Online Wind Tunnel Laboratory

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3 authors:

Elsayed S. Aziz
Stevens Institute of Technology

Sven Esche
Stevens Institute of Technology

C. Chassapis
Stevens Institute of Technology

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El-Sayed Aziz, Stevens Institute of Technology

Constantin Chassapis, Stevens Institute of Technology

Sven Esche, Stevens Institute of Technology

Sumei Dai, China University of Mining and Technology

Shanjun Xu, China University of Mining and Technology

Ruiqing Jia, China University of Mining and Technology

Online Wind Tunnel Laboratory

Abstract

Wind tunnels are among the most important design tools used in engineering to study the effects of air moving over or around solid objects such as airplane wings, cars, trains, skyscrapers, bridges, etc. While introducing wind tunnels to engineering students as part of their laboratory experience contributes to improving their understanding of fundamental fluid mechanics concepts, the significant equipment cost renders the student use of wind tunnels in a traditional hands-on mode infeasible for most educational institutions.

This paper presents the development of an online wind tunnel laboratory, which combines real-time remote access to an actual wind tunnel with a software-based virtual wind tunnel. The remote experiment system allows the students to explore the air flow patterns around various objects, the orientations of which can be controlled interactively. This experimental setup provides the students with real-time measurements for pressure, velocity and drag force in conjunction with streamed audio and video. These remote experiments can be complemented by virtual experiments, in which the shape, size and orientation of the physical objects available in the remote setup can be modified or these objects can be replaced entirely by other objects for which no physical models exist. This blended laboratory approach combining hardware-based experiments with software simulations expands the set of possible experiments well beyond that which could be performed within the confines of the remote laboratory alone. Using this powerful approach, the students can gain confidence in the validity of the software simulations through comparisons of the simulation results with data from actual hardware-based experiments. At the same time, the flexibility of software simulations enables the expansion of the scope of the experiments to parameter ranges and configurations that would not be suitable for the actual wind tunnel. For example, the virtual experiment allows the students to explore the lift and drag forces acting on different realistic airfoil types oriented at varying angles of attack.

1. Introduction

Traditional hands-on laboratories are educationally effective for illustrating complex theoretical concepts taught in lectures. While they add an active learning component to courses, they also impose significant space, time and personnel costs on the educational institutions. These costs can be significantly reduced by using Web-based remote or virtual laboratories. Currently, Stevens Institute or Technology (SIT)[1,2,3] as well as many other educational institutions[4,5] are using the Internet to implement and share remote and virtual laboratories and thus to enhance the educational experience of students. Real wind tunnels are very expensive, which renders their student use in a traditional hands-on mode infeasible for most educational institutions. Recently, an interactive Web-based virtual fluid mechanics laboratory for enhancing the students' understanding of some complex concepts of fluid mechanics was reported.[6] In this virtual laboratory, simulations of various fluid flow phenomena are integrated with interactive graphics and animations in order to give the students the feel of conducting realistic experiments. The set of available virtual fluid mechanics experiments includes for instance an airfoil/body wind tunnel, an air/oil flow rig, etc. A similar fluids mechanics and hydraulics laboratory was developed elsewhere, which combines course materials with real-time, remotely-controlled laboratory experiments and numerical simulations delivered "any time/any place" over the World Wide

Web.[7,8,9] An online laboratory experimentation network for control engineering was established by several collaborating institutions. This network integrates remote experiments with other multimedia learning resources and virtual reality simulations.[10,11,12] A remotely operated turbofan wind tunnel laboratory was described[13], where the apparatus was converted from manual to electronic control by installing data acquisition (DAQ)[14] hardware in conjunction with the LabVIEW[15] software and then connected to the Internet.

This paper presents the development of an online wind tunnel laboratory at SIT. Wind tunnels are among the most important design tools that are used in engineering to study the effects of air moving over or around solid objects such as airplane wings, cars, trains, skyscrapers, bridges, etc. While introducing wind tunnels to engineering students as part of their laboratory experience would contribute to improving their understanding of fundamental fluid mechanics concepts, the significant equipment cost makes the student use of wind tunnels in a traditional hands-on mode infeasible for most educational institutions. The online wind tunnel laboratory discussed in this paper represents a combination of real-time remote access to an actual wind tunnel with a software-based virtual wind tunnel. The remote experiment system allows the students to explore the air flow patterns around various objects (e.g. cubes, cylinders, disks, airfoils, etc.), the orientations of which can be controlled interactively. These remote experiments can be complemented by virtual experiments, in which the shape, size and orientation of the physical objects available in the remote setup can be modified or these objects can be replaced entirely by other objects for which no physical models exist.

