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Interactive Computer Graphics Applications for Compressible Aerodynamics

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Interactive Computer Graphics Applications for Compressible Aerodynamics

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ABSTRACT

Three computer applications have been developed to solve inviscid compressible fluids problems using interactive computer graphics. The first application is a compressible flow calculator which solves for isentropic flow, normal shocks, and oblique shocks or centered expansions produced by two dimensional ramps. The second application couples the solutions generated by the first application to a more graphical presentation of the results to produce a desk top simulator of three compressible flow problems: 1) flow past a single compression ramp; 2) flow past two ramps in series; and 3) flow past two opposed ramps. The third application extends the results of the second to produce a design tool which solves for the flow through supersonic external or mixed compression inlets. The applications were originally developed to run on SGI or IBM workstations running GL graphics. They are currently being extended to solve additional types of flow problems and modified to operate on any X-based workstation.

INTRODUCTION

Recent advances in computer related technologies are changing the ways that engineers solve aerodynamics problems. In the past, preliminary design was conducted using charts, tables and graphs of the performance of similar configurations and final design was tested and verified using wind tunnel results. With the advent of large, powerful mainframe computers, some of the preliminary design tables and graphs could be generated by solving the equations of motion and some of the final design results could be verified using computational fluid mechanics. Today's workstations and personal computers have computing power equal to that of the older mainframes. When coupled with window operating systems and graphical user interfaces, workstations can now be used to solve preliminary design problems interactively. Clusters of workstations are even beginning to rival the supercomputers for the solution of final design problems.

This paper will present extensions of work begun by the author in 1993, Refs. 1 and 2, concerning the development of a family of computer applications to solve basic, inviscid, compressible aerodynamics problems using interactive computer graphics on a workstation. In Ref. 1 an interactive inlet design tool was developed to solve for the flow through external compression inlets. Through the use of a graphical interface, the designer could change the geometry, and the upstream and downstream flow conditions and immediately see the effects on inlet performance and drag. As the geometry and flow conditions were altered, the application would recompute the important flow variables and redisplay the geometry, shock wave locations, and output flow parameters. It became evident during the development of the package that if the flow problem was simplified from flow through an entire inlet to simply flow past a wedge, undergraduate students could use this technology to study a fundamental flow problem in a highly visual and interactive way. This lead to the development of a second applica-

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tion which is described in Ref. 2. Some additional interactive features were added in this educational simulator to produce a prototype desk top wind tunnel. The student has a flow problem presented in a view window on the workstation, some controls over inputs to the problem in a second window, and the results of the solution presented in a third window. The student can then vary the input flow conditions and analyze and record the variation of the selected output flow variable with an interactive graphics generator.

Both applications packages have been expanded to solve additional flow problems. The inlet simulator can now solve for flow through either external compression inlets with the terminal normal shock generated outside the cowl, or mixed compression inlets with the terminal normal shock generated inside the duct. The simulator will signal flow conditions which can lead to inlet unstart, an undesirable instability of mixed compression inlets in which the normal shock moves from inside the duct to outside the cowl with a large loss in inlet performance. An inlet bypass system has also been added to the model, since most operational mixed compression inlets require some form of bypass to avoid unstarts and provide increased stability. The educational simulator has been extended to solve two additional flow problems: 1) flow past opposing wedges which produce crossing shocks, and 2) flow past two succeeding wedges which produce intersecting shocks. By setting one of the opposed wedges to zero deflection, the opposed wedge mode can also be used to study shock reflections from a solid surface. As previously discussed, the educational application is designed to mimic a wind tunnel, giving the student control over flow conditions and the taking of data for later analysis. With the two additional flow problems, a data probe has been added to the plotter package to allow the student to produce flowfield maps of these complex interactions. Details of the improved educational simulator are given in Ref. 3.

In the development of the two previously reported packages, it was necessary to check the results against previous analytical results, principally those in NACA 1135, Ref. 4, and certain compressible aerodynamics text books, Refs. 5 and 6. To facilitate this verification process, an interactive compressible flow calculator which runs on the workstation was also developed. This calculator employs no graphics other than the push button widgets used to select output variables and the text input widgets used to enter data to the program. The calculator returns a single flow variable for a given set of input conditions for the problems of simple isentropic flow, normal shock flow, oblique shock flow and centered Prandtl-Meyer expansion. The calculator has proven to be a nice utility for other unrelated tasks, such as the preparation of consistent input conditions for large CFD applications and the verification of the results of other codes. The calculator can be used in any instance where one would normally consult the NACA 1135 tables and graphs, except now it is available on the workstation.

ANALYSIS

The compressible flow calculator will solve for isentropic flow, normal shock flow, oblique shocks generated by a compression ramp, and centered Prandtl-Meyer expansion generated by an expansion corner. The equations relating the flow variables in these compressible flow problems all depend on the ratio of specific heats, γ , which must be specified by the user and which is defaulted to 1.4 . The isentropic and normal shock equations are algebraic equations of one parameter, as given in Ref. 4. In the calculator, all of the flow variables are calculated as functions of Mach number. If the user provides an input variable which is not the Mach number, the equation relating that variable to Mach number is solved for the Mach number and then all the output variables are computed. The oblique shock and centered expansion equations are algebraic equations of two parameters chosen from the flow variables plus the wedge deflection angle. In theory, any two of these parameters will determine the value of all the other variables. To simplify the programming for the calculator, it is assumed that the free stream Mach number and one other parameter are specified. The equations governing these two problems are given in detail in Ref. 2.

