Using Computers in Teaching Gas Dynamics

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Abstract

To assist in the teaching of undergraduate gas dynamics in the Mechanical Engineering Department at the University of Memphis, two workstation-based interactive flow simulators, VU-INLET and VU-SHOCK, developed at the NASA Lewis Research Center were used by students. The simulators were offered as supplements to a traditional lecture course in an effort to help students develop a better and more intuitive understanding of gas dynamics. The programs simulate flow through a supersonic inlet, and supersonic flow past a wedge or series of wedges. For each program the flow conditions and geometries were interactively specified by the student using a graphical user interface. The appropriate one-dimensional aerodynamics equations were quickly solved by the programs, and numerical and graphical output were displayed as the input conditions were varied. The quick response to variation of input parameters allowed the students to easily evaluate a large number of "what if" scenarios, to recognize immediately that they had specified invalid conditions when they did so, and to examine far more cases than would have been possible if obtaining solutions "by hand." The interactive nature of the programs, with immediate feedback, seemed to significantly accelerate the learning process. It appeared to the instructor that these software packages were a definite aid to the students in developing a better and more intuitive feel for the physics of gas dynamics.

Introduction

Personal computers and workstations are particularly well suited for the teaching of undergraduate gas dynamics. They are readily available, relatively inexpensive, and becoming much easier to use. The output from a modern personal computer may be directed to be principally visual if desired, allowing for quick evaluation of results. The use of personal computers and workstations in undergraduate fluids engineering education is a relatively recent development. Some of the earliest efforts (Koening and Hodge, 1993; Fox and McDonald, 1992; Gerhart et. al., 1991; and Mattingly, et.al, 1987) centered around the use of software developed for personal computers, but lacked the graphical interface available on workstations. With those packages, students type input conditions at the keyboard and are presented with principally numerical output. More recent efforts by Torella, 1994, and Benson, 1994a, 1994b, 1995a and 1995b, have included a graphical user interface (GUI) which enhances the student interaction

with the software. With these packages, students use a mouse and keyboard to vary input conditions and they receive principally graphical output.

The educational tools described in this paper were developed at the Nasa Lewis Research Center by Dr. Benson over the last several years and were intended to serve as supplements for laboratory or lecture courses. They were designed to behave as a desk-top laboratory which the student may use to develop a feel for, and an understanding of, gas dynamics. But unlike normal laboratories, the student can use these tools whenever and as often as he or she pleases, with little supervision, no physical danger, and at little expense. When incorporated into a lecture course, this software can be used for homework exercises to consider many configurations that would be too numerically intensive for a student to examine in a reasonable amount of time if doing the computations with a hand calculator.

Methods

The two interactive educational packages, with output being shown in Figures 1 and 2, share certain characteristics. Both of the programs run on an SGI workstation and are controlled by a graphical user interface based on the FORMS library developed by M.H. Overmars. Considering Figure 1 as an example, the student is presented with an engineering problem in the main view window of the computer terminal. The student can control the size, location and appearance of the figure by using the sliders and buttons located around the view window. The student can also access on-line help screens which serve as a user's manual, and describe the underlying theory and assumptions for the simulation. The student can control the input conditions of the problem to be studied by using the various buttons, sliders, and type-ins located on the panel at the lower left. All of the programs are based on one-dimensional aerodynamic analyses which can be solved quickly on a single workstation. As the input conditions are changed, the package computes the new output conditions, displays the change graphically and numerically in the output window at the lower right, and changes the descriptive picture in the main view window. The packages provide the student with an interactive plotter to generate performance curves, and include a provision for examinations; the program can access a data file which contains questions that the teacher prepares, and which the student is to answer using the program.

A guiding principal in the development of these educational tools was to do more than just present answers to problems; it was to involve the student in the learning process by having him or her work with the software to achieve a result. Again considering Fig.1 as an example, the student can use this package to analyze a supersonic inlet. She or he must choose a design condition, (inlet Mach number for instance), and then vary the geometry cross—sectional shape to produce desired conditions throughout the inlet. During this design process the student can monitor the changing conditions throughout the inlet by inspection of the varying bar graphs in the output box.