2. System Architecture

The online wind tunnel laboratory includes remote and virtual laboratories. This system was implemented using a client-server network approach that represents a three-tier Web architecture (see Figure 1). The client represents the first tier, which consists of the student's client PC with Internet connection. The Student interacts with the experiment through a Web browser that can remotely access either the virtual or the remote experiment. The Web server represents the middle tier, which is responsible for accepting and responding to Hypertext Transfer Protocol (HTTP)[16] requests from clients. The virtual and remote laboratories represent the third tier of this architecture. The dynamic and interactive graphical user interface (GUI) of the virtual laboratory provides a rendering of the wind tunnel that was created using the three-dimensional virtual reality software development platform WebMax.[17,18] The remote laboratory comprises the actual instrument, an instrument controller and a Web camera. The interface between the instrument controller and the experimental setup is realized with a DAQ card, which can be installed directly into the expansion slot of the computer acting as the instrument controller. The Web camera, which is employed for live streaming of the experimental procedure in the actual laboratory housing the wind tunnel, is connected to the Web server.

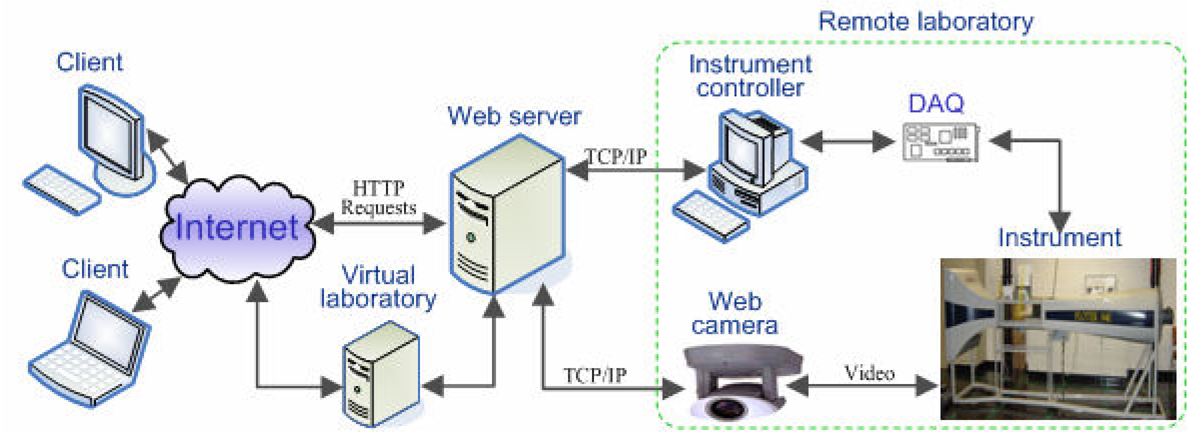


Figure 1: Architecture of online wind tunnel laboratory

3. Remote Laboratory

3.1 Experiment description

Figure 2 shows the real wind tunnel housed in the Fluid Mechanics Laboratory at SIT with a model of an airplane wing. When the fan is rotated by the motor, air is blown from the right to the left side through the entire wind tunnel. The solid object in the transparent box in the center (an airplane wing in this case) is exposed to the air flow with a certain velocity. According to the laws of fluid mechanics, this results in a pressure differential between the top and bottom surfaces of the wing, thus generating lift and drag forces that depend on the pressure profiles on the surfaces. In the traditional hands-on experiments using this experimental setup, the students first turn on the power supply of the wind tunnel. Then, they adjust the air flow velocity in accordance with the requirements of the experimental procedure by selecting the appropriate rotational speed of the fan via a control panel. Next, they change the angle of attack of the wing by changing its angular position in the transparent box. Finally, they measure the pressure distribution on the wing surfaces using a manometer bank and calculate the lift and drag forces and coefficients from these experimental results.