The educational simulator will solve for flow past a single wedge, opposed wedges, or two successive wedges. The flow phenomena present in these problems include oblique and normal shocks, intersecting and reflecting shocks, and the generation of slip surfaces at shock intersections. The equations governing oblique and normal shocks are given in Ref. 4, and their implementation in the simulator is given in

Ref. 2. For the opposed and successive wedge problems additional analysis is needed at the shock intersection. Details of this analysis is given in Refs. 3 and 5. For the intersecting shocks, two new shock waves are generated at the intersection point whose strength are determined such that the flow downstream of both new shocks has the same static pressure and the same deflection, see Fig. 1a. Because the incoming and transmitted shocks are generally all of different strength, the flow passing through the upper incoming and transmitted shocks will be at a different Mach number, velocity, temperature, and density than the flow which passed through the bottom incoming and transmitted shocks. A slipstream is then generated at the intersection point dividing the two dissimilar flows. For the successive wedge problem, Fig. 1b, the flowfield is similar although one of the transmitted shocks is usually very weak. Under some flow conditions, this "weak shock" must actually be a weak expansion to balance the downstream pressures. When the shock strikes a wall, as shown in Fig. 2, it is reflected and the angle of reflection and the change in conditions across the reflected shock are determined by turning the incoming flow parallel to the wall. The equations used to compute the conditions behind the reflected shock are those given in Ref. 2 with the "wedge" angle equal to the turning angle behind the incoming shock. The computational problem is simply one of locating the reflection point and properly orienting the problem to use the previously developed flow equations.

The inlet design simulator will solve for the flow through rectangular external or mixed compression inlets. The supersonic flow phenomena present in the educational simulator are also present in the supersonic portion of the inlet. There are, however, some additional flow phenomena which must be considered in the inlet. The incoming flow can be inclined to the first ramp by some aircraft angle of attack changing the effective ramp angle. The supersonic portion of the inlet is a succession of ramps in which the output conditions from one ramp become the input conditions to the next ramp. As the ramps turn the flow, some flow is spilled around the cowl creating a drag on the inlet which must be computed. The flow going into the engine at the end of the duct is subsonic and therefore a terminal normal shock is usually present somewhere in the inlet. For the external compression inlet, the normal shock sits outside the cowl with the exact distance from the cowl determined by the airflow requirements of the engine. A model for the change in flow conditions from the terminal shock to the engine face is included in the simulator with the details of this model given in Ref. 1. For the mixed compression inlet, the normal shock sits inside the inlet duct with its location again determined by the airflow through the engine. An additional oblique shock is formed from the cowl lip which may reflect from the ramp surfaces. If the normal shock is formed in a portion of the inlet duct where the area is decreasing as one heads downstream, the shock will immediately be disgorged by the inlet and sit outside the cowl in an external compression mode. This is referred to as an unstarted inlet and this flow situation is modeled in the simulator. To remain started, the normal shock must form in a portion of the inlet where the area increases as one heads downstream. To insure this condition, many mixed compression inlets provide for airflow bypass and the simulator also models this condition. The airflow through the inlet duct is determined by the supersonic conditions at the cowl. The engine airflow is set by the user and the difference between these airflows is dumped through the bypass system.

DESCRIPTION OF APPLICATIONS

A brief description of the development of these applications can aid future users or modifiers of these packages. Work began on the first of the three applications in May of 1993 on a Silicon Graphics 4D25TG Personal Iris. The codes are written in the C programming language to be fully compatible with the graphics. The graphical user interface is based on the FORMS library which runs on the SGI workstation and uses the shared GL graphics library. The author has written the view window graphics portion of the codes again using the shared GL graphics library. During the course of code development, a version was moved to an IBM RISC 6000 workstation running the GL graphics library with some minor modifications to the FORMS library required for successful operation on this platform. It was recognized early in the development that the codes would eventually be configured to operate on multiple platforms using some X-based

graphics system such as Open-GL or Motif. To facilitate the transition from GL, each code was originally configured in three sections, as shown in Fig. 3. The first section deals only with the layout and drawing of the graphical user interface (GUI). The second section performs the interactions between the GUI and computational portion of the code. The third section contains only the computational routines for each application and is totally independent of the graphics system used on a particular platform. This configuration leads to some inefficiencies, such as flags being set to pass information, but a large portion of the code remains unchanged when moving from one graphics system to another. The calculator was transitioned to X-based Motif and it required only several days of recoding. Additional time will certainly be required for the simulators because of the more complex widget sets and the graphics view windows.

Fig. 4 shows some examples of the compressible flow calculator. On the left side are two screen dumps from the GL version of the application while on the right is a screen dump of the Motif version. On the workstation screen, both calculators are small windows; on the order of 300x200 pixels for the Motif version. For the GL version, the user chooses the problem for solution by selecting one of the radio buttons at the top; the left example shows isentropic flow, the right shows an oblique shock. Depending on the problem, a screen of flow variable buttons and input windows appear in the center section. The user enters the input values in the text field, and selects the output variable to be computed by pushing the appropriate variable button. The output value then appears in the text box next to the "Exit" button. On the actual calculator the screens, buttons, and text fields are color coded for better understanding, but for this paper a black and white version was prepared. The Motif version is quite similar to the GL version except that now the radio choice buttons are located along the upper left corner. Each module must be loaded by pushing the "Load" button at which time the variable buttons specific to that module appear to the right. During development of the Motif version it was decided to use just one text window for both input and output. In the Motif version the user selects an input variable, types in the value of that variable, then selects an output variable and the value automatically appears in the text field. As previously noted, the GL version will run only on SGI or IBM machines running GL graphics, while the Motif version will run on any X-based workstation supporting Motif.

In the creation of the educational simulator, the inlet design package, and several packages still under construction, some common interface design principals have been developed. Referring to Figs. 6 through 10, all of these applications include a schematic drawing of the component or physics problem which changes as the user interacts with the application. To control the schematic drawing, the user employs sliders located around the view window to size and translate the images. In all of the packages, inputs and outputs are grouped on separate panels. In some cases, multiple panels are required which are displayed or hidden depending on the needs and wishes of the user. For inputs, wherever possible, the user is given the option of modifying variables using either sliders or type-in boxes. The former can be rather quickly manipulated, while the latter provides the precise specification of input conditions. For outputs, information is presented both through sliding bar charts and through numerical output boxes. Again, the former displays trends and sensitivities while the latter provides accurate numerical values. Color is used extensively to highlight and differentiate variables although, in the examples presented here, only black and white results can be shown. To record information from the packages, the user can press buttons which write restart files or formatted output files which can be printed. The user can use workstation utilities to capture pictures of the applications and later versions will include post script pictures. At any time the user may invoke the on-line "Help" screen, as shown in Fig. 5, which serves as a user's manual for the application. The "Help" screen consists of a text browser with selection buttons for the user's topic of interest.

