi}\right)\left(\frac{\partial \xi}{\partial y}\right)+\left(\frac{\partial}{\partial \eta}\right)\left(\frac{\partial \eta}{\partial y}\right) \qquad (5.3)$$

$$\left(\frac{\partial}{\partial t}\right)_{x,y}=\left(\frac{\partial}{\partial \xi}\right)_{\eta,\tau}\left(\frac{\partial \xi}{\partial t}\right)_{x,y}+\left(\frac{\partial}{\partial \eta}\right)_{\xi,\tau}\left(\frac{\partial \eta}{\partial t}\right)_{x,y}+\left(\frac{\partial}{\partial \tau}\right)_{\xi,\eta}\left(\frac{\partial \tau}{\partial t}\right)_{x,y} \qquad (5.4)$$

$$\left(\frac{\partial}{\partial t}\right)=\left(\frac{\partial}{\partial \xi}\right)\left(\frac{\partial \xi}{\partial t}\right)+\left(\frac{\partial}{\partial \eta}\right)\left(\frac{\partial \eta}{\partial t}\right)+\left(\frac{\partial}{\partial \tau}\right)\left(\frac{\partial \tau}{\partial t}\right) \qquad (5.5)$$

The first derivatives in the governing equations can be transformed using Eqs. (5.2), (5.3) and (5.5).

The coefficients of the transformed derivatives such as the ones given below are known *metrics*.

$$\frac{\partial \xi}{\partial x}, \frac{\partial \xi}{\partial y}, \frac{\partial \eta}{\partial x}, \frac{\partial \eta}{\partial y}$$

Similarly, chain rule should be used to transform higher order derivatives. Example:

$$\frac{\partial^2}{\partial x^2}=\left(\frac{\partial}{\partial \xi}\right)\left(\frac{\partial^2 \xi}{\partial x^2}\right)+\left(\frac{\partial}{\partial \eta}\right)\left(\frac{\partial^2 \eta}{\partial x^2}\right)+\left(\frac{\partial^2}{\partial \xi^2}\right)\left(\frac{\partial \xi}{\partial x}\right)^2 + \left(\frac{\partial^2}{\partial \eta^2}\right)\left(\frac{\partial \eta}{\partial x}\right)^2+2\left(\frac{\partial^2}{\partial \eta \partial \xi}\right)\left(\frac{\partial \eta}{\partial x}\right)\left(\frac{\partial \xi}{\partial x}\right) \qquad (5.9)$$

Metrics and Jacobian (5.3)
In CFD, the metric terms are not often available as analytical expressions. Instead they are often represented numerically.
The following inverse transformation is often more convenient to use than the original transformation

$$x = x(\xi,\eta,\tau)\text{..........................}(5.18a)$$

$$y = y(\xi,\eta,\tau)\text{............................}(5.18b)$$

$$t = t(\tau)\text{.............................}(5.18c)$$

Let x = x(ξ, η), y = y(ξ, η) and u = u(x, y).
then we can write

$$du = \frac{\partial u}{\partial x}dx + \frac{\partial u}{\partial y}dy\text{.................................}(5.19)$$

$$\frac{\partial u}{\partial \xi} = \frac{\partial u}{\partial x}\frac{\partial x}{\partial \xi} + \frac{\partial u}{\partial y}\frac{\partial y}{\partial \xi}\text{............................}(5.20)$$

$$\frac{\partial u}{\partial \eta} = \frac{\partial u}{\partial x}\frac{\partial x}{\partial \eta} + \frac{\partial u}{\partial y}\frac{\partial y}{\partial \eta}\text{............................}(5.21)$$

Eqs. (5.21) and (5.22) are two equations for the two unknown derivatives.

i3

Solving for the partial derivate w. r. t. x gives (using **Cramer's** i1 **rule**)

$$\frac{\partial u}{\partial x} = \frac{\begin{vmatrix} \frac{\partial u}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial u}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{vmatrix}}{\begin{vmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{vmatrix}} \text{..................................(5.22)}$$

Define the Jacobian, J, as

$$J \equiv \frac{\partial(x,y)}{\partial(\xi,\eta)} \equiv \begin{vmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{vmatrix} \text{................................(5.22}a\text{)}$$

$$\frac{\partial u}{\partial x} = J^{-1}\left[\left(\frac{\partial u}{\partial \xi}\right)\left(\frac{\partial y}{\partial \eta}\right) - \left(\frac{\partial u}{\partial \eta}\right)\left(\frac{\partial y}{\partial \xi}\right)\right] \text{............................(5.23}a\text{)}$$

Similarly we can write the derivative w.r.t y as

$$\frac{\partial u}{\partial y} = J^{-1}\left[\left(\frac{\partial u}{\partial \eta}\right)\left(\frac{\partial x}{\partial \xi}\right) - \left(\frac{\partial u}{\partial \xi}\right)\left(\frac{\partial x}{\partial \eta}\right)\right] \text{............................(5.23}b\text{)}$$

and we can define the following

$$\frac{\partial}{\partial x} = J^{-1}\left[\left(\frac{\partial}{\partial \xi}\right)\left(\frac{\partial y}{\partial \eta}\right) - \left(\frac{\partial}{\partial \eta}\right)\left(\frac{\partial y}{\partial \xi}\right)\right] \text{............................(5.24}a\text{)}$$

$$\frac{\partial}{\partial y} = J^{-1}\left[\left(\frac{\partial}{\partial \eta}\right)\left(\frac{\partial x}{\partial \xi}\right) - \left(\frac{\partial}{\partial \xi}\right)\left(\frac{\partial x}{\partial \eta}\right)\right] \text{............................(5.24}b\text{)}$$