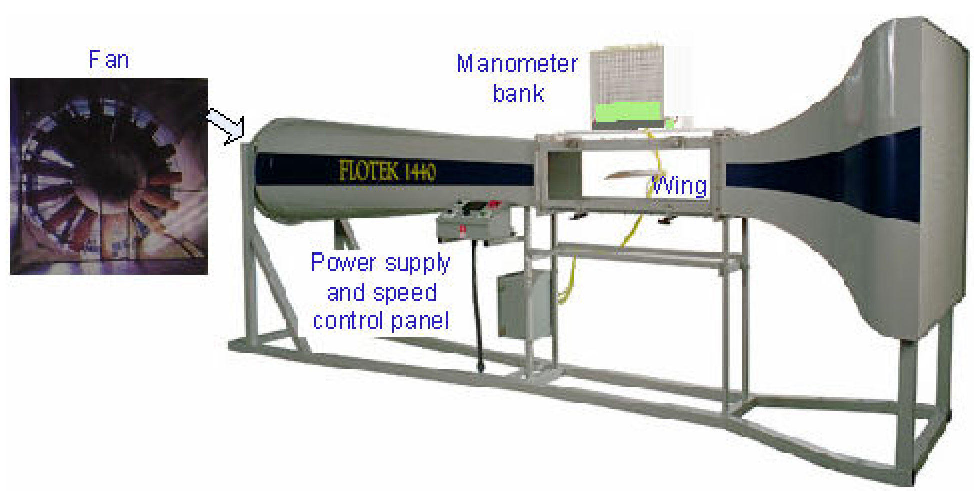


Figure 2: Real wind tunnel

3.2 Local control of experimental apparatus

The wind tunnel system described above and depicted in Figure 1 represents a manually operated system.[19] In order to accomplish the goal of remotely controlling this apparatus via the Internet, it needs to be retrofitted with an electronic control system, which is capable of turning on and off the power supply, adjusting the air flow velocity by setting the fan speed, changing the angle of attack of the body in the test section, and acquiring the experiment results. Figure 3 depicts the schematic of the wind tunnel control system. Figure 4 shows the computer interface used for switching on and off the power supply and for controlling the fan motor speed locally. Figure 5 shows the stepper motor controller with a belt drive, which allows for the angle of attack to be changed. Figure 6 depicts the data acquisition module, which enables the sampling of 16 channels of pressure data (0–10 inch water column) in real time. Figure 7 shows the stepper motor driver and the pressure transducers, which allow for the direct connection of the pressure hoses to the DAQ board.

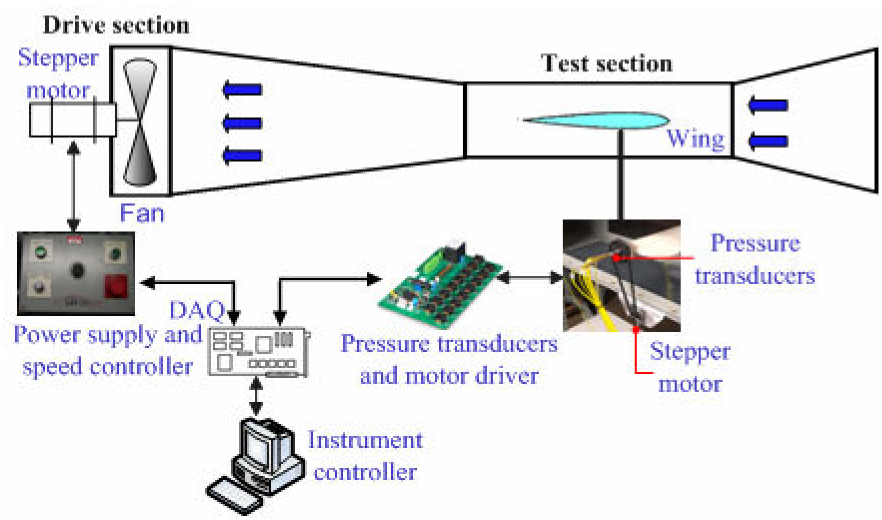


Figure 3: Schematic of wind tunnel control system

Figure 4: Computer interface for power switching and fan motor adjustment

Figure 5: Stepper motor controller and belt drive for adjusting the angle of attack

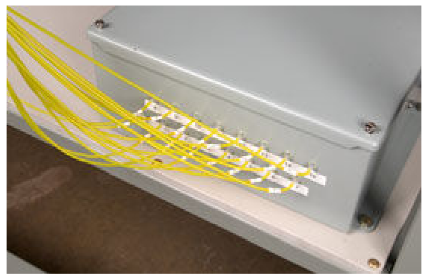


Figure 6: Data acquisition module for pressure measurement

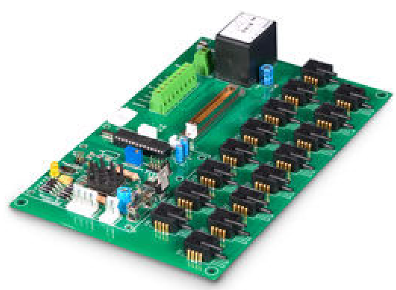


Figure 7: Pressure transducers and stepper motor driver of data acquisition module

LabVIEW was employed to implement the computer control of the experimental setup. The LabVIEW software integrates data acquisition, analysis and presentation in one system. For acquiring data and controlling instruments, it supports the RS-232[20]/RS-422[21] standards as well as plug-in DAQ boards.[22] The computer interface of the data acquisition module is shown in Figure 8. From the computer screen shown, the fan motor speed and the angle of attack can be controlled and the resulting experimental data can be viewed in real time. This computer control feature forms the basis for the implementation of the remote control function via the Internet described below.[19]

3.3 Remote control of experimental apparatus

In order to implement a remote instrument control, the overall software architecture for the real-time interactive remote laboratory system was developed, which has been described in detail elsewhere.[23] Figure 9 provides an overview of the remote laboratory software architecture. The system was realized using a multi-layer software approach that enables the various distributed applications to interoperate with each other. The first software layer is the GUI, a Web page that enables the students to communicate with the experimental instrument. The second software layer is the Web application, which accepts requests from the GUI, then activates the Lab agent, and posts back the results of these requests. The Lab agent forms the third software layer, which facilitates the interactions between Web application, database and experiment controller. The instrument and camera controllers constitute the fourth software layer. They are used to control the real physical instruments such as the experimental devices, lights, cameras and microphones.