When the student attempts to specify conditions which violate the assumptions of the analysis, warning lights flash in the output box. Through these visual output cues, and the control of the input conditions, the student learns how an ideal supersonic inlet would operate and perform. The teacher still, of course, must provide the theory and governing equations as part of normal course work. It was found instructive to have the students compare hand calculations for a number of cases with the computer results. This introduces some of the ideas of software

verification, comparison of analyses, and produces some interesting discussions as to why the answers disagree. Similar educational processes can be performed with both of the simulators described in this paper.

Simulation Results

The mathematical equations used to simulate compressible flow in the VU-Inlet and VU-SHOCKS software packages are well known and considerable detail about how they are implemented in the software has already been provided in the open literature, (Benson 1994b, Benson 1995a). We will now discuss the two applications packages and how each was used in the classroom. A brief review of VU-INLET and VU-INLET operation is presented here to familiarize the reader with the essentials necessary to get a "feel" for the software and therefore to understand how it can be used to support classroom instruction.

Figure 1 shows screen output from VU-INLET, a program for analysis and design of supersonic inlets. Details of the analysis used in this program are given in Benson, 1994b. This package features multiple input and output screens which allow the student to vary the free stream conditions, the engine airflow conditions, and all aspects of the geometry. The package computes the inlet recovery, mass flow and drag, and displays the variation of the major flow variables through the inlet. Both external compression and mixed compression inlets can be simulated. The simulator can calculate and display inlet spillage and its variation with engine airflow. It can demonstrate normal shock standoff and its variation with engine airflow for external compression inlets. It also illustrates the importance of total pressure recovery, how increasing the number of compression ramps increases the recovery, and how balancing the recovery losses optimizes the recovery. The increased recovery and decreased drag of a mixed compression inlet with respect to an external compression inlet can be clearly shown. There is an empirical model in the simulator for the subsonic duct which was difficult for the students to understand or verify, but they could, and did, check the supersonic portion of the inlet by using equations or plots in their text books.

The student could display the variation of any single variable along the flow path, or could display the value of all the output variables at a given location. On several occasions, the entire class was relocated from the classroom to the computer lab. First, a demonstration of the overall simulation capability of the software was presented, and later specific details of a simulation were investigated in more depth. The software was not demonstrated and made available for student use until *after* pertinent topics had been discussed in class, and appropriate homework problems had been solved using hand calculators. Then additional problems were assigned, these problems to be solved using VU-SHOCK or VU-INLET, as appropriate.

This program could also be used in a compressible aerodynamics course to demonstrate applications. However, because of the complexity of the analysis, it would be best suited for a propulsion course to introduce many of the concepts of high speed inlets. And it will, in fact, be used again in a senior elective (Aerospace Propulsion Systems) to be taught in the spring of 1999 at the University of Memphis.

Figure 2 shows typical results from the other software package, VU-SHOCKS. Details of the analysis used in this program are given in Benson, 1995a. This program was derived from the

VU-INLET program but it only solves for compressible flow past a single wedge, opposed wedges, or two wedges in series. By limiting the scope of the physics problems, the student could study these problems in more detail. He or she could vary the ratio of specific heats, the free stream Mach number, and the wedge angles and spacing. As the input was varied the view window displayed the variation in shock structure. Simultaneously, the output bars moved to provide the student with a feel for how much and in what direction the pressure, temperature, downstream Mach number, and density changed for a given change in input. Numerical output was also provided so that students could see the magnitude of this change and can check the results.

Figure 2 is a gray scale depiction of a typical screen displayed by VU-SHOCKS. Although a range of colors has been used to good advantage to communicate with the program operator during execution, the essential screen features are still visible in the figure. The screen is divided into four panes according to function. The upper-left pane displays the geometry specified by the current values of the input variables and, when appropriate, a line depicting the compression shocks or expansion waves. The lower left pane provides the user with the means to control the program function. The darkened box in the first row of the pane shows that the user has "picked" a single wedge as the configuration to be modeled. The approach Mach number and wedge angle are specified by the user in the next section of the pane. The balance of the pane controls the plotter pane in the upper-right quadrant of the window. The "Plotter" column provides controls for producing the curve displayed in the Plotter pane and this process is presented in detail in the following paragraph. The "Variables" column allows the user to "pick" the independent and dependent variables to appear in the xy-plot displayed in the Plotter pane. The upper-right quadrant of the window is occupied by the Plotter pane and the lower-right quadrant is occupied by the Output pane. The Output pane provide both graphical and numerical display of all of the pertinent variables. The combination of a numerical value with a bar-style depiction of that value is a very powerful pedagogical tool. The numbers are useful for recording information for later study whereas the bar display gives the student a "feel" for the physics: as inlet conditions are changed, the student can see trends in all of the variables at the same time. Finally, the output pane also provides a Question and Answer dialog box that will discussed in more detail in a subsequent paragraph.