Screen dumps of the educational simulator are shown in Figs. 6, 7, and 8 for the single wedge, successive wedges and opposed wedges respectively. Fig. 6 shows the basic layout of the simulator which is divided into four main sections. The main view window, in the upper left, shows the geometry, the shock (or expansion), and labels for the hinge and the wedge. The wedge appears as the lower nearly

horizontal line with the small semi-circle denoting the hinge location. The upstream flat portion is tagged "0" while the movable wedge is tagged "1". The shock appears as the upper nearly diagonal line originating at the hinge location and flow is from left to right above the wedge surface. The plotter view window is located to the right of the main view window. The student selects which sets of variables to plot using the input box. The computed output flow conditions are displayed in the output box below the plotter view window. As the flow conditions are changed, the recalculated numbers are displayed and the bar charts move much like a thermometer. This type of visual output allows the student to immediately sense in what direction the flow variables change and by how much for a given input. The input box is located to the left of the output box. It includes some buttons to select a problem for study and four sub-panels to vary conditions in the problem. The contents of the sub-panels depend on the problem chosen for study. In Fig. 6 a single wedge problem is indicated by the darkened "light" on the button and only three of the four sub-panels are required for input. The first sub-panel controls geometry and free stream flow conditions. The lower two sub-panels are used to control the plotting of data; two sub-panels are used to allow flexibility in the types of plots one can generate for different physics problems.

In Fig. 7, Mach 2.5 flow past two 10.0 degree wedges has been calculated resulting in the intersection of two shocks of the same family. The shocks tagged "1" and "2" appear to coalesce into the shock tagged "3". For this set of conditions a very weak secondary expansion, tagged "4" is necessary to match the static pressure and flow deflection conditions downstream of the intersection and a slipstream is generated between zones 3 and 4 as indicated by the dashed line. The results presented in the output box give the conditions in zone 4 downstream of shock "4". These results have been checked against the NACA-1135 curves to insure proper coding. An additional input sub panel appears when this problem is selected to allow the user to set the second wedge angle and the distance between the wedges. The right plotter sub panel has also changed from the single wedge problem. The new plotter sub panel allows the student to control the location of a probe for mapping the flow field.

In Fig. 8, the student has chosen to study the flow between two opposed wedges, one at 10.0 degrees and the other at 5.0 degrees. The generated shocks are of unequal strength, opposite family, and intersect with each other then reflect from the opposing wedge producing a diamond shock pattern. At the shock intersections, slipstreams are formed as indicated by the dashed lines in the main view window. The output box shows conditions in zone 3, the lower part of the first diamond. The flow in zone 3, as well as the slipstream, are inclined at 5.0 degrees to the horizontal while the flow in zone 1 is 10.0 degrees and zone 2 is -5.0 degrees. The plotter has been invoked by pushing the "ON" button in the left sub-panel of the input box. In the main view window a set of axes, labeled "X" and "Y" appear as does a set of cross-hairs which define the location of a probe. In Fig. 8, the user has chosen to plot static pressure ratio versus X direction as indicated by the lights on the buttons in the "Probe" sub-panel. The student uses the "X" and "Y" sliders to move the cross-hairs in the main view window until the desired location is found. The student then pushes the "Take Data" button and a "*" appears on the graph corresponding to the chosen value of location and calculated value of dependent variable (pressure ratio). The student can repeat the process to a maximum of twenty five data points per curve. The data can be taken in any order, so the student can fill in interesting portions of the curve.

Since no educational tool would be complete without an examination, a question and answer box has been added at the lower right corner as shown in Fig. 8. The questions and answers are stored in a data file which the simulator accesses. Teachers can edit this data file and add, modify, or delete questions and answers as required. To operate this feature, the student pushes the "Question" button for a question, then uses the simulator to obtain an answer, then presses the "Answer" button to check the answer. The questions can appear in the window either sequentially or randomly as chosen by the student with the appropriate buttons. The current set of questions and answers initially presents easy questions to promote an interaction of the student with the simulator. Gradually, more difficult questions are introduced. If the student chooses the random order of presentation, difficult and easy questions are intermingled. As currently configured,

the simulator runs through the same questions every time the simulator is invoked. This portion of the tool can be modified to present questions from different data files or even questions with a timer but without the provided answers - a true examination tool.

Figs. 9 and 10 display screen dumps from the inlet simulator for an external compression and mixed compression inlet respectively. There are many options available to the inlet designer using this package and the reader is referred to Ref. 1 for the details. The simulator is divided into three main sections; a view screen at the top, the input box in the lower left, and the output box in the lower right. The view screen shows a schematic drawing of the inlet geometry, the oblique and and normal shock waves, the capture streamtube, numerical labels on the flow zones between the shock waves, and an arrow indicating the free stream flow direction. The input box to the left and below the view screen controls the geometry and flow input variables. The user can fix the flow conditions and vary the geometry, or fix the geometry and vary the flow conditions by selecting the appropriate button at the top of the box. The darkened window in the button indicates the choice and a separate interaction screen appears in the box. Fig. 9 shows the analysis screen in the input box. This screen contains buttons to specify what type of analysis is to be performed; either external or mixed compression, with or without drag calculation. Free stream, engine face, and bypass conditions can be specified using either sliders or input text boxes. Fig. 10 shows the geometry screen which is divided into separate sections for the external ramps, the cowl lip, the shoulder, and the engine face. As the geometry is changed the simulator recalculates all of the flow variables, displays the current output parameters, and changes the geometry and the shocks in the view window. The output box to the right of the input box controls the presentation of numerical results to the user. The box contains a fixed screen at the bottom showing drag, Mach number and recovery through the inlet, and optional screens at the top. The optional screens can display either a single flow variable through all of the flow zones as in Fig. 10 or all of the flow variables within a single zone as in Fig. 9. In Fig. 9, the user can pick which variable to display through the inlet and the reference conditions. The previous zone reference will display the ratio of variables from zone to zone, while the free stream reference will display differences in the flow variable.

SUMMARY

Three computer applications have been developed to solve inviscid compressible fluids problems using interactive computer graphics. The first application is a compressible flow calculator which solves for isentropic flow, normal shock flows, and oblique shocks or centered expansions produced by two dimensional ramps. The second application couples the solutions generated by the first application to a more graphical presentation of the results to produce a desk top simulator of three compressible flow problems: 1) flow past a single compression ramp; 2) flow past two ramps in series; and 3) flow past two opposed ramps. The third application extends the results of the second to produce a design tool which solves for the flow through supersonic external or mixed compression inlets.