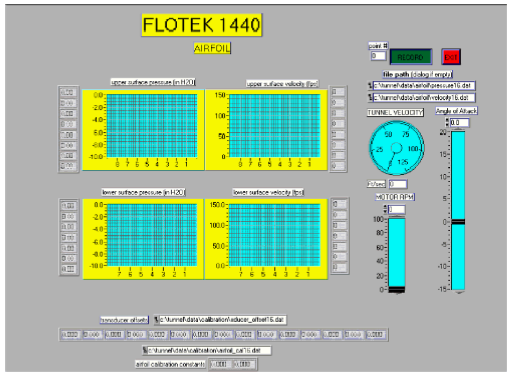


Figure 8: Computer interface of data acquisition module

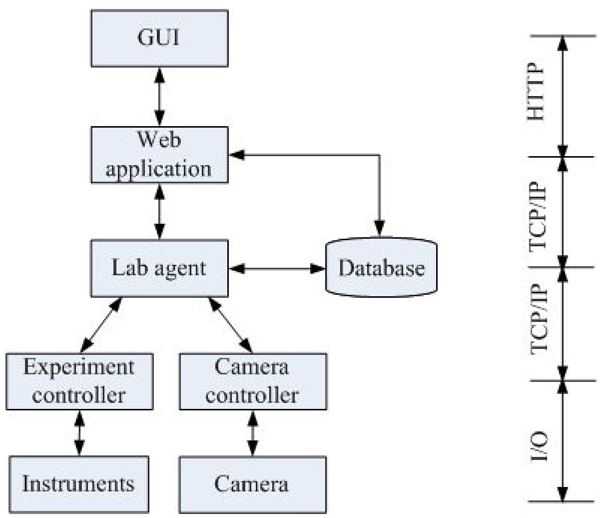


Figure 9: Software architecture of remote laboratory

3.4 Sample remote experiment

An airfoil system was selected for the first pilot of the remote wind tunnel. An airfoil is any planar cross-section of the wing parallel to the xz plane. The airfoil size and shape usually varies along the span. Airfoils and wings are designed to generate a lift force L_f (normal to the free stream air flow) that is considerably larger than drag force D_f (parallel to the free stream air flow). Both the lift and drag forces are strongly dependent on the geometry (shape, size, orientation to the flow) of the wing and the speed V_0 as well as other parameters, including the density ρ, viscosity μ and speed of sound a in air. Lifting airfoils are intended to provide a large force normal to the free stream and as little drag force as possible. A typical wing geometry with airfoils is sketched in Figure 10, indicating the chord length c, the chord line connecting the leading and trailing edges, the angle of attack α relative to the free stream velocity V_0, and the thickness t, which represents the distance between the upper and lower surfaces perpendicular to the camber line.[24]

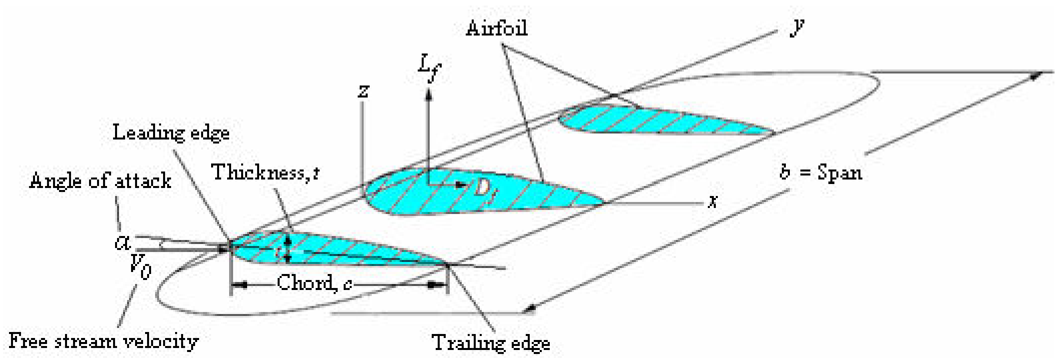


Figure 10: Typical wing geometry with airfoils

The GUI is of critical importance to the learning effectiveness of remote laboratories. Through interaction with the remotely accessed real equipment via the GUI, the students should be able to visualize the experimental process, better understand the underlying concepts of fluid mechanics, and gain a feel of immersion in the real laboratory environment. The GUI shown in Figure 11 represents the control interface in which the instrument control options, the experimental input and subsequently the experimental results are provided. In accordance with the control parameters of the local experiment setup, the experimental input of the remote setup also includes the fan power, the test velocity and the angle of attack. In the GUI's experimental result section, a table with airfoil surface pressure values is displayed. The instrument control section of the GUI includes lighting, audio and video and data acquisition options. These options and the experimental inputs are provided interactively. Then, the resulting experimental output is requested and stored, and the global video (showing an overview of the experimental setup) and the local video (zooming in on the analyzed airfoil) are streamed in real time and/or saved to a file. A camera with pan, tilt and zoom functions was chosen such that the students can adjust the camera view based on their requirements and preferences. The GUI was implemented using ASP.NET[25] in conjunction with the Visual Studio .NET Development Environment[26].

