Comparisons of Wind Tunnel Experiments and Computational Fluid Dynamics Simulations

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Abstract : This paper describes the architecture of an image and data level comparative visualization system and experiences using it to study computational fluid dynamics data and experimental wind tunnel data. We illustrate how the system can be used to compare data sets from different sources, data sets with different resolutions and data sets computed by using different mathematical models of fluid flow. We include recent improvements including use of the comparison of vector fields, ability to interactively interrogate the comparisons, addition of new metrics, the latest FEL2.0 and VisTech libraries, and GUI for a calculator module.

Keywords : Comparative visualization, Flow visualization, Similarity, Difference, Metric, Isosurface, Cutting planes.

1. Introduction

Most comparative visualization studies use juxtaposition where the user is presented with side-by-side images. This is effective only when the differences are significant and easy to detect. Beyond that, it unduly burdens the viewer with the task of finding then estimating the location and degree of difference. Two other image level comparative visualization techniques are popular: (a) difference images, and (b) overlays or super-imposition. Both of these are more effective than juxtaposition. However, they do not provide any additional investigative or analytical capability.

We present an image and data level comparative system that builds upon these popular techniques. In particular, one of the key contributions is the use of data level comparison techniques to allow users to compare two data sets by using a variety of metrics calculated from raw or derived data sets and visualize them in a variety of ways.

We report on how this system is used to evaluate four aeronautics data sets by using a variety of pair-wise comparisons. In particular, we demonstrate how this system shows regions of small differences that would be difficult to discern by using image level techniques, and the versatility of this system to compare other gridded data sets.

2. Comparison Framework

2.1 Definition

We distinguish between three general types of comparisons: image level, data level, and feature level. *Image level comparison* techniques are those which use images as the starting point for comparison, particularly images produced by visualization of data. Examples that fall under this category are: side-by-side, image differencing, most Fourier analysis, and summary image statistics such as root mean square. Pagendarm and Post(1997) and Shen et al.(1998) describe *data level comparison* techniques as those which use raw data as the starting point for comparison. The main advantages of this approach are the ability to generate different metrics for comparing raw data, access to intermediate calculations while generating the derived data, and apply visualization techniques to the data produced by the comparison. The main drawback of this approach is that comparison systems become less general and more application specific; the choice of operators and metrics must be made in the context of the application. Data level comparison does not preclude the use of images when images are the raw data – e.g. pressure sensitive paint images (Uselton, 1997), (Mebarki and Le Sant, 2001), and images of oil streaks (Pagendarm and Post, 1997). *Feature level comparison* techniques are those which compare extracted features. We further distinguish between domain specific features and domain independent features. Examples of domain specific features are vortex cores and shock waves. On the other hand, domain independent features are the graphical representations of the domain specific features. Examples of domain independent features are isosurfaces, streamlines and ribbons, etc. Feature comparisons are usually limited to higher dimensional analogs of image level comparisons, such as side-by-side (e.g. ribbon comparison (Pagendarm and Post, 1997)) or overlays (e.g. vortex core comparison (Kenwright, 1997)). More recently, feature level comparisons of streamlines are carried out with glyphs and animation (Lodha et al., 1996). Feature comparisons at a higher semantic level, incorporating application specific knowledge, are of great interest to users.

2.2 Architecture

Our data sets are in PLOT3D format (Walatka et al., 1993). Each data set comes in two separate files – the grid file specifies the physical position of each point in the grid, while the solution file specifies up to five physical parameters associated with each grid point. It is possible to compare data sets in other file formats but file readers or converters will have to be provided if the Field Encapsulation Library (FEL2.0) (Bryson et al., 1996) does not support it. After the data sets are read in, the important aspect, as will be discussed later, is to provide sufficient information to do point location – determine the relevant computational cells given a physical location and interpolate the appropriate values.

