The Beginner's Guide to Wind Tunnels With TunnelSim and TunnelSys

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Abstract

The Beginner's Guide to Wind Tunnels is a Web-based, on-line textbook that explains and demonstrates the history, physics, and mathematics involved with wind tunnels and wind tunnel testing. The Web site contains several interactive computer programs to demonstrate scientific principles. TunnelSim is an interactive, educational computer program that demonstrates basic wind tunnel design and operation. TunnelSim is a Java (Sun Microsystems Inc.) applet that solves the continuity and Bernoulli equations to determine the velocity and pressure throughout a tunnel design. TunnelSys is a group of Java applications that mimic wind tunnel testing techniques. Using TunnelSys, a team of students designs, tests, and post-processes the data for a virtual, low speed, and aircraft wing.

Introduction

The development of personal computers and the Internet presents new methods for students to learn mathematics and physics. The Web requires the use of a browser program that retrieves information from anywhere in the world and displays the information on the monitor screen. Special computer software like Java has been developed that can execute programs (or applets) within the browser. The input to and output from these programs is principally graphical and visual. Since vision is the most perceptive sense used in education, applets are particularly well suited for education. Educational applets can provide a student with a simulated desktop laboratory that can be used to develop a feel and an understanding of math and physics. Although the Web is currently used primarily for news, business and advertisement, engineers and scientists are beginning to develop software for the Web that can be used in education. For example, Reed and Afjeh, Reference 1, have developed a turbine engine design and analysis package, and Devenport and Shetz, Reference 2, have developed several aeronautical software packages that execute on the Web. Martindale, Reference 3, currently lists over 23,000 calculator programs, covering a wide range of engineering disciplines that are available on the Web. Most of these programs are intended for practicing engineers, but some of them are finding their way into undergraduate education.

A team at the NASA Glenn Research Center has been investigating the use of the Internet for educational purposes. The studies have lead to the development of a large Web site called the Beginner's Guide to Aeronautics (BGA). The BGA is a Web-based textbook that includes interactive programs to demonstrate science, technology, engineering, and mathematics using airplanes, jet engines, model rockets, kites, and compressible, and hypersonic aerodynamics. The BGA is divided into several sections with each section built around an interactive software program. The Beginner's Guide to Propulsion (BGP) section provides the math and physics background information for EngineSim, Reference 4.

EngineSim is a Java applet that calculates the thrust and fuel usage of a jet engine by performing a Brayton cycle thermodynamic analysis as described by Hill and Peterson, Reference 5, and Mattingly, Reference 6. EngineSim allows the student to vary all of the parameters involved in the thermodynamic analysis of a turbojet, turbofan, or ramjet engine and estimates the weight of the engine based on engine size and the component materials. The BGP is intended for students and teachers who desire a more thorough understanding of propulsion physics. Similarly, FoilSim and the Beginner's Guide to Aerodynamics section, Reference 7, were built for students to explore the fundamentals of airfoils and the generation of lift and drag.

The current paper presents information on a new section of the BGA that deals with wind tunnels. The science and mathematics are described in a new Beginner's Guide to Wind Tunnels (BGT) and there are several new applets and applications that allow students to learn the basics of wind tunnel design and testing techniques. TunnelSim allows the students to design a wind tunnel by changing the geometry and flow conditions in the tunnel. TunnelSys explores the process of wind tunnel testing from the design of tunnel models, through the actual testing, post-processing, and model modification. Additional background information is provided by nearly one hundred hyperlinked Web pages covering such topics as wind tunnel force balances, instrumentation, and flow visualization techniques. In the same way that the Web-based BGP was able to provide the technical information from the classical propulsion textbook of Mattingly and Hill and Petersen, it is hoped that the BGT will provide much of the technical information from the classical wind tunnel textbooks of Pope, References 8 and 9.
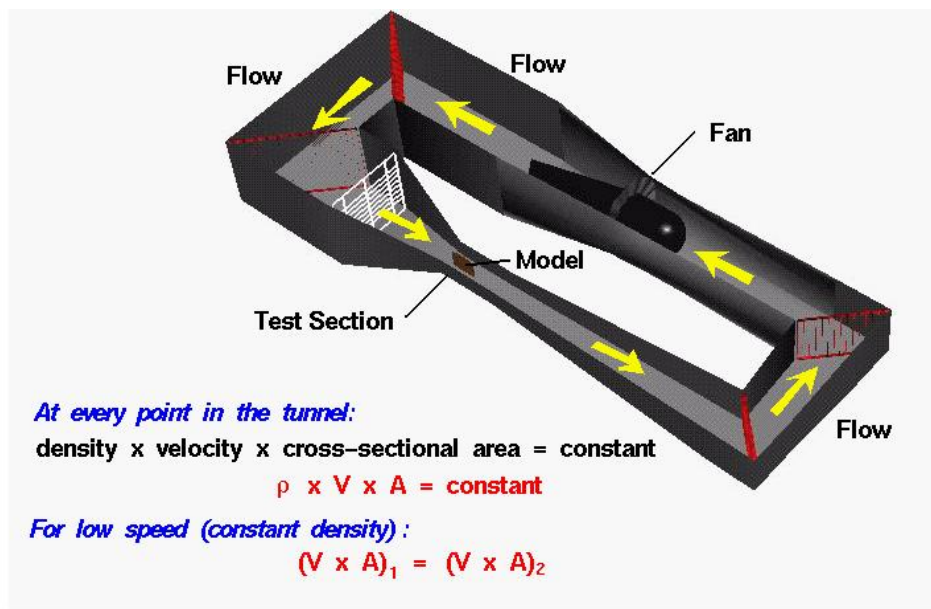
Nomenclature

