



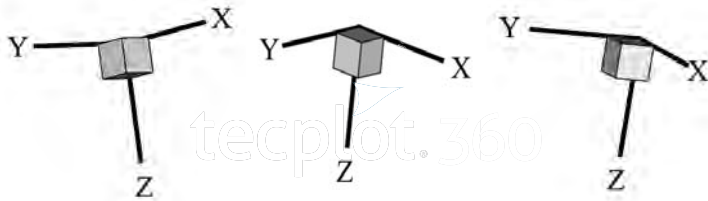
## White Paper

# Translation Between Common Aerodynamic Coordinate Systems: Visualization and Analysis of Heterogeneous Data

## Heterogeneous Data

*[het-er-uh-jee-nee-uh s, -jee-n-yuh s] [dey-tuh, dat-uh, dah-tuh]*

Related data from different sources, modeling different components of the design. Sources may include simulation codes like computational fluid dynamics (CFD), finite-element (FEM) structural mechanics, or experimental tests.



Gordon Moore's famous 1965 law,<sup>1</sup> which presaged the doubling of processing power every two years, has driven an astonishing level of technological development for more than a generation.

One benefit of the massive increases in computer power has been the rapid drop in the cost of running simulation codes such as computational fluid dynamics (CFD) or finite-element methods (FEM) for structural mechanics.

The codes themselves also have matured to the point where engineers are confident they can depend on them for the bulk of their analysis and computer simulations, making them the dominant tools in the engineering design process. However, a couple of well-known weaknesses of CFD computer simulations—such as inadequate turbulence modeling and poor prediction of vehicle drag—continue to require validation by wind tunnel tests. As a result, engineers find themselves constantly wrestling with a mix of data from different sources.

The visualization and analysis of this heterogeneous data is complicated by the wide diversity of formats, units, and coordinate systems used by the various simulation codes and experimental facilities.

<sup>1</sup> Moore, Gordon E., "Cramming more Components onto Integrated Circuits," *Electronics Magazine*, pp4, 1965.

The basic steps for analyzing this kind of heterogeneous data are:

- 1. Load the desired data set into the visual analysis software.** The formats and contents of CFD, FEM, and experimental data files are quite diverse. With a few notable exceptions, formats are not completely self-describing and are generally binary. The user must ensure that variables are appropriately mapped to obtain a useful analysis and visualization.
- 2. Modify the data for consistent units (English or Metric).** Data may be in English or metric units or be non-dimensional. For direct comparisons it is often necessary to convert the data to consistent units.
- 3. Transform the data (translate and rotate) to create consistent coordinate systems.** Engineers typically use three coordinate systems in vehicle analysis: body coordinates, wind coordinates, and stability coordinates. Comparing heterogeneous data sets requires that they all be transformed to the same coordinate system.
- 4. Analyze and visualize.** Solve and visualize your results using a CFD visualization software application.

As you might guess, a couple of the steps described here are reasonably easy; a couple of them are not. This paper focuses one of the more difficult tasks: transforming the data for consistent coordinate systems, commonly called "Coordinate System Registration."



## Coordinate System Registration

The most difficult part of analyzing and visualizing heterogeneous data is registering the data to a consistent coordinate system. A vehicle analysis example, specifically a large jet, is used in this paper to illustrate how

### Body Coordinates

CFD and FEM are nearly always in body coordinates. The only requirement for body coordinates is that they are fixed to the body, move with the body, and are independent of far-field flow conditions. In the most common body coordinate system used for aerodynamics (Figure 1) the origin is at an approximate center of gravity:

- The  $x_B$  coordinate points in the general direction of the nose of the aircraft.
- The  $z_B$  coordinate points downward, normal to  $x_B$ , in the plane of symmetry.
- The  $y_B$  is perpendicular to  $x_B$  and  $z_B$  and points in the general direction of the right wing tip.

Different analyses may use different body coordinate systems. For example, a CFD analysis may be in the body coordinates described above while the FEM analysis may have an origin and axis alignment that is more meaningful for those evaluating the structure. To get a consistent coordinate system may require translation and rotation of the coordinate systems for one or both of the analyses.

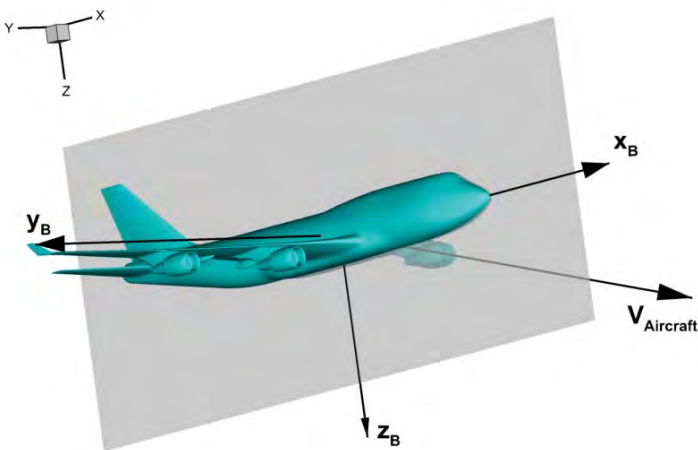


Figure 1: Body Coordinates

### Wind Coordinates

Aerodynamic data from wind tunnels is generally in wind coordinates (Figure 2), where the:

- $x_W$  coordinate is aligned with the far-field velocity.
- The  $z_W$  coordinate points downward, perpendicular to  $x_W$ , and in the plane of symmetry.
- The  $y_W$  coordinate is perpendicular to  $x_W$  and  $z_W$  the general direction of the right wing tip.