For data level comparison, we want to compare physical parameter values at the same physical coordinates. With this in mind, we base the comparisons on an intermediate mesh or grid (see Figure 1). The intermediate mesh is any grid used to resample values from both data sets. Note that either of the original grids can be used as the intermediate mesh. In our implementation, a regularly gridded mesh is also provided as a third choice for an intermediate mesh. This mesh may be interactively resized, refined, and positioned over a volume of interest. This ability allows one to zoom in and examine an area in more detail.
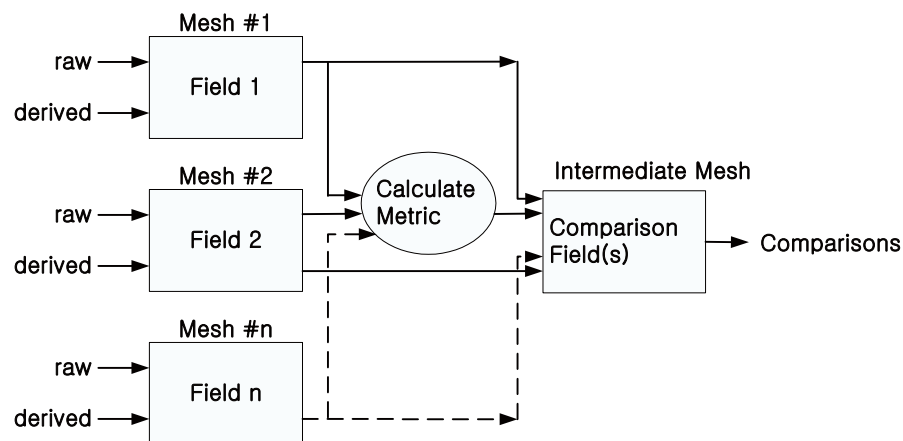
Fig. 1. Schematic of image and data level comparison architecture.

The input fields to be compared can either be some raw data field e.g. momentum components, or a derived data field e.g. velocity, vorticity, helicity, etc. The derived data field can further be distinguished as either a predefined scalar or vector field as provided in FEL2.0, or it can be a user-defined field where the user enters the expression to be evaluated. The latter is supported by the Calculator library which is built on top of FEL2.0. Its functionality is very similar to the calculator module of FAST (FAST). Currently, our system can support the comparison of two input fields at a time, but can be extended to support the comparison of more than two fields at a time.

Based on the input fields, certain metrics may be calculated to obtain a measure of similarity or difference between the data sets being compared. Examples include: absolute or signed differences between the two input data sets, minimum or maximum values of the two input data sets, or the average between the two input data sets. In general, the metric will be any function of the input data sets that would make sense in the comparison task. For example, to do data level comparison between two vector fields, the dot product between the vector components measures similarity between the two vector data sets. Our implementation provides a set of pre-defined metrics as well as the ability to specify and name new user defined metrics. The latter is achieved by using the same Calculator library to obtain derived input fields.

Comparison is performed by using an intermediate mesh to resample data from one or both of the input meshes. Both metrics and data values are evaluated at locations in the intermediate mesh. Here is where we greatly utilize the point location routines of FEL2.0. Using the values calculated in the intermediate mesh points, we can then visualize them by using standard visualization techniques.

2.3 Implementation

The major task necessary for the comparison framework above is support for point location. That is, given the physical coordinate of each point in the intermediate grid, we need to find the cell that contains that point from each of the two data sets, and then interpolate the value at that point from the values of the surrounding data points. This is one of the main tasks that FEL2.0 (Bryson et al, 1996) supports, providing a uniform interface to a wide variety of grid types. This capability makes it a natural choice for building this tool. Furthermore, FEL2.0 supports different data file readers thereby accommodating those wind tunnel experiment data which are not in PLOT3D format. In addition to FEL2.0, our implementation is coded in C++, and uses OpenGL for graphics and xforms for its user interface. Development and testing is carried out on SGI platforms.

The top half of Figure 2 shows the user interface for our comparison system. It combines the side-by-side image level comparison of the data in the top panels, and the data level comparison using the intermediate mesh on the bottom. The lower right panel varies depending on the visualization technique selected, and is used primarily for controlling the comparison window on the lower left panel. Different visualization techniques can be used to visualize the different metrics available to the user. Some of these are demonstrated in Section 4.