These tools can be used in either an educational environment or for preliminary design. The calculator can be used for many external or internal compressible flow problems. The tools are being upgraded to work on any X-based platform. The technology demonstrated by these applications can be utilized in many areas of aerodynamics including airfoil design, turbojet analysis, stability and control, shock tube aerodynamics, and nozzle flow problems.

ACKNOWLEDGEMENTS

The current simulator uses the FORMS library for graphical user interfaces developed by Mark H. Overmars, Department of Computer Science, Utrecht University, The Netherlands for Silicon Graphics workstations. Some modifications to this library have been made to allow the package to also be used on IBM Risc 6000 machines. All of this software is public domain and may be copied and used for non-commercial products, but not resold. Copies of the source are available from the author at the NASA Lewis Research Center.

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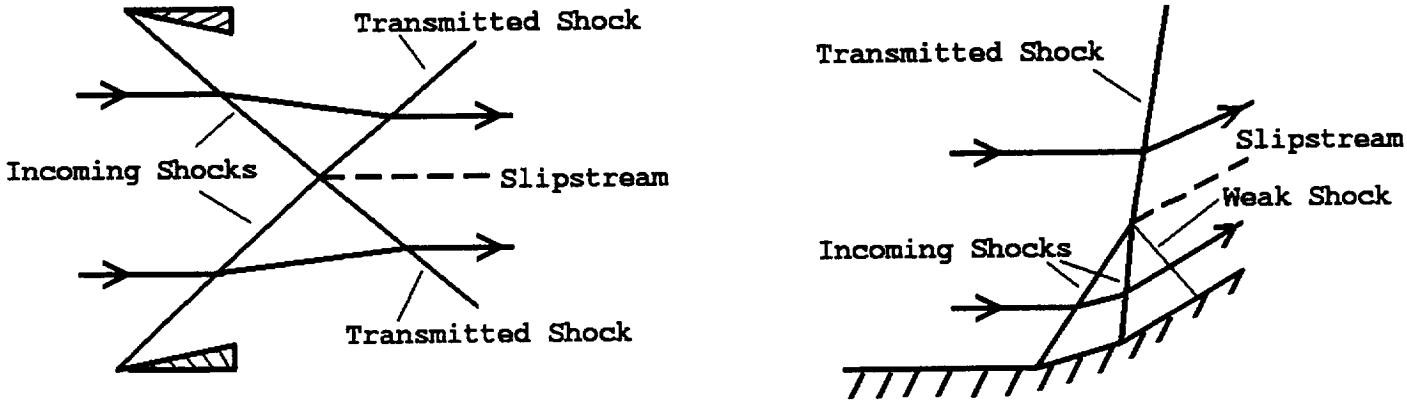


a. Opposed wedges.

b. Successive wedges.

Fig. 1. Intersecting shocks.

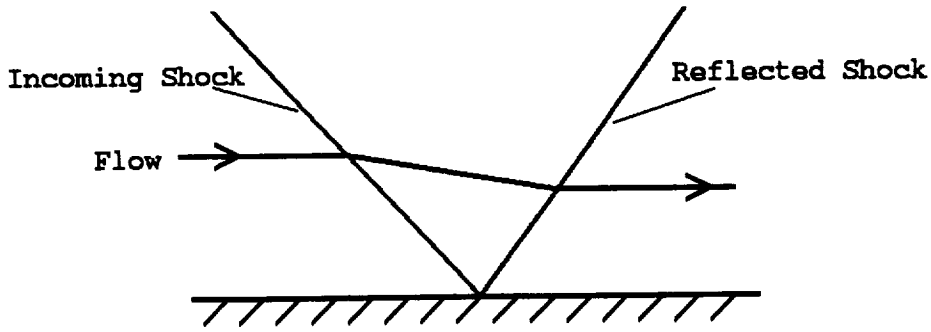


Fig. 2 Reflecting shock.

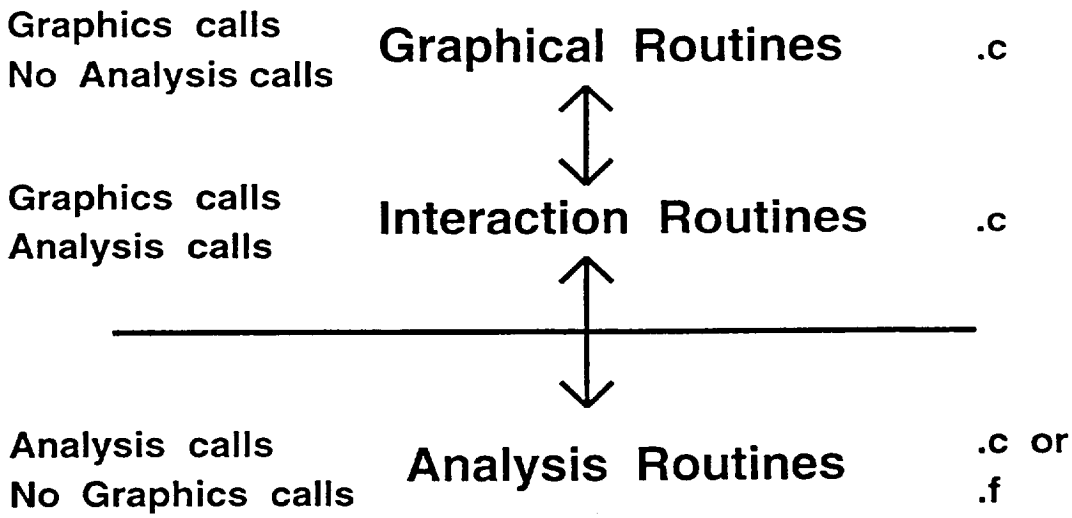
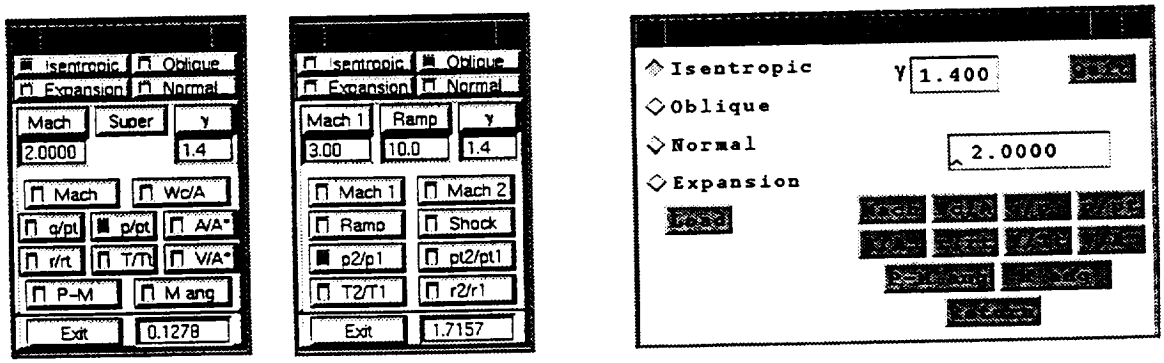