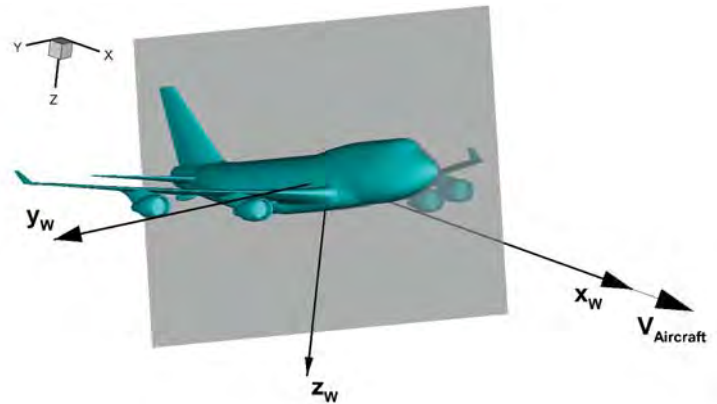


Figure 2: Wind Coordinates



## Stability Coordinates

In the stability and control, the coordinate system commonly used is called "stability coordinates." A hybrid between the body coordinates and wind coordinates (Figure 3), the:

- The  $x_s$  coordinate is aligned with the projection vehicle velocity on the vehicle plane of symmetry.
- The  $z_s$  coordinate is perpendicular to the  $x_s$  coordinate and in the plane of symmetry.
- The  $y_s$  coordinate is perpendicular to  $x_s$  and  $z_s$  pointed in the general direction of the right wing tip.

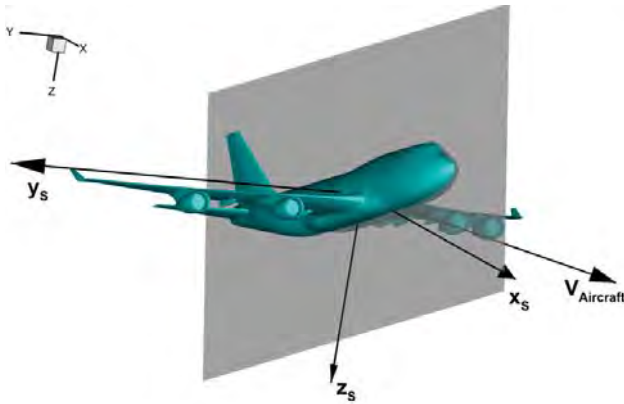


Figure 3: Stability Coordinates

In our case, we define the yaw angle  $\beta$  as positive when the aircraft velocity is pointing to the left wing of the airplane. Others may define it as positive when the velocity is pointing toward the right wing, and the formulas for coordinate transformations will need to be modified accordingly.

The angle-of-attack  $\alpha$  is positive when  $X^S$  is below  $X^B$ . In other words, when the right-handed rotation around  $y^S$  is used to transform from stability to body axes.

## Transformation of Coordinates

### Field Data

With Field data, the transformation affects coordinate data, vector data like velocities or displacements, and tensor data like stresses and strains.

To transform from wind coordinates  $X^W$  to stability coordinates  $X^S$  use the formula

$$X^S = T^{SW} X^W$$

where  $T^{SW}$  is the transformation matrix

$$T^{SW} = \begin{bmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Likewise, to transform from stability coordinates  $X^S$  to body coordinates  $X^B$  use the formula

$$X^B = T^{BS} X^S$$

where  $T^{BS}$  is the transformation matrix

$$T^{BS} = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix}$$

A direct transformation from wind to body coordinates is computed by combining the two formulas

$$X^B = T^{BS} T^{SW} X^W$$



# Visualization and Analysis of Heterogeneous Data: Coordinate System Registration

## Integrated Quantities

In aerodynamics, forces and moments are also affected by coordinate transformations.

The aerodynamics quantities lift  $L$ , drag  $D$ , and side force  $Y_A$  are defined in Wind coordinates.

$$\vec{F}^W = \begin{bmatrix} -D \\ Y_A \\ -L \end{bmatrix}$$

This force vector can be transformed to Stability or Body coordinates in the same way as the position vector  $\vec{X}^W$ . For example,

$$\vec{F}^S = T^{WS} \vec{F}^W$$

The rolling moment  $l$ , pitching moment  $m$ , and yawing moment  $n$ , may also be arranged in a vector.

$$\vec{M}^W = \begin{bmatrix} l \\ m \\ n \end{bmatrix}$$

This moment vector is transformed between coordinate systems using the same transformation matrices. However, unlike the force vector, translation of the coordinate system origin will change the moments. If  $\delta\vec{X}$  is the vector containing the difference in position between the origins,

$$\vec{M}^{new} = \vec{M}^{old} + \delta X_x \vec{F}$$

where all vectors are in the same coordinate axis orientation (Wind, Stability, or Body).

I hope this information makes it a little easier to convert your heterogeneous data to consistent coordinate systems for better analysis and visualization. As mentioned earlier, you can apply these techniques across a number of applications, as well as in Tecplot software.

As this paper illustrates, the ability to load data from many different sources is crucial to the fast, accurate and efficient analysis of scientific and engineering results.

**Tecplot 360** is a suite of CFD visualization tools designed to handle large data sets, automate workflows, and visualize parametric results. Integrated XY, 2D and 3D plotting helps you quickly make engineering decisions. Publication-quality images and animations can be exported in many different formats to communicate your results with detail and accuracy.

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