A Area
p static pressure
u velocity
ρ gas density

Beginner's Guide to Wind Tunnels

The Beginner's Guide to Wind Tunnels (BGT) provides teachers and students with the basic science, technology, engineering and mathematics (STEM) that is used in wind tunnels. The BGT is a Web-based textbook with pages that utilize the power of the Internet. Each page includes many linked references to other pieces of information, sophisticated computer graphics and animations, and interactive applets to demonstrate math and physics principles. The Web site includes galleries of pictures of wind tunnels and their application, Microsoft PowerPoint (Microsoft Corporation) presentations about wind tunnels that have been developed by NASA scientists, and copies of NASA publications on wind tunnels that the user can download or read on-line. Construction plans for several student wind tunnels are also available at the Web site.

The format for a typical page from the BGT is shown on Figure 1. At the top of each page is a slide describing some topic associated with a wind tunnel; in this case, the operation of a low speed wind tunnel. The size of the slide was chosen so that it can be easily copied by the user and dropped into the user's Microsoft PowerPoint presentation. Below the slide is a technical description of the topic of the slide with numerous hyperlinks to other pages. The hyperlinks appear as underlined words in different colors from the normal text and can be used to obtain a broad span of information related to the topic, or greater depth of information on a particular topic. Some of the related topics for this page include the flow conditions that affect the forces on the model and the various speed regimes for different types of wind tunnels. Detailed information on this page includes the mathematical equations that describe the variation of speed in the various sections of the tunnel as a function of the cross-sectional area. Mathematical equations and derivations are presented on many pages so that students can see how engineers use math to describe physical systems.

At every point in the tunnel:
density x velocity x cross-sectional area = constant

$$\rho \; x \; V \; x \; A = constant$$

For low speed (constant density):

$$(V \; x \; A)_1 = (V \; x \; A)_2$$

Aerodynamicists use wind tunnels to test models of proposed aircraft. In the tunnel, the engineer can carefully control the flow conditions which affect the forces on the aircraft. By making careful measurements of the forces on the model, the engineer can predict the forces on the full scale aircraft. And by using special diagnostic techniques, the engineer can better understand and improve the performance of the aircraft.

Wind tunnels are designed for a specific purpose and speed range and there is a wide variety of wind tunnel types and model instrumentation. The tunnel shown in the figure is a low-speed, closed tunnel which we are viewing from above. The air inside the tunnel is made to move by the fan on the far side of the tunnel. Air continuously circulates through the wind tunnel, passing over the model that is mounted in the test section.

Figure 1.—Typical beginner's guide Web page.

The model is instrumented to provide the engineer with test data. To obtain meaningful data, the engineer must insure that the flow similarity parameters of Mach number and Reynolds number match the desired flight conditions. Both the Mach number and the Reynolds number depend on the velocity and density in the tunnel.

Activities:

9-12   9-12   9-12   9-12

Navigation ..

Wind Tunnel Index   Aerodynamics Index   Propulsion Index

Beginner's Guide Home Page

Figure 2.—Bottom of typical Web page for beginner's guide.

At the bottom of every Web page there are navigation buttons, as shown in Figure 2. The activities buttons are linked to problems that were generated by teachers at summer workshops hosted at NASA Glenn. The "Wind Tunnel Index" button links to a list of all the pages at the BGT. Figure 3 shows the current status of the index page.