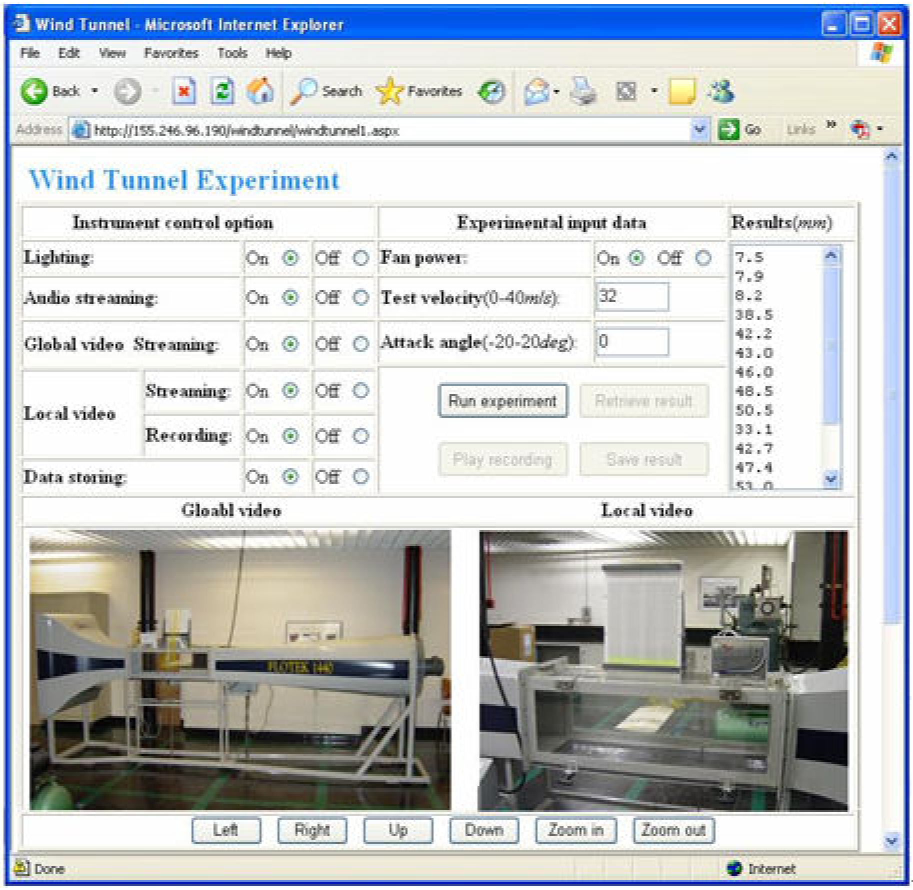


Figure 11: GUI of real-time wind tunnel remote experiments

In the laboratory assignment used in the undergraduate course on fluid mechanics at SIT, the students are given the values for the planform area S of the airfoil and the lift coefficient C_L as a function of the angle of attack α (see Figure 12). Subsequently, the students are asked to test the pressure under the planform area S for several different angles of attack α. Finally, the students are asked to calculate the lift force L_f and draw the test velocity versus lift force plot for the different angles of attack α (see Figure 13).

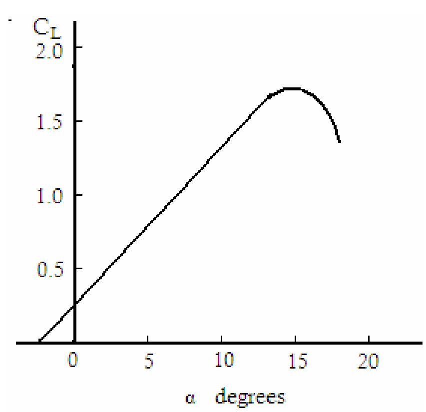


Figure 12: Typical lift coefficient C_L as a function of angle of attack α

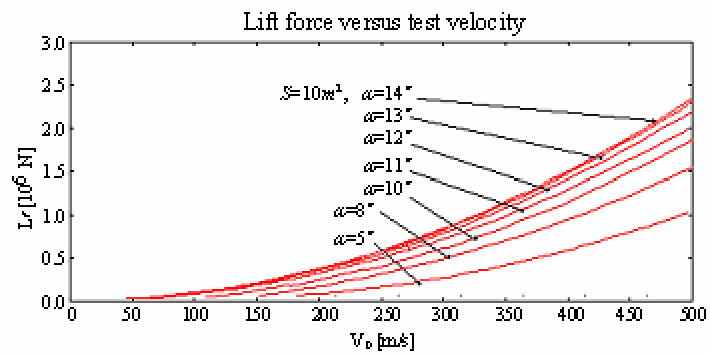


Figure 13: Typical lift force L_f as function of test velocity V_0 and angle of attack α

4. Virtual Laboratory Modules

The wind tunnel setup can be used to conduct experiments on airfoils as well as various other bodies. Generally, airfoils are designed to generate a lift force with minimum drag force while other bodies are designed to reduce the lift and drag forces generated. Because airfoils and bodies are quite different in their properties and associated models, two separate virtual laboratory modules for airfoils and bodies were designed and implemented. These virtual laboratory modules have more features than the remote experiment setup using the actual wind tunnel and thus can be employed to complement the remote experiments. For example, the virtual module enables the students to measure the lift forces acting on different airfoil types oriented at varying angles of attack and free stream velocities, and to measure the drag forces acting on different body shapes by modifying their size. This blended approach of remote experiments complemented by virtual experiments expands the scope of the experimental experience that the students could be given in a traditional hands-on laboratory course.

