Visualization for Fluid Dynamics Education

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ABSTRACT

Effect of visualization as a tool for the education of fluid dynamics is mainly discussed. Visualized images are much more understandable compared to the explanation using equations and texts. Several examples are presented to clarify this statement. Then, the software system for teaching fluid dynamics using the results by the numerical simulation is discussed. Two important issues on what is needed in the system are given. First, such systems should be capable of animating images. Second, such systems should be interactively used by students. Changing parameters, coefficients, equations, etc. themselves and watching the difference are important for them to understand the nature of physics underlying the equations. The teaching system with visualization is no doubt a good tool for introducing fluid dynamics.

INTRODUCTION

There is one important nature in the research field of fluid dynamics compared to other engineering fields. That is "fluid motions can not be seen directly". Therefore, visualization has been one of the important research topics in fluid dynamics. The same is true for the research in computational fluid dynamics(CFD). In the process of the CFD growth, visualization was used just to show nice pictures to demonstrate the capability of computational fluid dynamics. Recently, as the CFD is matured as a research field, visualization really became used for research and it has become very effective tool to help researchers to understand flow physics from the computational results.

Visualization can also be a good tool for the education of fluid dynamics just from the same reason. Students can learn a lot from the visualized imaged of the computer simulations of fluid motions. In the present paper, usefulness of flow visualization using computers is discussed. Some of the examples of how we can use the visualized images in teaching principles of fluid dynamics are presented. Also discussed is the requirements of such education system.

2. LEARNING FROM VISUALIZED IMAGES

2.1 Understanding of nature of equations

In most of the CFD textbooks(Andersion, Tanehill and Pletcher, 1984; Hirch, 1988), linear scalar equations appear first. The purpose is to let the readers understand the numerical methods to integrate such relatively simple equations. For instance, scalar advection equation (wave equations) is written as

$$\frac{\partial u}{\partial t} + c\frac{\partial u}{\partial x} = 0$$

Using a finite difference approximation of many computational schemes, readers understand the characteristics of each scheme. LAX-Friedrich integration scheme is very dissipative, leap-frog algorithm creates oscillations due to phase error, and so on. Mostly, simple discontinuity is assumed in space at time being equal to zero and the solution of what happens in time is pursued. The result for the 1st order upwind scheme is shown in Fig. 1. As well known, the disturbance at x=0 propagates toward the positive x direction in time.

In these text books, the nature of the equations is a priori given. In the case of scalar advection equation, it is given that the equation represents the phenomenon that wave propagates at the speed of coefficient of the first derivative in space.

Let's think about teaching the nature of partial differential equations instead of teaching numerical methods. In this case, any accurate scheme is fine. Analytical solution is also fine. The result should be something like the plot in Fig. 2(a). Now, changing the sign of c , the result becomes like Fig. 2(b). Changing the value c to be twice, the result becomes like Fig. 2(c).

Changing the parameter(characteristic speed) c like this, students would easily learn that the disturbance propagates at the speed of c . Of course, they learn the nature of convective terms (first derivative in space) that transport physical phenomenon in space. When the system of equations are solved, there are two waves propagating both in positive and negative directions. An example of the solution using upwind leap-frog scheme(Roe, 1993) is presented in Fig. 3. In the case of multi dimensions, wave propagation occurs cylindrically in two dimensions as shown in Fig. 4 and spherically in three dimensions. Students could learn a lot from these simple simulations.

The same is true for heat equations. Assuming one peak in space at one time instance, watch what happens in time. Students would easily learn the nature of second derivatives by looking at the animation of time sequence that some peaks becomes flattened in time. Again, changing parameters, boundary conditions, and so on, they learn the nature of second derivative in space.

2.2 Understanding of behavior of fluids

Let's take a transonic flow over an airfoil as another simple example. Figures 5 (a) and (b)) show the close-up views of density and pressure contour plots of the computed flow field for an NACA0012 airfoil at Mach number 0.80 and angle of attack 2.0 degrees. It may be interesting to ask students to tell which plot is pressure. Some students may remember that there is no pressure gradient in the boundary layer and there should not be any contours in the normal direction to the body. Then, they say Fig. 5(b) is pressure. That is a correct answer. There may be many questions to be asked using these figures. Local Mach number contours, entropy contours and other contour plots may be added to these figures.