WIND TUNNEL HISTORY

Wind Tunnels of NASA NASA/SP-440 pdf
On-line Wind Tunnel Information
Historical Wind Tunnel Gallery
Whirling Arms & the First Wind Tunnels

WRIGHT BROTHERS

Bicycle Test
1901 Wind Tunnel Tests
1901 Wind Tunnel
Wind Tunnel Models
Wind Tunnel Results
Lift Balance Design
Lift Balance Operation
Lift Equation of the 1900's
Drag Balance Design
Drag Balance Operation
Drag Equation of the 1900's
Smeaton's Pressure Coefficient
Interactive Wright 1901 Wind Tunnel

WIND TUNNELS

Wind Tunnels
Control Rooms
Wind Tunnel Design
Wind Tunnel Theory
Wind Tunnel Parts
Low Speed Tunnel Operation
PowerPoint by Dr. Judy Van Zante
PowerPoint by Dr. Charles Trefny

WIND TUNNEL TYPES

Types of Wind Tunnels
Open Return Wind Tunnel..Interactive**
Closed Return Wind Tunnel
Blowdown Wind Tunnel
TunnelSim Open Return Version

TEST TECHNIQUES

Wind Tunnel Testing
Force Balance
Idealized Force and Moment System
Force Balance Coordinates
Flow Diagnostics
Flow Visualization
TunnelSys -Wind Tunnel Testing Process
Interactive Tunnel Test Program

WIND TUNNEL MODELS

Aerodynamic Force Model
Inlet Performance Model
Nozzle Performance Model
Model Mounts
Wing Geometry ..Interactive**
Interactive Model Design Program

CONSTRUCTION

Build Your Own Tunnel
Student Wind Tunnel Gallery
Aviation High Wind Tunnel
Barberton Wandering Wind Tunnel
Vision in Aeronautics Wind Tunnel
Flow Visualization Wind Tunnel

INSTRUMENTATION

Static Pressure Measurement
Total Pressure Measurement
Pitot-Static (Prandtl) Tube
External Force Balance
Internal Force Balance
Spring Gage
Strain Gage
Hot-Wire Velocity Probe
Smoke Flow and Tufts
Surface Oil Flow
Schlieren Systems
Laser Sheet
Laser Doppler Velocimetry - LDV
Five Hole Probe - Flow Direction
Inlet Instrumentation - 40 Probe Rake

AERODYNAMICS

Aerodynamic Forces
Center of Pressure - cp
Aerodynamic Center
Similarity Parameters..Interactive**
Mach Number..Interactive**
Role of the Mach Number
Mass Flow Choking..Interactive**
Reynolds Number..Interactive**
Boundary Layer
Bernoulli's Equation
Dynamic Pressure
Lift Coefficient
Drag Coefficient
Aerodynamics References

SCIENCE FUNDAMENTALS

Three States of Matter
Newton's Laws of Motion
Newton's First Law
Newton's Second Law - F=ma
Newton's Third Law - Action & Reaction
Torque (Moment)
Equilibrium
Ohm's Law
Resistors in Parallel
Resistors in Series
Wheatstone Bridge Circuit

MATH FUNDAMENTALS

Functions
Area
Volume
Scalars and Vectors
Comparing Two Scalars - Ratio
Comparing Two Vectors
Vector Addition
Vector Components
Trigonometry
Sine-Cosine-Tangent
Ratios in Triangles
Pythagorean Theorem..Interactive**

Figure 3.—Partial index of the BGT.

From the index page, a user can move to any other page at the site by clicking on the name of the page. With the index page, the user is never more than two clicks from any other page at the Web site. The index currently lists nearly one hundred individual pages covering a range of topics including the history of wind tunnels, wind tunnel design and operation, test techniques, instrumentation, types of tunnels, an extensive section on the Wright Brothers' 1901 tunnel, plans for building several wind tunnels, and the fundamental mathematics and aeronautical science pertaining to wind tunnels. The BGT is a "living document" that is constantly being updated to include new features suggested by the users of the Web site. The BGT includes Java applet programs on as many pages as possible to allow users to learn through interaction. The following sections of the paper will discuss two of the major programs available at the BGT.