4.1 Basic considerations for airfoils and wings

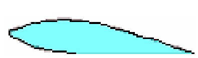
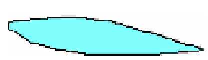
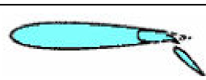
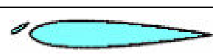
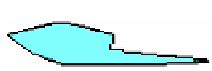
The virtual laboratory introduces the students to the main characteristic parameters of airfoils. Besides the lift force L_f, the performance characteristics of airfoils are normally given in terms of the dimensionless lift coefficient C_L and drag coefficient C_D. Table 1 summarizes the relationships between the parameters that determine the lift force of airfoils.

Table 1: Airfoil parameters

Parameter	Equation	Remarks
Lift coefficient	$C_L = L_f / (q_0 S)$	S: planform area of airfoil
Drag coefficient	$C_D = D_f / (q_0 S)$	D_f: drag force
Dynamic pressure	$q_0 = 0.5 \rho V_0^2$	ρ: density of air
Lift force	$L_f = C_L q_0 S$	q_0: dynamic pressure of air
Reynolds Number	$Re = \rho V_0 b / \mu$	V_0: free stream velocity μ: viscosity of air b: characteristic length
Mach Number	$Ma = V / a$	a: speed of sound V: speed of airplane

An efficient wing has a large lift-to-drag ratio C_L / C_D. The lift force L_f of an airfoil can be altered by changing the angle of attack α. This actually represents a change in the shape of the object, and these shape changes can be used to alter the lift when desired. Various types of airfoils have been developed over the years in response to changes in flight requirements. Typical shapes of airfoil designs are sketched in Table 2 and the corresponding experimental lift coefficients C_L are summarized as functions of the angle of attack α. In these relationships, the working area of the angle of attack α is different for different airfoils, but for a specific angle of attack α, the lift coefficient C_L is a constant, even for different velocities V_0.

Table 2: Experimental lift coefficients for various airfoil types

Airfoil	Shape	Lift coefficient C_L	Attack angle α
With camber		$0.1096\,\alpha$ $-0.0017\,\alpha^2 + 0.05\,\alpha + 0.96$	$(0^\circ < \alpha \leq 12^\circ)$ $(12^\circ < \alpha < 18^\circ)$
Without camber		$0.1096\,\alpha + 0.357$ $-0.0224\,\alpha^2 + 0.493\,\alpha - 1.2586$	$(-3^\circ < \alpha \leq 8^\circ)$ $(8^\circ < \alpha < 18^\circ)$
Plain flap or aileron		$0.103\,\alpha + 1.542$	$(-3^\circ < \alpha < 10^\circ)$
External airfoil flap		$0.103\,\alpha + 1.714$	$(-3^\circ < \alpha < 10^\circ)$
Slotted flap		$0.103\,\alpha + 2.114$	$(-3^\circ < \alpha < 9^\circ)$
Double-slotted flap		$0.103\,\alpha + 2.629$	$(-3^\circ < \alpha < 7^\circ)$
Leading-edge slat		$0.103\,\alpha + 0.743$	$(-3^\circ < \alpha < 15^\circ)$
Kline Fogleman airfoil		$-0.0011\,\alpha^2 + 0.0931\,\alpha - 0.3548$	$(4^\circ < \alpha < 50^\circ)$

4.2 Airfoil and wing experiments

According to the theory for airfoils and wings mentioned above, the virtual airfoil and wing wind tunnel laboratory shown in Figure 14 was developed. In the left panel, the airfoil input parameters (angle of attack α, wing planform area S, free stream velocity V_0, airfoil type) are provided by the students, and the resulting lift force is tabularized and plotted. In order to better visualize the wind tunnel, the students can display a 3-D rendering of the wind tunnel equipment in the right panel, which has pan, tilt and zoom functions built in. In order to accommodate different student preferences, these functions can be controlled by either moving the mouse in the 3-D space, by key combinations using the "←", "→", "↑", "↓", "Page Up" and "Page Down" keys, or by game keys "A", "D", "W", "S", "E" and "R". During the experimentation, any changes in parameters and variables are immediately reflected numerically and graphically as a response to the students' inputs. For example, by selecting a different airfoil type from the "Model Selection" list, all corresponding outputs are refreshed automatically. This design is expected to create a strong feel of immersion in the represented space for the students.