Some of the standard "bread and butter" visualization techniques that are supported by this system are cutting planes, isosurfaces, image-based operators and histograms. Cutting planes can be moved, added and deleted. In addition, they can be oriented along any of the three major axes. To calculate isosurfaces, we use a grid independent isosurface extraction routine from the VisTech library – a collection of visualization techniques being built on top of FEL2.0. For small data sets, the user can interactively create new isosurfaces in real time by adjusting the threshold using a slider. However, for larger data sets (e.g. the 1.5 and 2.5 million point data sets described below), it takes somewhat longer. Several operators for images or slices are currently available, including signed and unsigned differences, and they can apply different colormaps to the resulting difference image.

In addition to the standard visualization techniques, an extension was made to make histograms pickable. If the user picks one of the histogram color bars, the range of values for that bin is selected as "active" (see Figure 3). Information about global minimum and maximum, active minimum and maximum, and percentage of points in the active range appears on the screen. More importantly, all data points outside of the selected range are made transparent. This is very useful for identifying regions that have data within the selected range of values. Based on user feedback, we have also added the ability to obtain data values directly from the image by clicking on it.

In all cases, the user can apply any one of eight colormaps to both original data sets and the comparison output. The same colormap applies to the input data sets, while a separate colormap applies to the comparison in the intermediate mesh. This separation is essential since they have very different ranges of values.

3. Data Sets

We use this system to investigate four different data sets. Three of these are from CFD simulations while the fourth is from measurements taken during a wind tunnel experiment. More detailed information about these data sets is described in Dacles-Mariani et al.(1995). These data sets are briefly described below:

1. Experimental. 6,699 grid points (dimension: $11 \times 21 \times 29$). A seven-hole pressure probe was used to measure the velocity and pressure at each point.
2. Computational. 1.5 million grid points (dimension: $115 \times 157 \times 83$) using the Baldwin-Barth (BB) turbulence model.
3. Computational. 1.5 million grid points (dimension: $115 \times 157 \times 83$) using the Spalart-Allmaras (SA) turbulence model. Same grid as previous data set.
4. Computational. 2.5 million grid points (dimension: $115 \times 189 \times 115$) using the SA turbulence model.