TunnelSim

TunnelSim is a Java applet that allows students to study and design their own low-speed wind tunnel. There are two distinct versions of the software; one for an open return tunnel, and the other for a closed return tunnel. Figure 4 shows a picture of the open return version of TunnelSim as it appears in the browser. The display is divided into five sections. At the upper right are several buttons and a drop down menu. The red "Reset" button returns the program to the default conditions. Calculations and input may be performed in either Imperial (English) units or metric units by using the menu button. A row of buttons describes the components of the wind tunnel; the bellmouth, the test section, and the diffuser. The buttons are used to reveal input panels for each component with the current selected panel indicated by the yellow-colored button. At the middle right, the selected input panel is displayed. Each component has a distinct input panel with its own design variables for input. Input variables include flow parameters, such
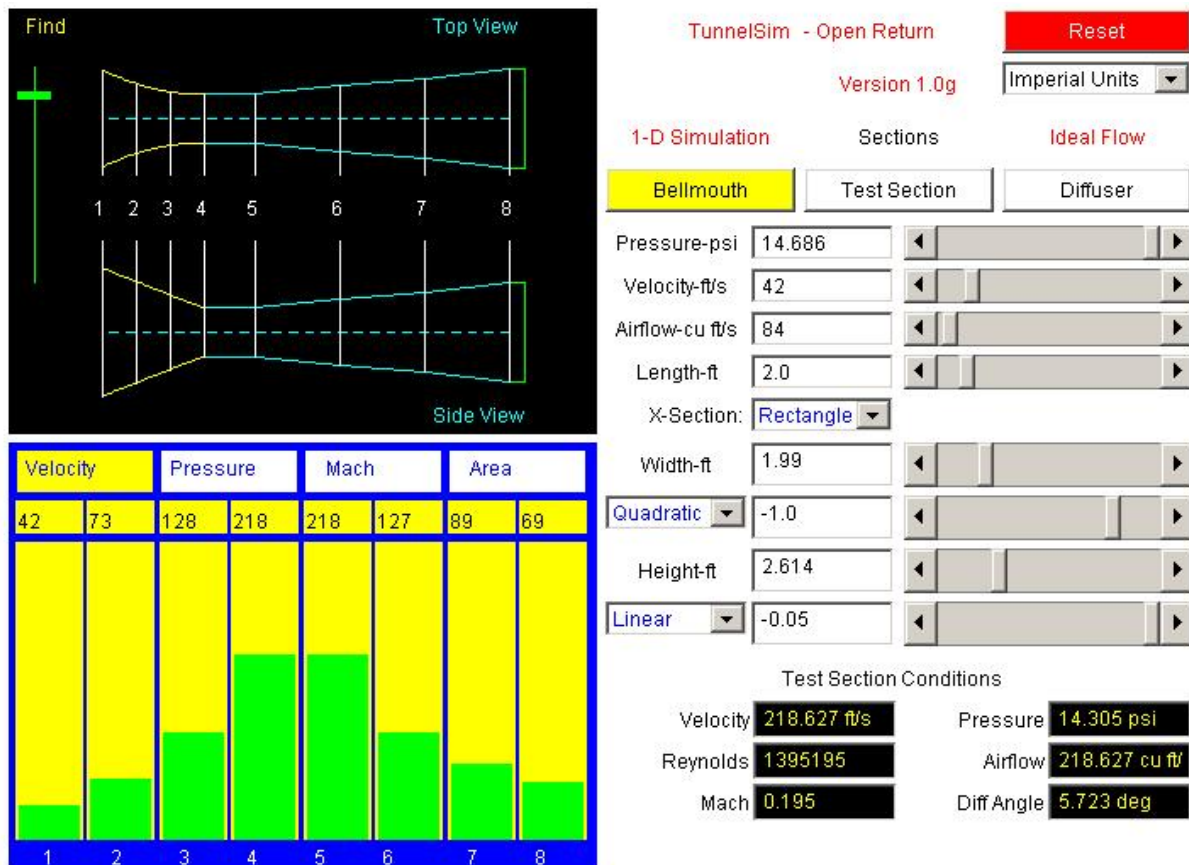

Figure 4.—TunnelSim open return version.