One more example for the three-dimensional flow field over a delta wing at large angle of attack is shown in Fig. 6. Total pressure contour plots in the cross-sectional planes at several chordwise stations are presented. The motion of leading-edge separation vortex can be well recognized by the total pressure contours. It may be interesting to let students consider what should be plotted to find the position of leading-edge separation vortex without telling them what should be plotted. In this example, one solution may be vorticity magnitude. However, strong magnitude exists in the viscous layers near the wing surface, and, therefore, leading-edge separation vortex is not clearly seen without restricting contour levels. It is always interesting to let students to consider what they should plot to find out important nature of the flow fields that they computed.

2.3 Animations for unsteady fluid dynamics

Steady flow simulations are useful especially in aeronautical engineering which has been leading practical CFD technology. However, in reality, most of the flow fields that appear in our life are unsteady. Research for unsteady flows is increasing compared to research for steady flow in CFD as computer capability and software adaptability are increased. Animation is an useful tool to analyze the computed results for unsteady flows.

Let's take one example. Figures 7(a)-(d) show the time sequence of the flow field inside the tunnel when a two-dimensional high-speed train runs into the tunnel. As well known, high pressure wave is created in front of the train and it propagates at almost sound speed toward the other exit of the tunnel. The gradient of the front becomes steepened as it propagates because of the nonlinear nature of the fluid physics. This high pressure wave goes out from the exit and creates booming noise nearby. Expansion wave is created and moves back toward the train when the compression wave goes out from the exit because the tunnel exit is an open end. The animation of the time sequence clearly shows what happens. Animations for three-dimensional train would show more about the pressure wave. The pressure contour on the train surface would tell strong negative pressure acts on the train surface at the entrance(Ogawa and Fujii, 1993).

Figures 8 (a)-(c) show the time sequence of some of the components of the forces and moments acting on the three-dimensional high speed trains passing by each other in a tunnel(Fujii and Ogawa, 1993). To help understanding the result, relative position of the trains at several time stations is attached to Figs. 8. At t=-9.09, the trains start moving with the steady-state solution as an initial condition. At t=0.0, both the train noses come to the point x = 0.0. At t=5.68, both trains are aligned side by side. At t=11.36, crossing is finished and both the train rear noses are located at x = 0.0. Time history of the forces and moment is good information but is difficult for interpreting the computed results without animation of the flow field. With the animation of the pressure contour plots on the train surface, it is easily observed that low pressure acts on the shoulder of the train and that creates attractive forces of two trains when passing by each other. All the time history of the forces and moments can be analyzed similarly with the help of the animation of the pressure contours.

Animation is an effective tool for education even in the case of steady flows. Three-dimensional flow field can be understood easier by changing view point sequentially. Interactive particle release would also help understanding flow phenomenon.

2.4 Why Computational Fluid Dynamics?

One thing to note is that we can plot many flow functions from the results obtained by the computations. In fluid dynamics experiments, information obtained is restricted to what are measured. In the CFD, all the information can be stored, and many functions can be deduced from the stored data. Even the functions that are not directly measured can be plotted. Entropy may be one example. It can be recognized by plotting total pressure, but is not the same. Here computational fluid dynamics with the visualization can be a very flexible tool for teaching fluid dynamics.

We always have to remember that the computational results include many types of errors. Typical one is a discretization error. The solution is not strict and sometimes misleading. The results to be used for education should be carefully examined, validated and verified before being used. For instance, small increase of total pressure, or entropy is frequently observed in the discretized flow field at adiabatic subsonic flows if body geometry is not precisely described by the computational grid. Simple discontinuity tends to be smeared in the propagation process as time goes on.

Another type of problem might occur in creating visualized images. In case that we prepare visualized images to teach something, we choose what to plot and show. We could intentionally hide something by restricting the plots or might forget to plot some important ones. The visualized images are very instructive but sometimes dangerous because they represent the intension of the person that created those images. They are not everything. Here again, it is important that students visualize the results themselves interactively rather than just watch the given animations or graphic plots.

3. REQUIREMENTS FOR THE EDUCATION SYSTEM

It has been shown that the software system with visualization capability is useful for fluid dynamics education. Now, let's consider the requirements for such systems.

Firstly, visualization should be done interactively. Viewing of the object, selection of plotting functions, zooming, and else should be carried out interactively. Students set up parameters themselves. For that purpose, graphic workstations or personal computers with strong cpu and graphic capability are useful. With the rapid progress of the workstation performance, two dimensional Euler equations, for example, can be solved with visualizing the images such as density contour plots. Contours are smoothly moving in real time and we can easily see the growth of the solution in the iteration process.