Fig. 3 Philosophy for code development.



a. GL graphics

b. Motif widgets

Fig. 4 Examples of compressible flow calculator.

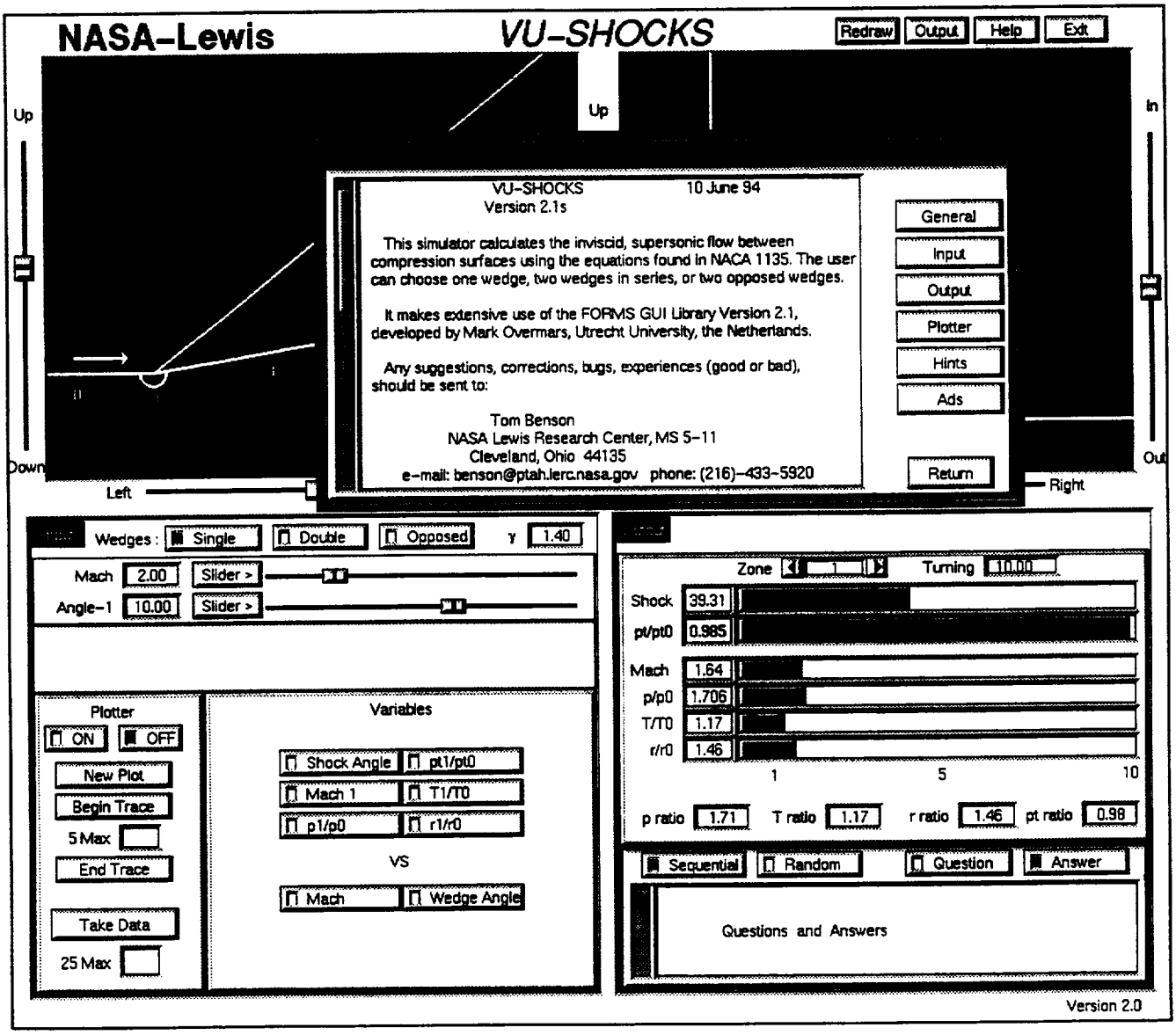


Fig. 5 On-line help screen.