as the pressure, velocity, and airflow, and geometric parameters that define the shape of the component. The student changes the value of an input variable by using the computer mouse to move the sliders, or the computer keyboard to type into the input boxes next to the sliders. On some input panels a drop-menu is used to select an option. As the value of an input variable is changed, the program instantly calculates the values of the flow variables in all of the components of the tunnel as well as the performance variables in the test section and graphically displays the results. At the bottom right, the flow conditions through the test section are displayed, including the Mach number, Reynolds number, velocity, pressure, and diffuser angle. The diffuser angle is the half angle formed by the change in height from the test section exit to the diffuser exit divided by the length of the diffuser. When applicable, warning flags are also displayed at the lower right as discussed below. At the lower left is the output for the various flow variables through the tunnel. The display includes a bar graph and a numerical value for the flow variable at each cross-section indicated on the schematic. The user selects the variable to display by using the buttons located above the graph; the velocity is shown in this figure. At the upper left, the geometry of the wind tunnel is shown. Views from the top and side of the tunnel are indicated on the display. The user can move the display within the window by using the computer mouse and resize the display by using the green slider at the left. As the user changes geometry input variables, the output geometry changes and the flow variable bar graphs are changed. Eight cross-sections are noted on the geometry display corresponding to the locations of the output bar graphs.

The analysis used in TunnelSim assumes low speed flow and neglects the effects of fluid viscosity. The flow is assumed to be one-dimensional with a constant density (incompressible). The conservation of mass, or continuity, equation specifies that

$$\rho \, u \, A = \text{constant}$$

where ρ is the density of the flow, u is the velocity, and A is the cross-sectional area. The value of the constant is determined at some selected cross-section and remains constant throughout the tunnel. For the one-dimensional flow through the tunnel, Bernoulli's equation can be used to relate the velocity and density to the local static pressure, p, in the tunnel:

$$p + \tfrac{1}{2} \, \rho \, u^2 = \text{constant}$$

Since the density is assumed constant through the tunnel, the continuity equation reduces to:

$$u_1 \, A_1 = u_2 \, A_2$$

where the subscripts 1 and 2 represent different locations in the tunnel. As the student changes geometry input variables, the program calculates the change in the local cross-sectional area and the resulting change in velocity and pressure.

There are certain combinations of input variables that violate the assumptions used in the analysis. If a speed of 300 mph occurs anywhere in the tunnel, the density in the tunnel would not be constant because of compressibility effects. If the program detects a high velocity in the tunnel, a red flashing warning is displayed at the lower right of the screen to warn the student that compressibility effects are present. If the diffusion angle from the test section to the exit exceeds 7°, another warning is flashed to warn about possible flow separation in the diffuser. The analysis does not include viscosity, so it cannot predict boundary layer development or separation. But experience has shown that a diffusion angle of 7° or greater often results in boundary layer separation in diffuser ducts.

TunnelSys

TunnelSys is a series of three Java application programs that simulate the systems engineering process of wind tunnel analysis. The separate programs allow students to design a wind tunnel model, test that model in a simulated tunnel, and post-process the data generated during the test to develop performance plots for the design. The individual TunnelSys programs communicate with each other via data files. Because Java does not allow the reading or writing of files from an applet, the programs of TunnelSys are written as Java applications and must be compiled and executed on a personal computer without access to the Internet. Because Java is platform-independent, any operating system may be used on the computer. The user must download and install the Java Development Kit (JDK) on the computer before compiling the programs. The source codes for Tunnelsys are provided for download at the BGT. An applet version of each program with an on-line user's manual is provided so students can learn how the programs operate without saving data files. Each of the applications of TunnelSys writes an output file which can be printed by the student as a record of their calculations.