Secondly, we have to prepare good database of the computed results. As described above, such database should be carefully chosen and validated. It would be nice to set up good education database using CFD results as a collaborative work in the world.

Also important is that the time sequence of the result is shown as an animated image on the graphic screen. Video tape may be useful, but is not competitive to the real time animation on the screen because we cannot change the view point, plotted functions, level of the contours, and anything once the video tape is created. Therefore, the system for teaching should be interactive. In relatively simple examples, it is better that graphic output is connected to the solution process and visual computing is realized. In the case requiring large scale computations, the computed results are stored on the disks, and then students creates animations interactively.

4. CONCLUSIONS

Visualization has been used extensively for computational fluid dynamics. Initially, it was used just to show nice pictures to demonstrate the capability of computational fluid dynamics. Recently, visualization really became used for research and it has become very effective to help researchers to understand flow physics from the computational results.

Visualization in computational fluid dynamics is an effective tool for the education of fluid dynamics as well. It has been shown that the educations system with visualization should have an interactive capability. Animations should also be created interactively. It is necessary to create good and reliable database to establish such systems and we should carefully examine and validate the computed result before using them for education.

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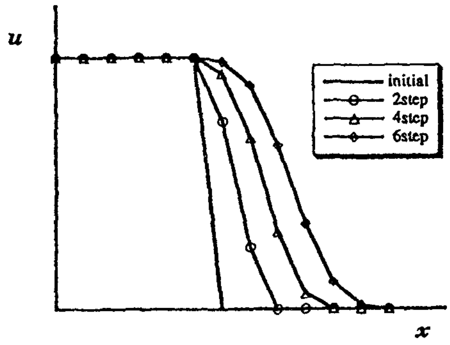
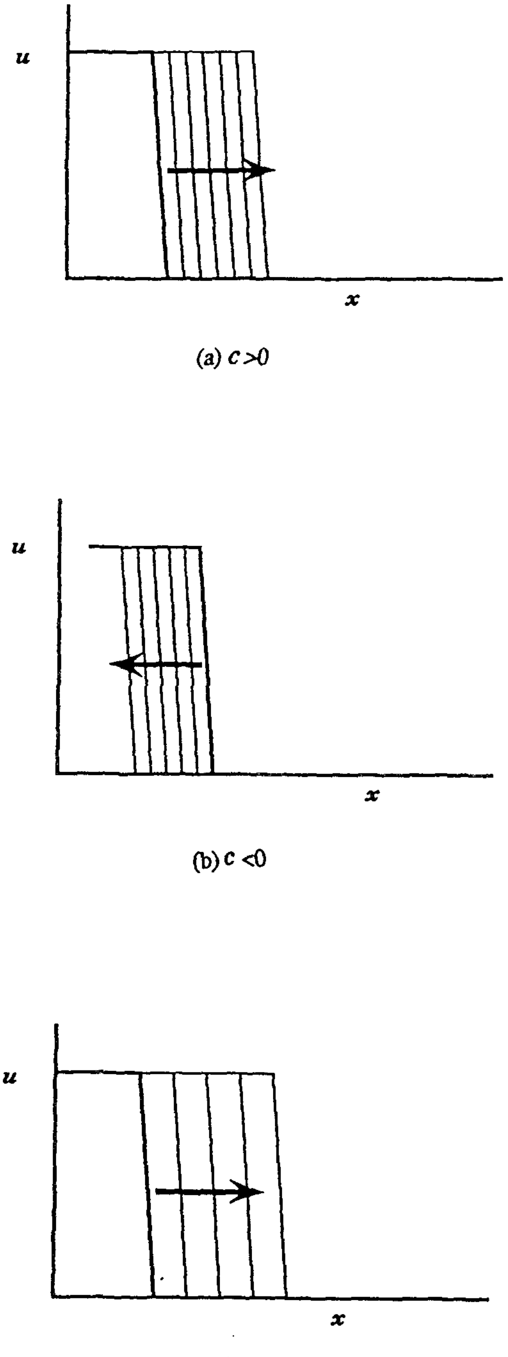


Fig. 1 Finite difference solution of the wave equation. (1st-order upwind method)



(a) $c>0$

(b) $c<0$

(c) c'(twice)>0

Fig. 2 Solution of the wave equation.