The plotter pane in the upper-right quadrant of the window is one of the most exciting aspects of the software because it requires the student to interact with the simulation in much the same way that an experimenter might interact with a wind-tunnel used for instructional purposes. When the student "picks" the dependent and independent variables to be studied, an x-y display appears in the plotter pane with axes labeled and scaled appropriately. The student then specifies a value for the independent variable and "presses" the Take Data button in the plotter column causing a "data point" to appear in the plotter pane display. As many as 25 data points can be acquired to produce a curve and they need not be acquired in order of increasing or decreasing value of the independent variable. In fact, after roughing out the relationship to be investigated, the student can return to regions that appear interesting to acquire additional data to further illuminate the relationship, much as an experimenter might conduct a research study. When the student decides that an adequate amount of data has been collected, "pressing" the End Trace button will cause a solid curve to be drawn and appropriately labeled. The student can then change one of the parameters, such as inlet Mach number, press the "Begin Trace" button, and repeat the data acquisition process to produce another curve. Up to five curves can be placed on a single x-y

chart providing the student with ability to study the influence of a third parameter on the relationship between the dependent and independent variables. Finally, pressing the "New Plot" button clears the plotter pane and the entire process can be repeated as many times as desired.

The lower portion of the output pane is devoted to a Question and Answer dialogue box. A set of questions has been provided with the software package that are designed to "promote an interaction of the student with the simulator to bring out several important topics regarding compressible aerodynamics", (Benson 1994a). Pressing the "Question" button will cause a new question to appear in the box. After the student uses the simulator to seek an answer to the question, pressing the "Answer" button reveals the correct answer so that the student can obtain immediate feedback. If the "Sequential" button is "picked", questions will appear in exactly the same order every time the simulator is run; selecting the "Random" button will cause the order of presentation to vary. The software has been written so that the questions (and answers) can be easily modified to suit a particular application and it is reasonably easy to reconfigure as an examination tool. Examples of questions and answers of the type provided with the software package are presented in Appendix A.

In the solution of homework problems, the student controlled the generation of performance plots as opposed to simply being presented with plots "automatically" generated by the program. The student chose which variables to plot, then used the input box to vary a parameter. He or she then pushed a button labeled "Take Data" and the values of independent and dependent variable were indicated in the graph by an asterisk ("*"). The student then changed the input variable and repeated the process. As the student took the data the plot was generated. This process is much like the one that occurs in wind-tunnel testing where conditions are varied, data are taken, and plots prepared to determine how a component performs. The final output from this process was a performance curve which was compared to results presented in typical compressible flow text books. In using this program the student saw the same output presented in three ways; performance plots, numerical data, and bar graphs.

This software was particularly useful in gas dynamics in demonstrating many basic concepts such as oblique and normal shock waves and Prandtl-Meyer centered expansions. The package demonstrates intersecting shock waves of the same family when considering two wedges in succession. The intersection of shock waves of opposite family occurs in the opposed wedge problem. By setting one of the opposed wedges to zero degrees, simple shock reflection from a solid surface was also studied. The student examination option described earlier proved to be a most convenient and effective means for the students to assess their mastery of the subject whenever they desired. Additional evaluation of student progress was accomplished by the assignment of specific problems to be solved using the software and then turned in to the instructor for grading.

Conclusions

Two workstation-based, interactive flow simulators were used to enhance the teaching of undergraduate gas dynamics. The students were required to work with the software to solve basic problems in gas dynamics. They controlled the input to the problems with a graphical user interface and were presented with output data in a variety of forms. The ease with which solutions were obtained encouraged students to evaluate far more problems than were examined

in previous offerings of this course which did not have access to this software. The interactive nature of the programs, with immediate graphical and numerical feedback in response to variation of input parameters, seemed to significantly accelerate the learning process. In summary, it appeared to the instructor that the software definitely aided the students in developing a better, more complete, and more intuitive feel for the physics of gas dynamics.