The TunnelSys design program is shown in Figure 5. The design engineer must design a wing model that will be wind tunnel tested to determine the lift of the design. At the upper left is a computer generated picture of the wing model design. Below the picture are a series of input boxes and sliders that allow the design engineer to change the camber, span, and chord of the model. As the input parameters are changed, the wing drawing is also changed. Output boxes at the bottom of the figure provide information on the wing area and aspect ratio, while engineering drawings of the wing are shown at the right. When the design engineer has completed the design, the blue "Save Data" button is pressed and a form appears on the screen to allow the design engineer to create and save a data file on the computer. The data file can contain several different wing designs that can be wind tunnel tested by another student. Output from the design program is used as input to a wind tunnel simulator.
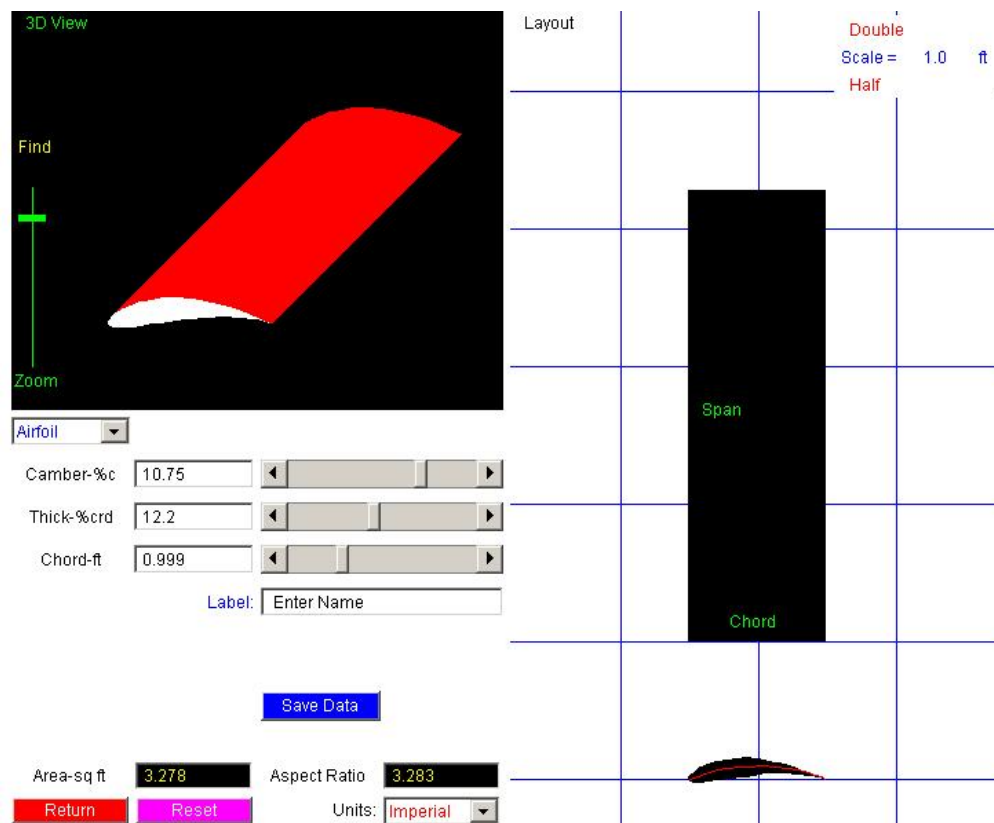

Figure 5.—TunnelSys design program.

The wind tunnel simulator is shown in Figure 6. At the upper left is an animated picture of the model in the wind tunnel. On the computer screen, the blue and white particles flow past the model and separate from the upper surface should the angle of attack become too great. The test engineer sets the speed in the tunnel, the angle of attack of the wing, and the static pressure by using the sliders and input boxes located below the wing graphic. The test engineer selects the wing model for testing by pressing the yellow "Load Models" button. A browser screen appears that allows the test engineer to select the data file generated by the design engineer. At the bottom right the test engineer selects the particular model in the file for testing and the geometric