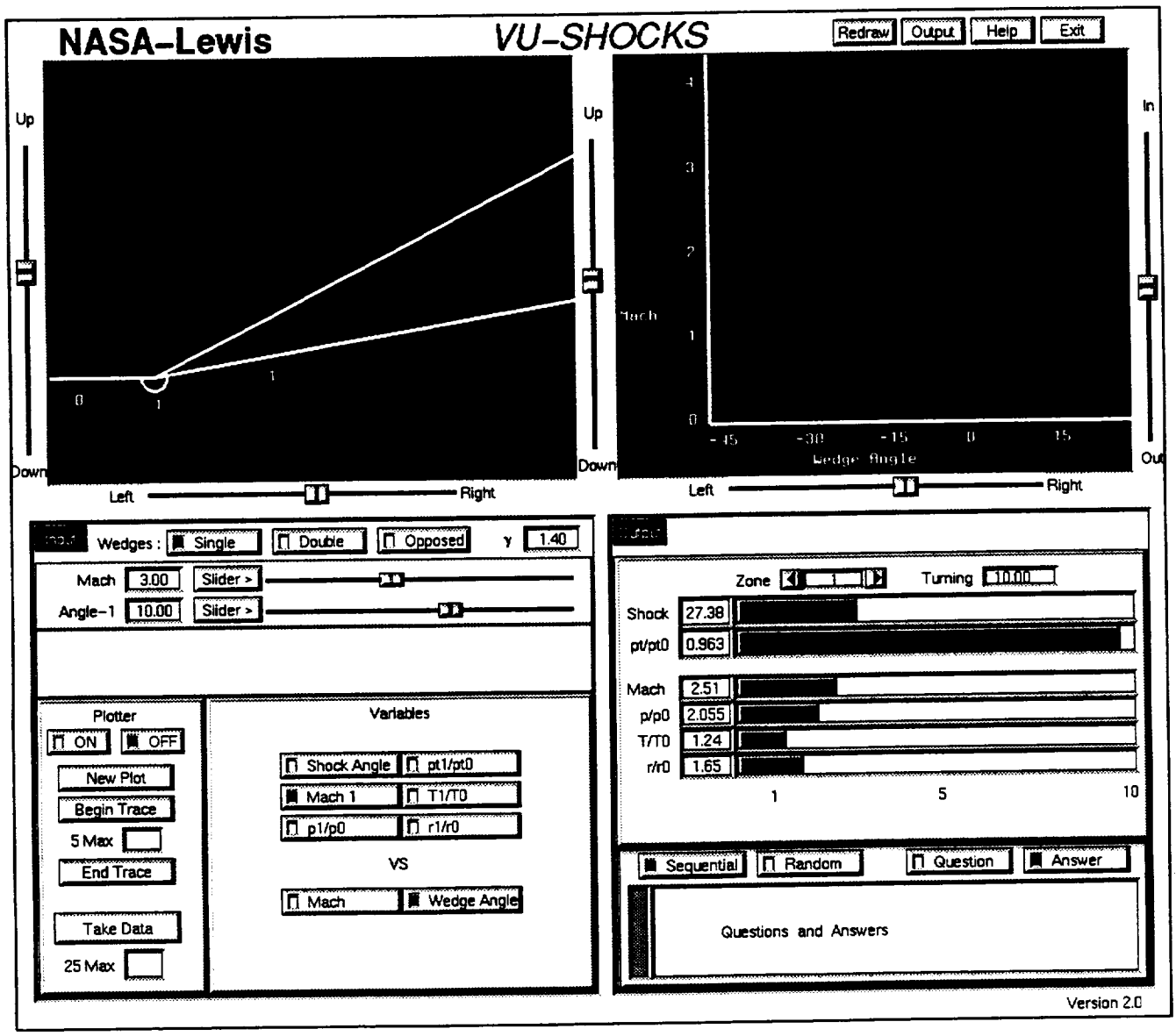


Fig. 6 Educational simulator.

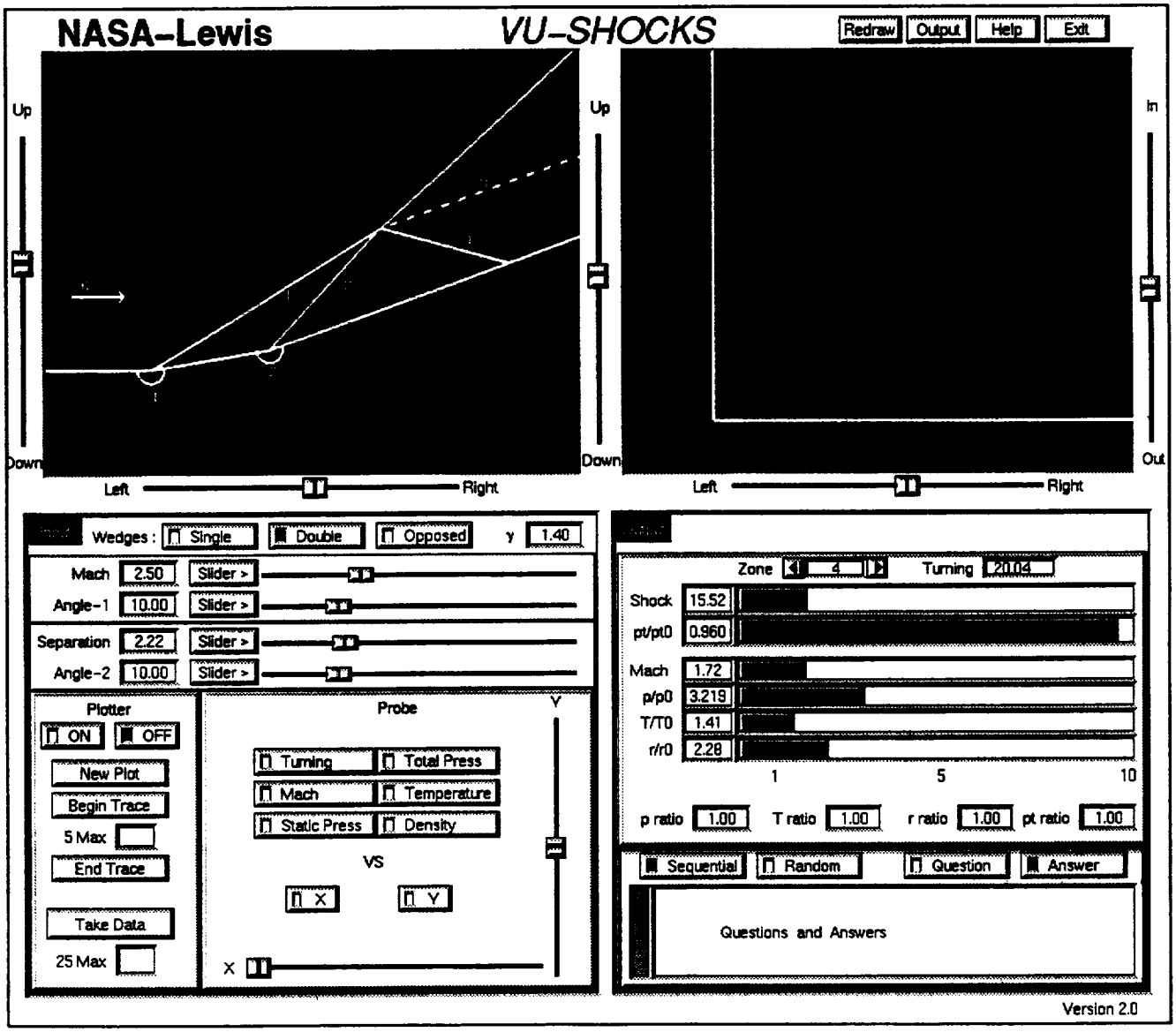


Fig. 7 Successive wedge problem.