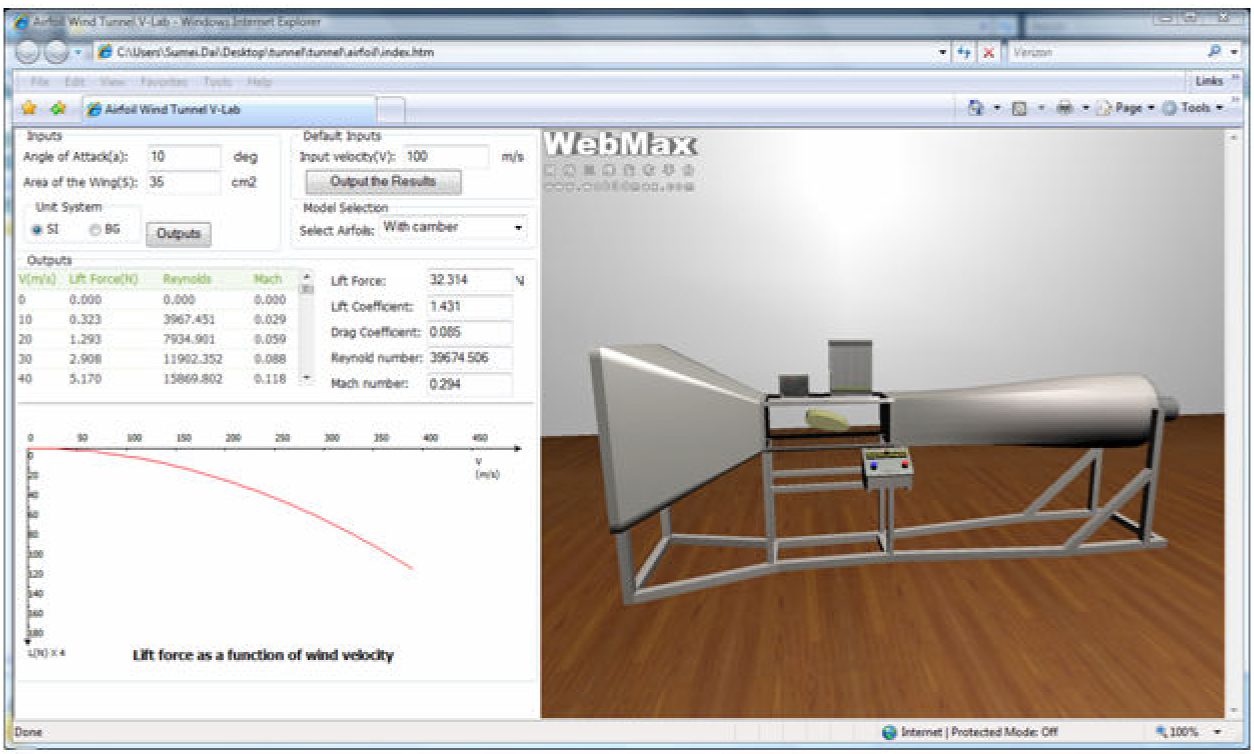


Figure 14: GUI of virtual airfoil and wing wind tunnel

The virtual laboratory modules were implemented using WebMax[30,31] in combination with VGS[27] technology. VGS is a user interface tool, which has a JavaScript Application Programming Interface and provides interactivity between the users and the WebMax environment. First, the 3-D models were designed using the 3ds Max[28] software, and then these models were loaded into WebMax. WebMax is a 3-D virtual reality software development platform that can be used to edit virtual interactive 3-D scenes and publish them on the Web. It works even with low-level computer configurations and low-bandwidth Internet connections because of the high compression ratio possible and the resulting small amount of transmitted data. The students access the virtual laboratory Web address directly and do not need to install the WebMax environment on their computers.

4.3 Body experiments

When immersed into a fluid stream, any body of arbitrary shape experiences forces and moments due to the flow. If the body has an arbitrary shape and orientation, the flow exerts forces and moments about all three coordinate axes. It is customary to choose one axis to be parallel to the free stream flow and positive in the downstream direction. The force on the body along this axis is denoted as drag force, and the moment about this axis represents the rolling moment. The drag is essentially a flow loss and must be overcome if the body is to move against the stream (see Figure 15). The drag force D_f is strongly dependent on the geometry (shape, size, orientation to the flow) of the body, the free stream velocity V_0 as well as other parameters, including the density ρ; viscosity μ; etc.[29,30]

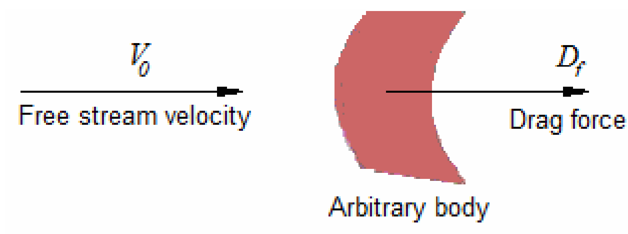


Figure 15: Definition of drag force D_f of an arbitrary body in a uniform flow with velocity V_0

The virtual wind tunnel can also be used to conduct experiments on various bodies such as cubes, spheres, cylinders, flat plates and cars. Figure 16 depicts the GUI of the virtual body wind tunnel laboratory, which was designed similarly to the airfoil wind tunnel module described above. In this laboratory, typical 2-D and 3-D bodies are investigated (see Table 3, Table 4 and Table 5).[29,30] When the students select a different body from the pull-down menu in the "Model Selection" section, all corresponding outputs (drag force, drag coefficient, Reynolds number and stream lines) are refreshed automatically, i.e. it is not necessary to click the button "Plot" or "Output the Results" again. By modifying the size of the body in the "Inputs" panel, the drag force can be measured for different free stream velocity values.