Acknowledgements

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Appendix A

Q I: For Mach number = 2.5 and wedge angle = 10°, what is the shock angle?
Q 2: What is the Mach number downstream of a 20.0 degree wedge at Mach 3.5?
Q 3: For Mach number = 2.0 and wedge angle = 24.0^o, what is the shock angle? What type of shock is this?
Q 4: For Mach number = 2.0 and wedge angle = 24.0^o, is the downstream flow supersonic or subsonic? Why?
Q 5: For Mach number 3.0, how does the static pressure ratio vary with wedge angle? At what wedge angle does the shock become a normal detached shock? How does the static pressure ratio vary with wedge angle after the shock becomes detached?
Q 6: For Mach number 2.0,how does the downstream Mach number vary with wedge angle?
Q 7: For Mach number = 2.0, how does the total pressure ratio vary with positive wedge angle ?

Q 8:   For wedge angle = 15.0°, how does the shock angle vary with the upstream Mach number?

Q 9:   For wedge angle = 15.0°, how do the pressure and temperature ratios vary with the upstream Mach number?

Q 10: For wedge angle 15.0° and Mach 1.62, is the shock normal detached or oblique? What is the downstream Mach number? How is this possible?

*For Problems 11,12: Select <Problem> then <Opposed Wedge> from the Main Menu.

Q 11: For an upstream Mach number = 2.0 and wedge angles of 100° in the converging duct, what is the downstream Mach number for zones 1,4,5?

Q 12: For a wedge angle of 10.0°, how does downstream Mach number vary with increasing upstream Mach number? How does this change affect the position of the shocks in the duct? At what upstream Mach number does the normal shock move outside of the duct?
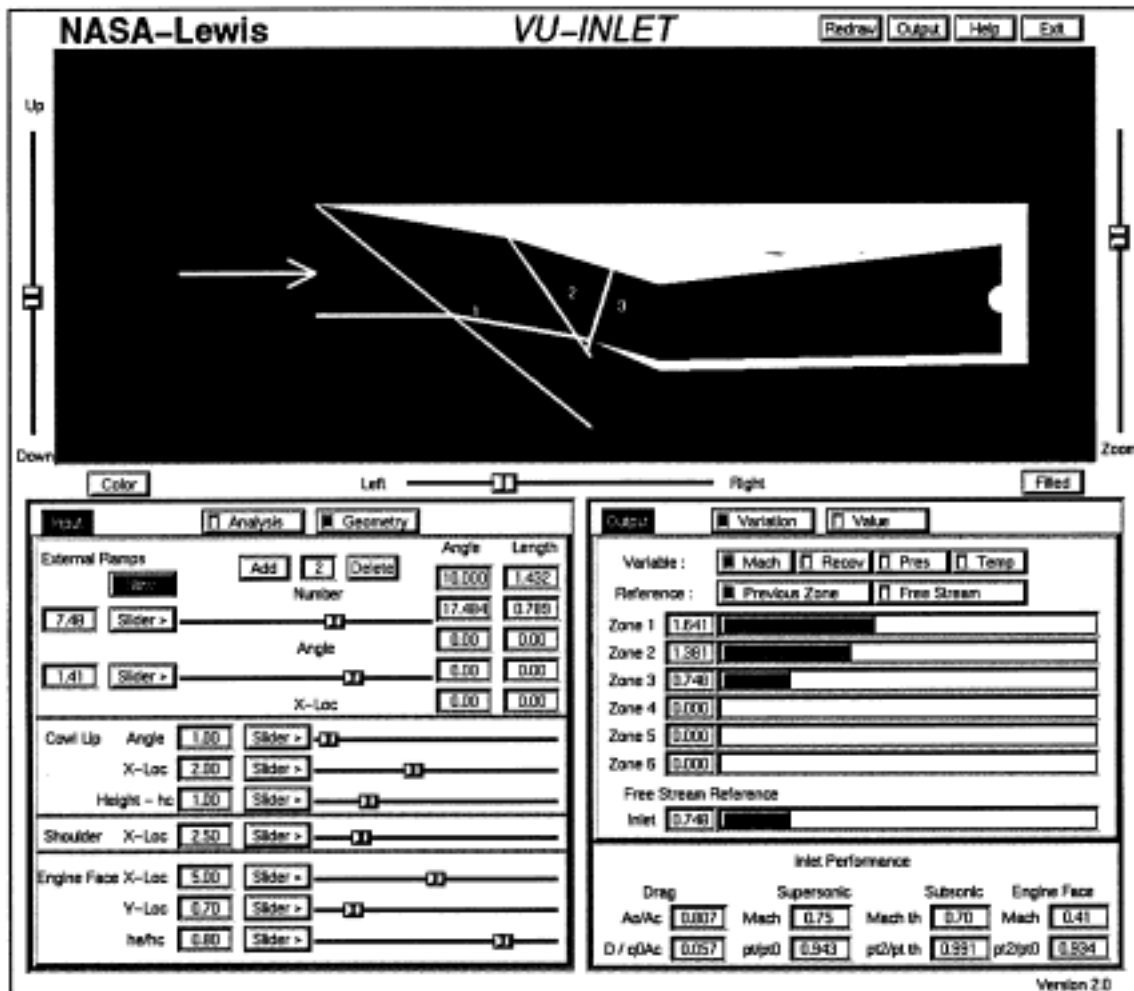