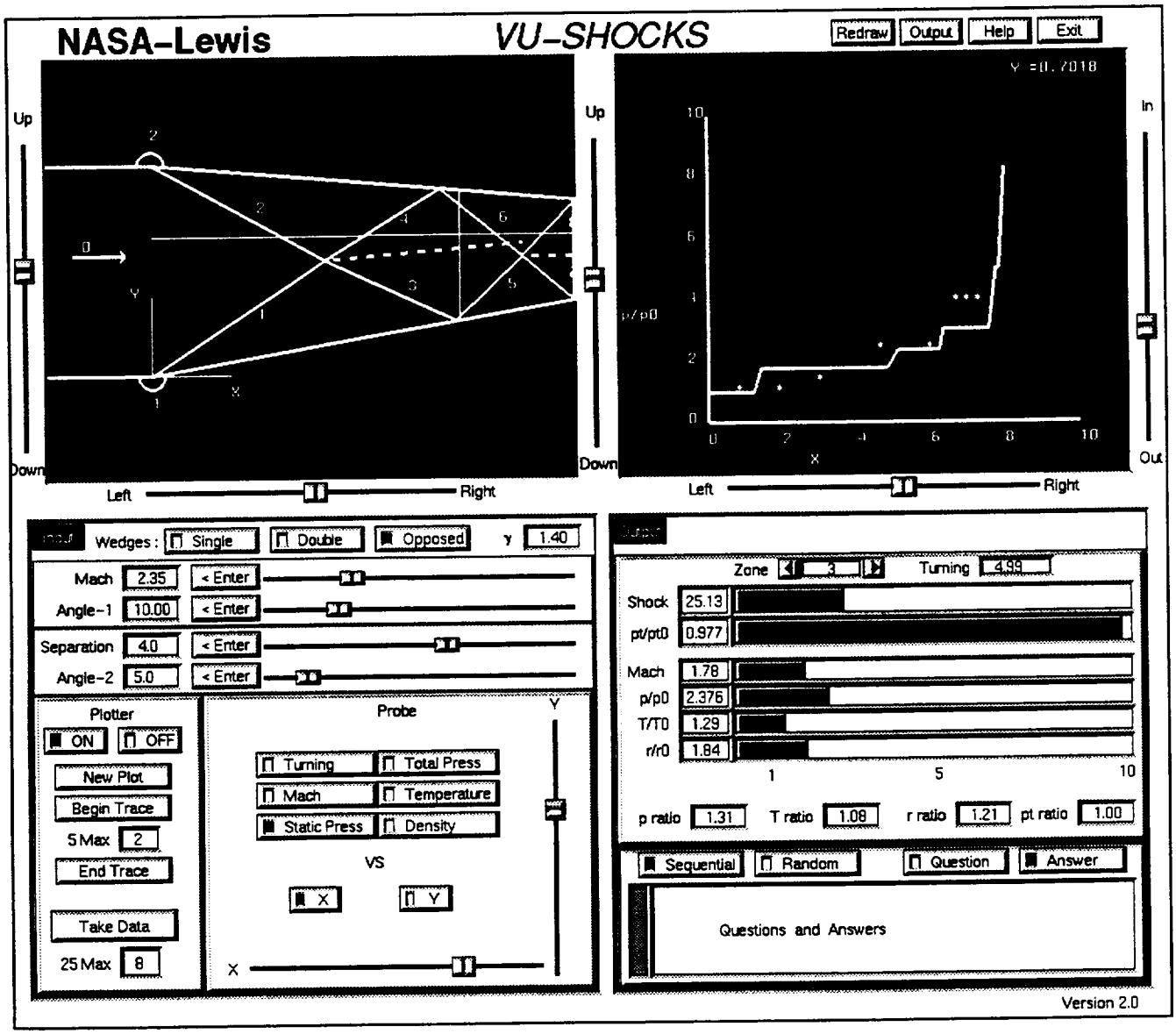


Fig. 8 Opposed wedge problem.