In all cases, the same wing geometry, boundary conditions and initial conditions were used in the computed solutions, and the computed solutions are all steady state solutions. The computational grids are hexahedral curvilinear grids commonly used in high fidelity CFD calculations. The same wing geometry and flow conditions were used in the experimental measurements. The measurements for each point were taken after sufficient time to allow any transients to die down. While the numerical solutions were calculated over a period of several hours each on supercomputers at NASA Ames Research Center, it took several months to collect the experimental measurements. The main feature of interest being investigated and validated by these modeling and experimental efforts is the vortex in the flow at the trailing edge of the wingtip.
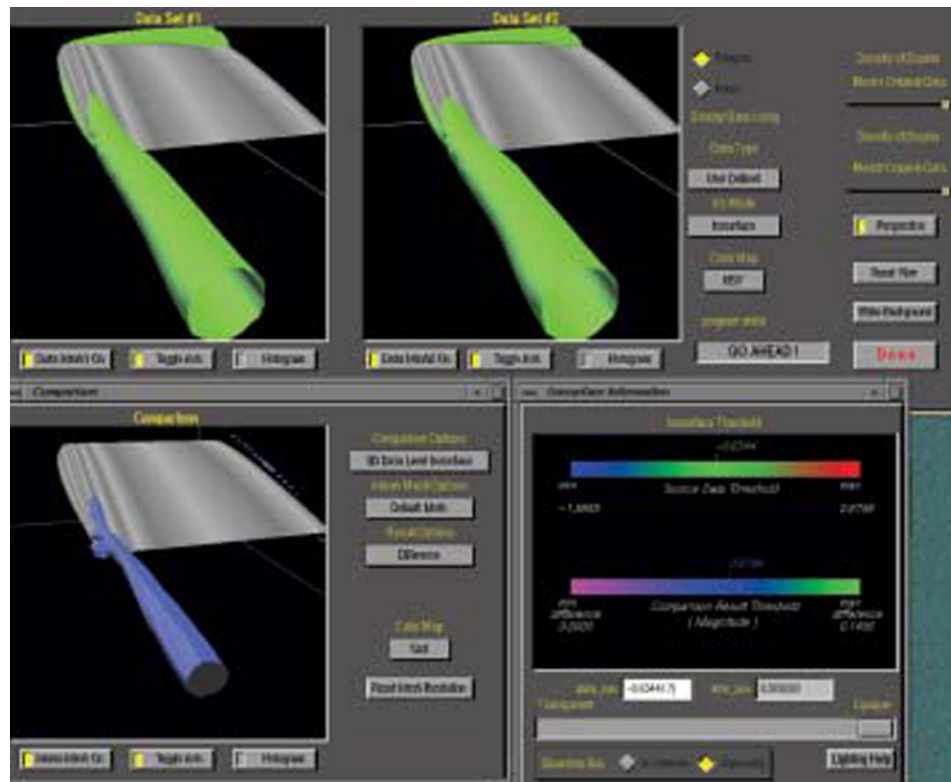
Fig. 2.   Graphical user interface and illustration of data level comparison. Temperature field of two 1.5 million grid data sets using different turbulence models.
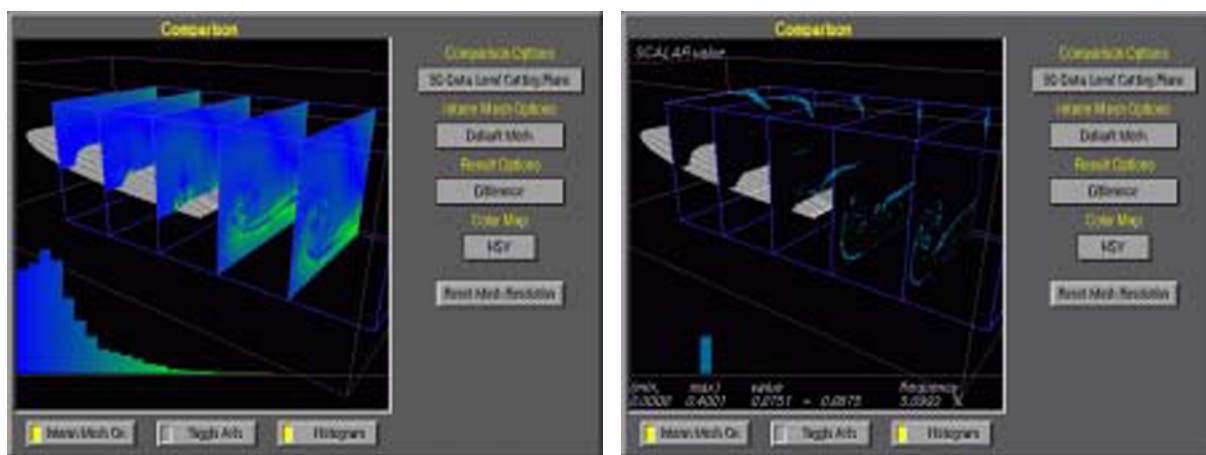

Fig. 3.   Comparison of the velocity magnitude field between the experimental data set and the 1.5 million nodes SA turbulence model. The left image shows pseudo-colored difference fields and accompanying histogram of the difference values. The image on the right is generated by either clicking one of the bins in the histogram, or clicking on a pixel in the image whose value belongs to the same bin. Only pixels belonging to that bin are visible.

4. Results

The images in this section are selected to illustrate the different combination of data sets, the variety of visualization techniques available in our comparative visualization system, and interesting features in the data sets.

4.1 Image vs. Data Level Comparison

Figure 2 shows the overall layout of the comparison software. The top half shows the registered side-by-side views of the data sets being compared. The bottom left shows a data level comparison using isosurfaces, while the bottom right shows a GUI associated with the visualization tool used in the comparison – in this case, isosurfaces. Note that the isosurface tool allows separate thresholds for the input data set and the comparison window. The colorbars in the isosurface tool also doubles as a slider for selecting the isosurface thresholds.