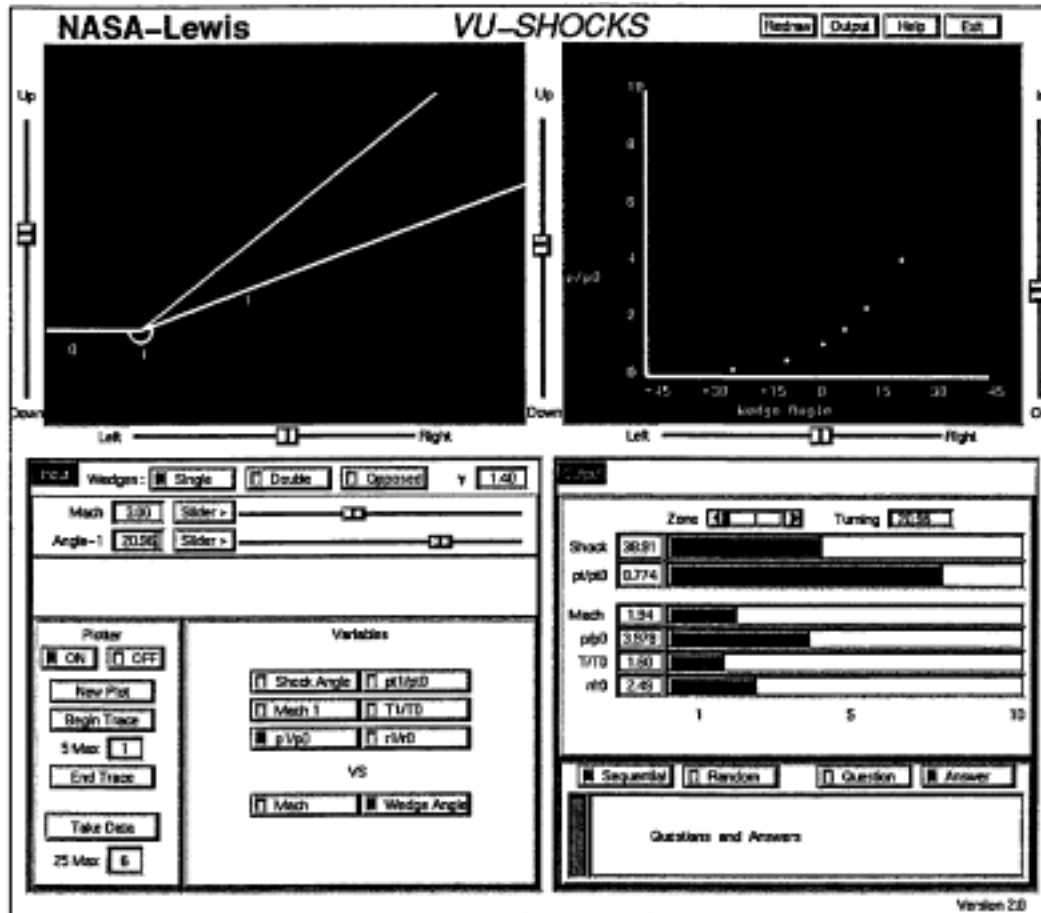Figure 1 - Sample Display for Inlet

Figure 1 - Sample Display for Oblique Shock

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