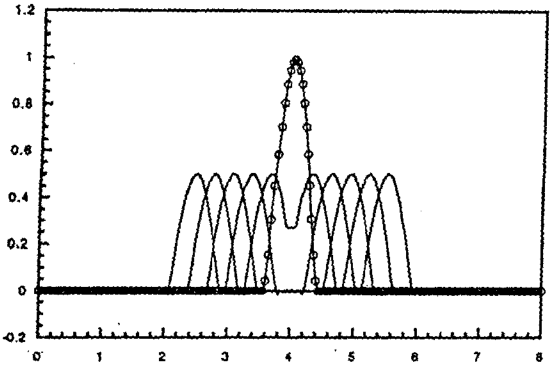


Fig. 3 Finite difference solution of a system of equations. (upwind-leapfrog method)

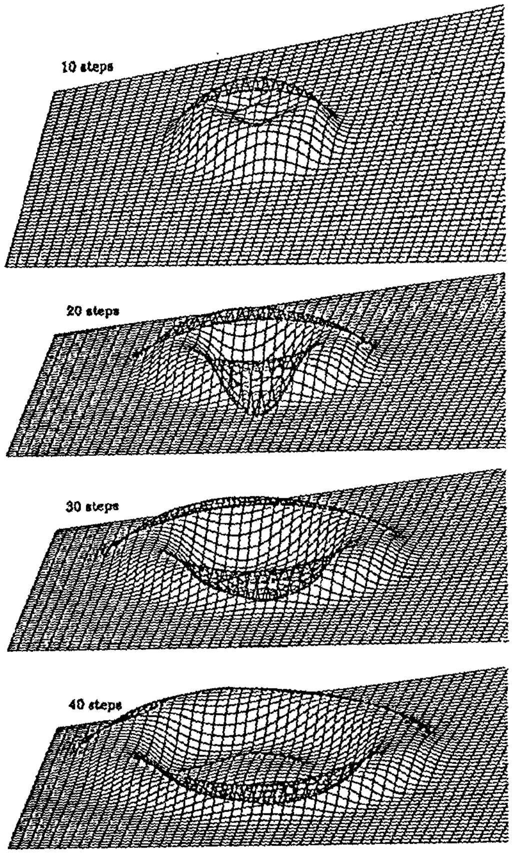
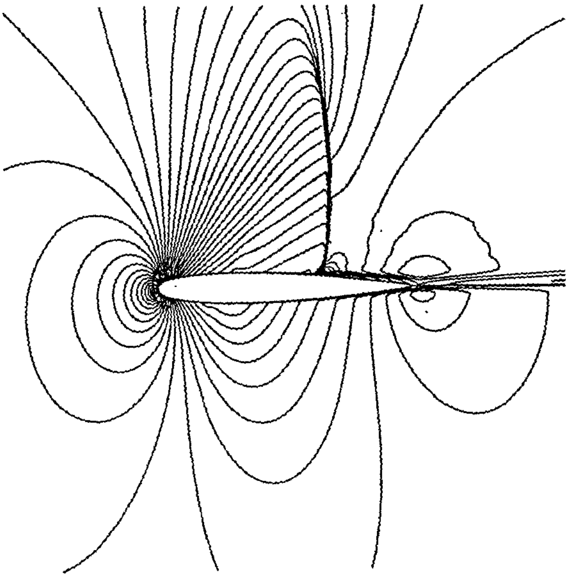
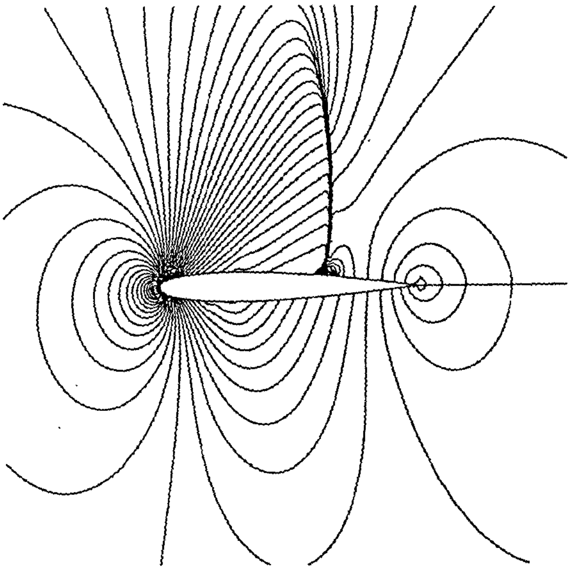