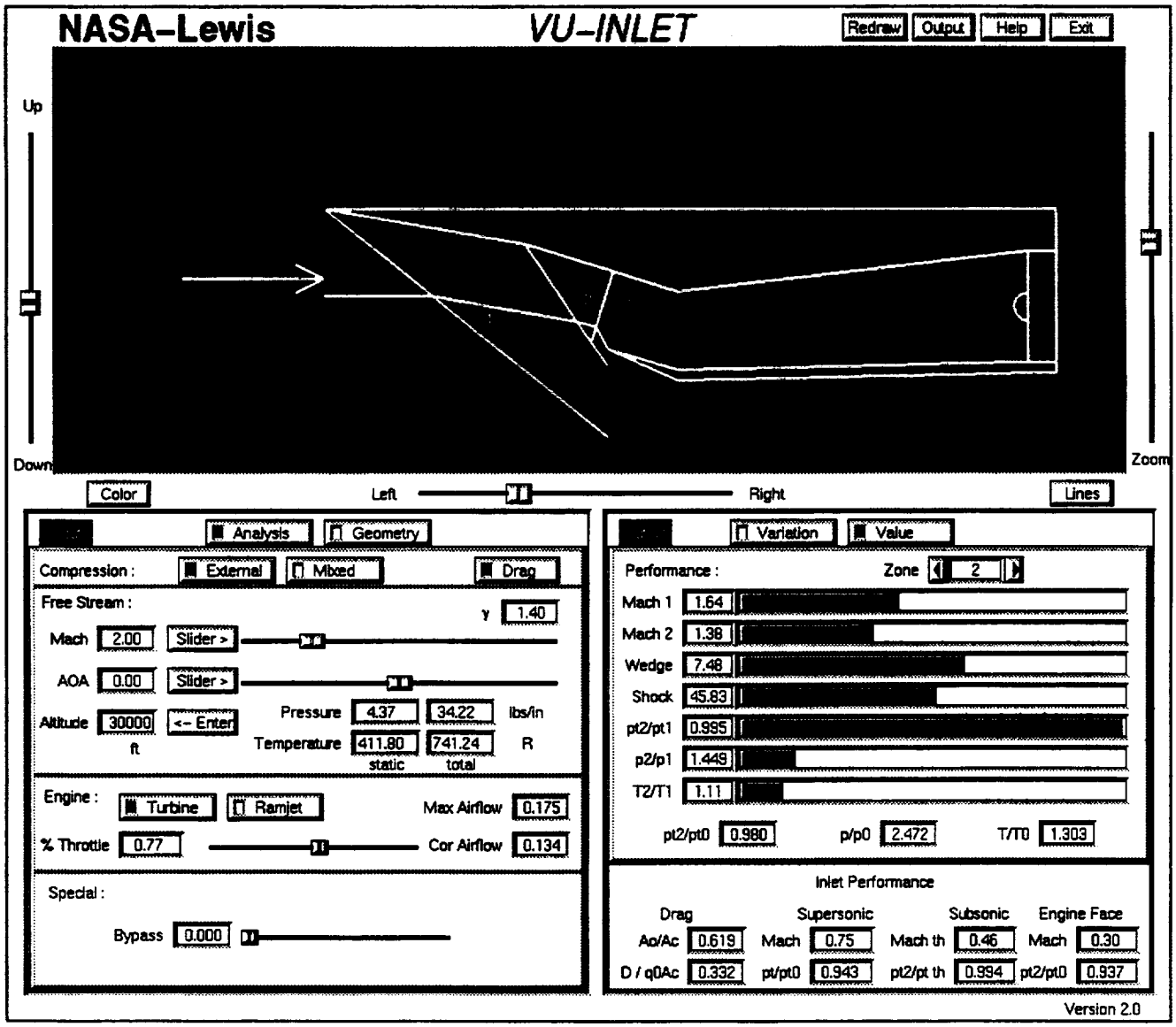


Fig. 9 External compression inlet.

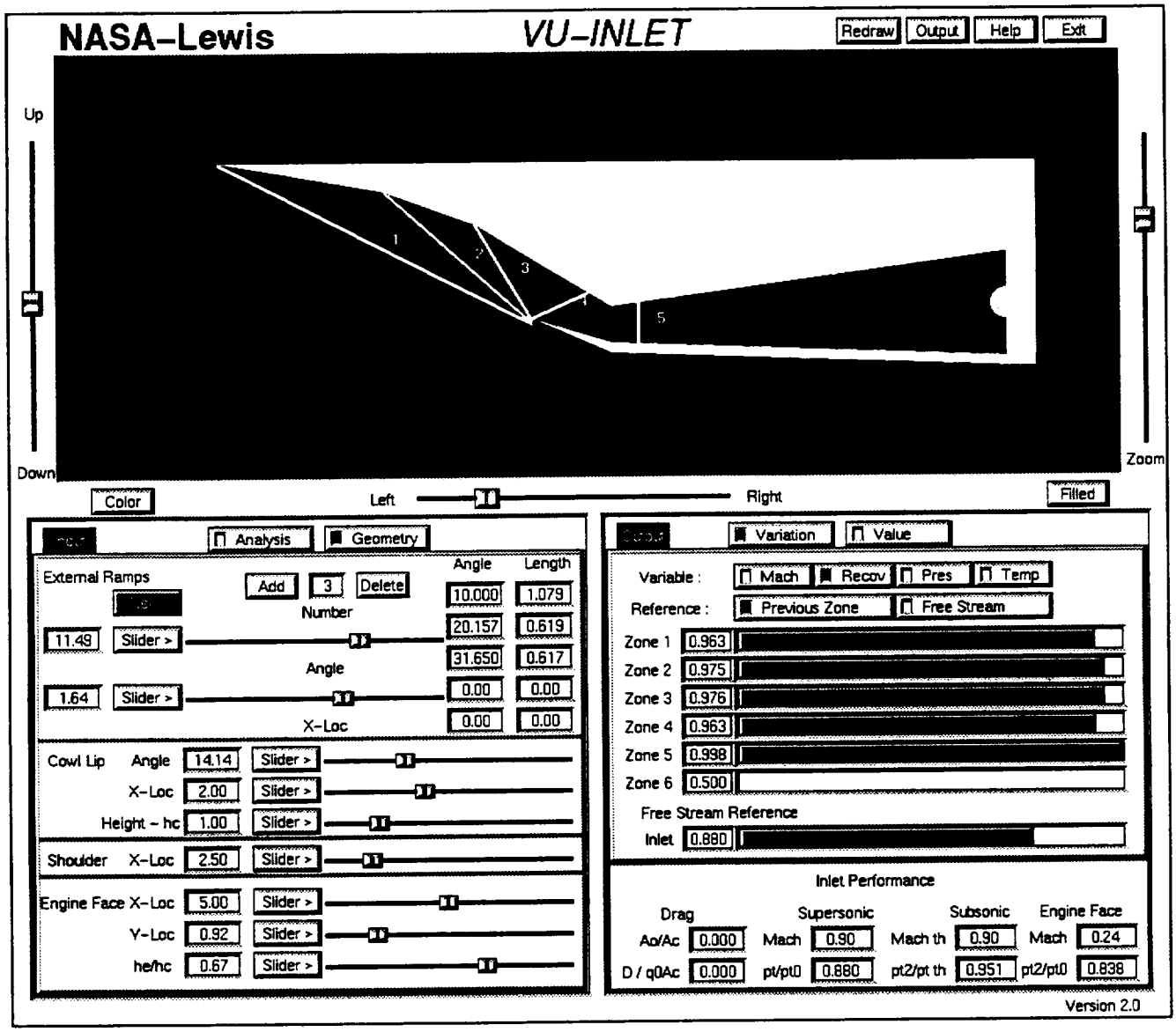


Fig. 10 Mixed compression inlet.

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13. ABSTRACT ***(Maximum 200 words)***

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