In this example, we examine the temperature field of two computational grids that have the same structure and contain 1.5 million grid points each. However, they use different turbulence models (i.e. data set 2 vs. data set 3 from Section 3). Here, we see that the selected temperature threshold follows the region where one would expect that the vortex would occur at the trailing edge of the wing. In addition, we see that the regions near the front of the wing are at the same temperature. The isosurface in the comparison window is significantly different from the ones in the top windows since we are looking at the difference between the two temperature fields. Here we notice that there is some differences near the wall where the wing is attached as well as along the trailing vortex. It would have been impossible to detect these differences by using image level comparison.

In Figure 4, we show two additional image level comparison methods. The top half demonstrates side-by-side comparisons of the same temperature data set as above, but with a single cutting plane across the profile of the wing. A different colormap is used this time. It is impossible to see any differences in this pair of side-by-side images. Taking the difference image between these two also produces a very dark image, until we apply a different colormap. The lower left image shows the randomly pseudo-colored difference image. Note that the image of the wing has also been subtracted out and not visible unlike the data level comparison in Figure 2. One notable difference between image level comparison and data level comparison is that image level comparison works with pixel values that were quantized from physical values, while data level comparison works with physical values first before quantizing them to pixel values. On the lower right, we first use a data level metric to calculate the difference between the two data sets for each point of the cutting plane. We then colormap this plane and present the histogram of the data distribution in the same window on the bottom right. Note that the colorbar doubles as a histogram and shows the distribution of values in the data set. By clicking on the colorbar or on the cutting plane, we can subset the data being displayed to just those values that fall within the selected bin or selected value on the cutting plane. This technique is a hybrid between image and data level methods. This figure also illustrates how one can zoom in on an area of interest by using the reconfigurable intermediate mesh.

4.2 Comparing CFD Grids with Different Resolutions

In this example, we demonstrate the comparison of two CFD data sets with the same turbulence model but different grid resolutions (i.e. data set 3 vs. data set 4 from Section 3). This time we are looking at the energy field instead of the temperature field. Figure 5 shows how cutting planes and

isosurfaces can be used to study the energy field. On the top panel, it shows 4 cutting planes with very similar characteristics and data distribution. This can be expected as both data sets use the same turbulence models and are both very high resolution data sets. Instead of calculating the difference between these two data sets, the comparison window on the lower left window shows the maximum of the two data sets on the 4 cutting planes. As one would expect, there are differences near the vortex core from the trailing edge of the wing. However, the energy values at the vortex core are actually significantly less compared to other values on the cutting plane. The lower right window shows that there are significant differences around the vortex core using a threshold value of 0.1. Nevertheless, this difference is much smaller compared to comparing wind tunnel experiments against a CFD data set.
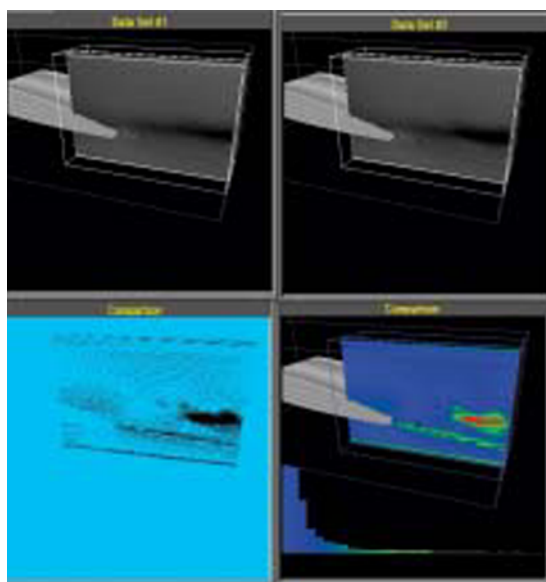