parameters associated with the wing design are shown in the boxes at the lower right. As air flows over the model, the diagnostic plot of the static pressure variation around the airfoil section of the wing is shown at the upper right. Below the plot is a control panel for a diagnostic probe that can be moved through the test section of the tunnel. The probe location is given by the tip of the L-shaped white line in the graphics window at the left. The probe can display the local value of the velocity or pressure or can inject "smoke" into the tunnel for flow diagnostics. Below the probe control panel on the right, the program displays the calculated value of the lift of the wing. To record the output from a wind tunnel test, the test engineer uses the blue buttons in the middle of the program at the left. There are three types of tests that can be conducted: varying the speed while holding the angle of attack and pressure constant; varying the angle of attack while holding the speed and pressure constant; varying the pressure while holding the speed and angle of attack constant. When the test engineer selects the type of test, a screen appears to select a name and location for the output data file containing the results. The test engineer then presses the black "Begin Test" button and changes the selected variable using the slider or input box. Data is recorded by pushing the blue "Take Data Point" button and then a new value of the variable is selected. This process is repeated until the "End Test" button is pushed. Output boxes record the test number and point number as the output is generated. The test engineer may perform additional tests and store the results in the same output file. The output file from the test program is used as input for the data reduction program.
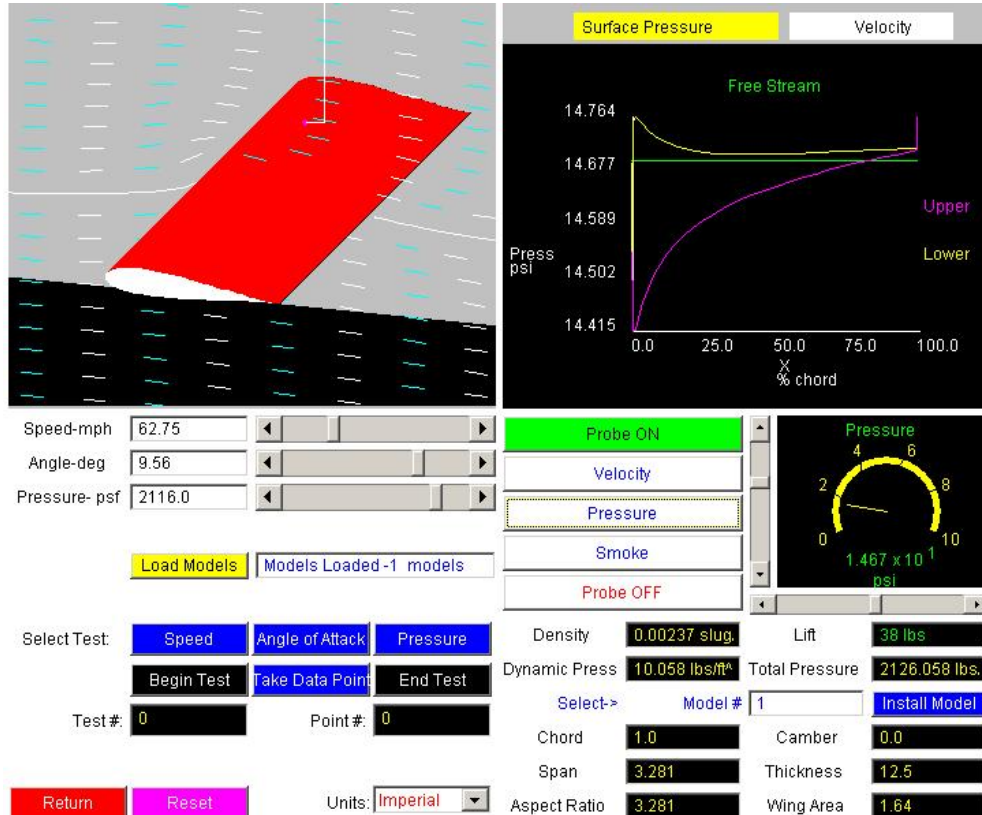