Fig. 4 Finite difference solution of a two-dimensional system of equations. (Yee-Harten high resolution upwind method)

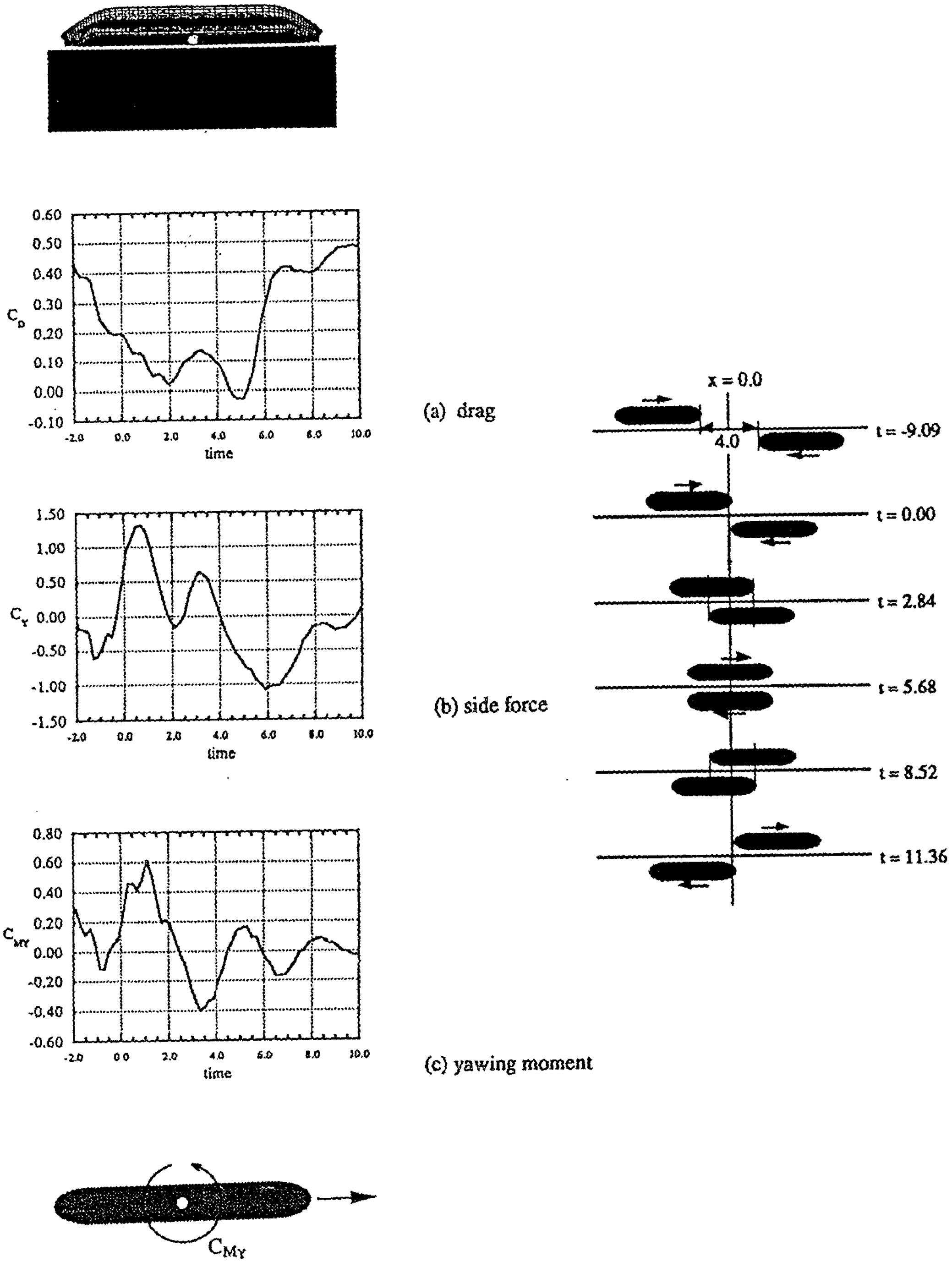


(a) density contour plots



(b) pressure contour plots

Fig. 5 Computed result of thin-layer Navier-Stokes equations for NACA0012 airfoil (M=0.8, α=2.0).



(a) drag

(b) side force

(c) yawing moment

Fig. 8 Time sequence of some of the forces and moments acting on high-speed trains passing by each other in a tunnel.