Fig. 4. Side-by-side (top), difference images (lower left), and pseudo-colored differences with histogram (lower right) – examples of image level comparison. Same data set as in Figure 2.
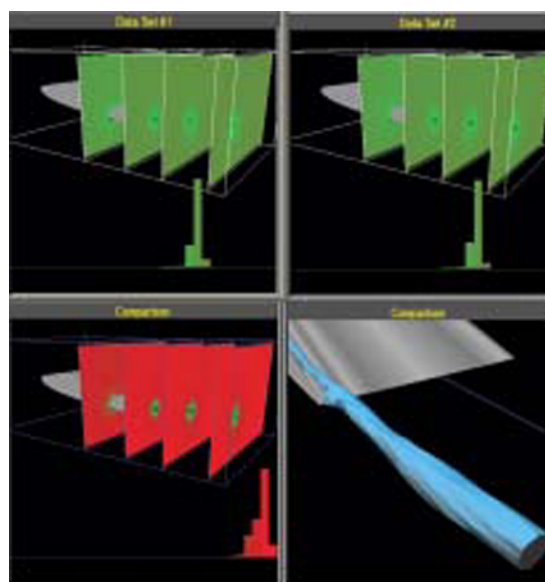
Fig. 5. Comparison of the energy field on different resolution grids.

4.3 Comparing CFD with Wind Tunnel Experiments

The example in Figure 6 illustrates data level comparison of the velocity vector field by using a variety of techniques. The data set we are comparing are the wind tunnel experiments and the 1.5 million SA turbulence model CFD data (i.e. data set 1 vs. data set 3 from Section 3). The top panel shows three different pairs of streamlines produced by seeding the same three physical points in the two vector data sets. The differences in the streamlines are highlighted by using glyphs in the top right window as described in Lodha et al.(1996). The lower left window shows the difference in velocity magnitude, while the lower middle window shows the difference in angular directions. The isosurface of the angular differences on the lower right window gives a better idea of how the complex pattern evolves.

5. Future Work

There are several improvements to be made. We list the three most important items on our list. These are: (a) investigation of interpolation errors introduced during the resampling and point location process; (b) integrating the image and data level comparison sub-systems so that one may compare 2D images against metrics derived from a 3D data set; and (c) incorporating more feature level comparison techniques.

6. Conclusion

We presented a framework that allows one to compare experimental measurements against computer simulations using a combination of image and data level comparisons. The paper also demonstrated the utility and versatility of our comparison system on four different aeronautical data sets. This paper shows that this approach is viable and particularly useful when the differences between two data sets become smaller. Hence, as experimental methods become more accurate and as modeling becomes more realistic, we believe our approach will become even more important.
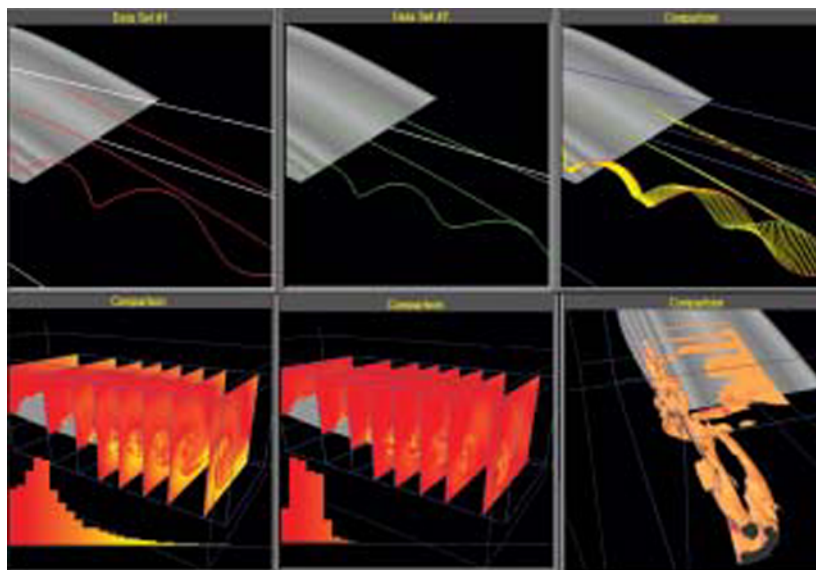

Fig. 6.   Data level comparison of velocity field between wind tunnel experiments and a 1.5 million grid point CFD simulation. A different colormap from the one in Figure 3 is used for the velocity magnitude difference in the bottom left image.

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