Figure 6.—TunnelSys wind tunnel test program.

The data reduction program is shown in Figure 7. The data analysis engineer begins by selecting the data for analysis by clicking on the "Load Data" button. A browser appears and the analysis engineer selects the data file generated by the test engineer. Since a single file may contain multiple tests, the analysis engineer enters the test number and clicks on the "Open Test" button. The number of data points and the type of test is noted by the program and a plot of the data is displayed at the upper left. The analysis engineer may rescale the plot by using the buttons on the graphics panel. The analysis engineer may also select a different plot display by using the blue buttons on the left. At the upper right of the program is an additional display window. The analysis engineer may select to compare the plot at the left with other test plots in the window at the upper right, or the engineer can display a "movie" of a previous test point, as shown in the figure. The selection is made with the "Display" menu located below the right window. Details of the selected test point are given in the output boxes at the right.

With the information generated by the analysis engineer, the lift performance of the wing design has been determined. The team engineers (design engineer, test engineer, and analysis engineer) must now determine if the process should be repeated to produce a better wing design or whether to proceed to flight test of the design. When used in a design class, the team should probably include a "program manager" to keep the team members on schedule and to determine when the design is finished. As currently configured, TunnelSys can only determine the lift of the wing design. Future versions of the program will also include the drag of the wing.
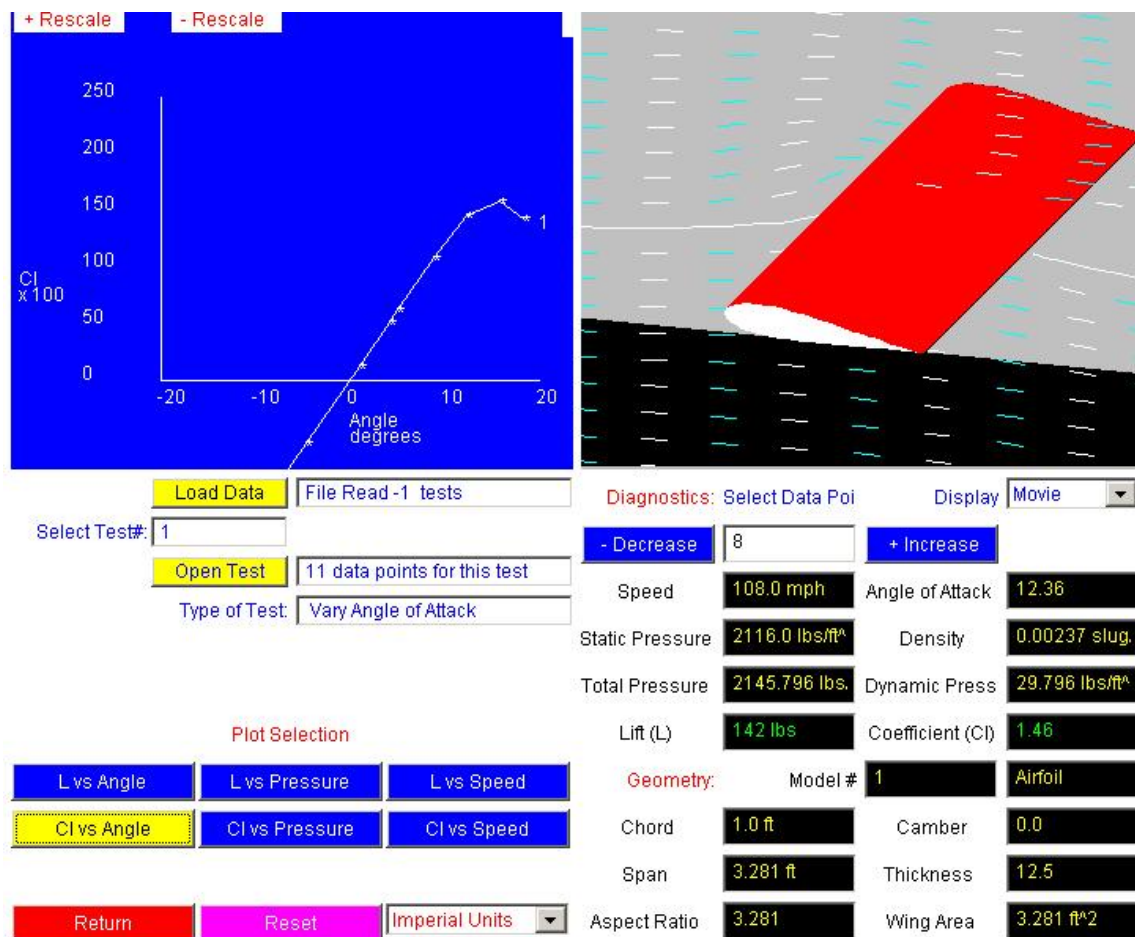

Figure 7.—TunnelSys data reduction program.

Conclusions

High speed personal computers coupled with the Internet, interactive operating systems, and computer graphics provide many opportunities for new techniques to learn science, technology, engineering and mathematics. This paper has presented two new products that use interactive flow simulators and a Web-based textbook. The subject of wind tunnel design is used to introduce the ideas of functions, graphing, physical units, test techniques, and flow measurement and visualization. A guiding principal in the development of the BGT, TunnelSim and TunnelSyS is to do more than just present answers to problems; it is to involve student in the learning process by having them work with the package to achieve a result. When using TunnelSim, as the design parameters are changed, the output panels show the variation in conditions throughout the tunnel, the change in the configuration of the tunnel, and the change in test section performance. With control of the input conditions, the student learns how a wind tunnel operates and performs. More importantly, students see how graphs are used to present data, and develop a feel for the physical concepts of velocity, pressure, density, and the units used to describe them.

TunnelSys has been developed to introduce a team of students to the systems engineering aspects of wind tunnel testing. Each student is responsible for their own part of the wind tunnel testing process; design of a model, testing of the model, and post-processing the data from the test. Communication between the team members and a project manager is important for the success of the project. With the TunnelSys computer programs, students can practice the process without the expense of actually building and testing a physical model.

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14. ABSTRACT
The Beginner's Guide to Wind Tunnels is a Web-based, on-line textbook that explains and demonstrates the history, physics, and mathematics involved with wind tunnels and wind tunnel testing. The Web site contains several interactive computer programs to demonstrate scientific principles. TunnelSim is an interactive, educational computer program that demonstrates basic wind tunnel design and operation. TunnelSim is a Java (Sun Microsystems Inc.) applet that solves the continuity and Bernoulli equations to determine the velocity and pressure throughout a tunnel design. TunnelSys is a group of Java applications that mimic wind tunnel testing techniques. Using TunnelSys, a team of students designs, tests, and post-processes the data for a virtual, low speed, and aircraft wing.

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