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i1 Cramer's Rule: The solution vector x of a system of linear equations $Ax = c$ with the regular matrix of coefficients A is uniquely determined by:
$x_i = \text{Det } A_i / \text{Det } A$.
Where A_i denotes the matrix obtained from the coefficient matrix A by replacing the ith column by the vector of constants c.
Not efficient for systems with more than 3 equations.
isaac, 11/1/2003

i3 isaac, 10/27/2004

The formal procedure for the transformtions would be as follows:

$$\xi = \xi(x, y) \text{........................} (5.25a)$$

$$d\xi = \frac{\partial \xi}{\partial x} dx + \frac{\partial \xi}{\partial y} dy \text{.................................} (5.26a)$$

$$\eta = \eta(x, y) \text{........................} (5.25b)$$

$$d\eta = \frac{\partial \eta}{\partial x} dx + \frac{\partial \eta}{\partial y} dy \text{.................................} (5.26b)$$

$$\begin{bmatrix} d\xi \\ d\eta \end{bmatrix} = \begin{bmatrix} \frac{\partial \xi}{\partial x} & \frac{\partial \xi}{\partial y} \\ \frac{\partial \eta}{\partial x} & \frac{\partial \eta}{\partial y} \end{bmatrix} \begin{bmatrix} dx \\ dy \end{bmatrix} \text{......................................} (5.27)$$

Similarly

$$x = x(\xi, \eta) \text{..................................} (5.28a)$$

$$y = y(\xi, \eta) \text{..................................} (5.28b)$$

$$dx = \frac{\partial x}{\partial \xi} d\xi + \frac{\partial x}{\partial \eta} d\eta \text{.................................} (5.29a)$$

$$dy = \frac{\partial y}{\partial \xi} d\xi + \frac{\partial y}{\partial \eta} d\eta \text{.................................} (5.29b)$$

$$\begin{bmatrix} dx \\ dy \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \eta} \end{bmatrix} \begin{bmatrix} d\xi \\ d\eta \end{bmatrix} \text{...................} (5.30)$$

Eq. (5.30) can be solved for dξ, dη

$$\begin{bmatrix} d\xi \\ d\eta \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \eta} \end{bmatrix}^{-1} \begin{bmatrix} dx \\ dy \end{bmatrix} \text{..................(5.31)}$$

Compare Eqs. (5.27) and (5.31)

$$\begin{bmatrix} \frac{\partial \xi}{\partial x} & \frac{\partial \xi}{\partial y} \\ \frac{\partial \eta}{\partial x} & \frac{\partial \eta}{\partial y} \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \eta} \end{bmatrix}^{-1} \qquad (5.32)$$

Using results from matrix algebra for inversion of matrices, RHS can be written as follows i2

$$\begin{bmatrix} \frac{\partial \xi}{\partial x} & \frac{\partial \xi}{\partial y} \\ \frac{\partial \eta}{\partial x} & \frac{\partial \eta}{\partial y} \end{bmatrix} = \frac{\begin{bmatrix} \frac{\partial y}{\partial \eta} & -\frac{\partial x}{\partial \eta} \\ -\frac{\partial y}{\partial \xi} & \frac{\partial x}{\partial \xi} \end{bmatrix}}{\begin{vmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \eta} \end{vmatrix}} \text{...........................(5.33)}$$

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i2 Replace matrix elements by the determinants of the complementary matrices, following the alternating sign rule and transpose. And divide by the determinant of the original matrix.

isaac, 10/27/2004

Since the determinants of a matrix and its transpose are the same we can write

$$\begin{vmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial x}{\partial \eta} \\ \frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \eta} \end{vmatrix} = \begin{vmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{vmatrix} \equiv J \text{............................(5.34)}$$

Substitute Eq. (5.34) into Eq. (5.33)

$$\begin{bmatrix} \frac{\partial \xi}{\partial x} & \frac{\partial \xi}{\partial y} \\ \frac{\partial \eta}{\partial x} & \frac{\partial \eta}{\partial y} \end{bmatrix} = \frac{1}{J} \begin{bmatrix} \frac{\partial y}{\partial \eta} & -\frac{\partial x}{\partial \eta} \\ -\frac{\partial y}{\partial \xi} & \frac{\partial x}{\partial \xi} \end{bmatrix} \text{.................................(5.35)}$$

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Comparing corresponding elements of the two matrices on the LHS and the RHS gives the following relations.

$$\frac{\partial \xi}{\partial x} = \frac{1}{J}\frac{\partial y}{\partial \eta} \text{..............................(5.36}a\text{)}$$

$$\frac{\partial \eta}{\partial x} = -\frac{1}{J}\frac{\partial y}{\partial \xi} \text{..............................(5.36}b\text{)}$$

$$\frac{\partial \xi}{\partial y} = -\frac{1}{J}\frac{\partial x}{\partial \eta} \text{..............................(5.36}c\text{)}$$

$$\frac{\partial \eta}{\partial y} = \frac{1}{J}\frac{\partial x}{\partial \xi} \text{..............................(5.36}d\text{)}$$

The above procedure can be easily extended to three dimensions.