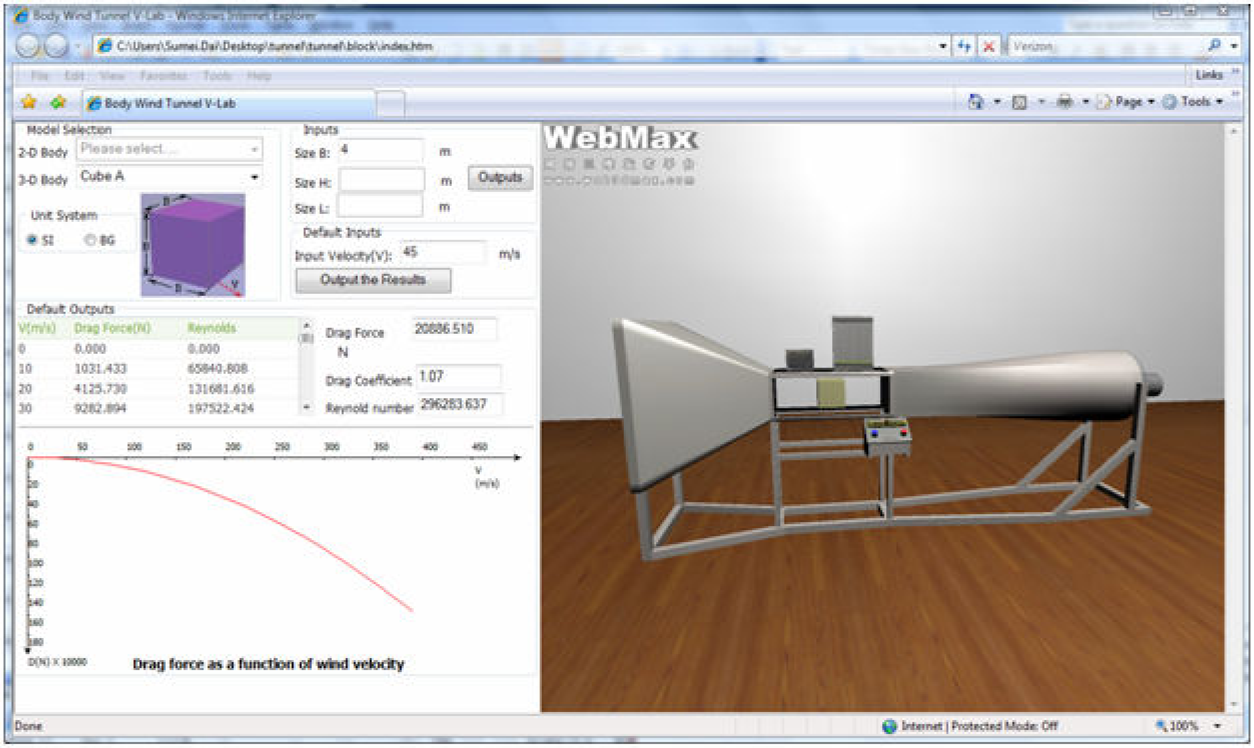


Figure 16: GUI of virtual body wind tunnel

Table 3: Typical drag coefficients for regular 2-D objects

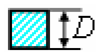
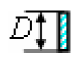
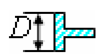
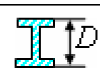
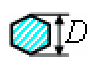
Type of body		Reference area S (b = length)	Reynolds number Re	Drag coefficient C_D
Square rod		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 2.00$
		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 1.50$
Semicircular shell		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 1.20$ $\leftarrow 2.30$
Semicircular cylinder		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 1.15$ $\leftarrow 2.15$
Equilateral triangle cylinder		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 1.40$ $\leftarrow 2.10$
Flat plate		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 1.90$
T-beam		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 1.80$ $\leftarrow 1.65$
I-beam		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 2.05$
Hexagon		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 1.00$
		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 0.70$
Circular cylinder		S = b D	$\mathrm{Re} > 10^4$	$\rightarrow 0.51$

Table 4: Typical drag coefficients for regular 3-D objects

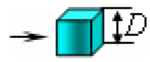
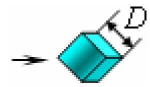
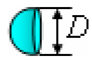
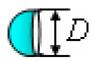
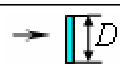
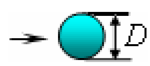
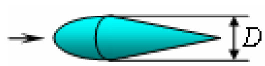
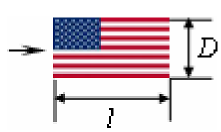
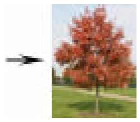
Type of body		Reference area S	Reynolds number Re	Drag coefficient C_D
Cube		$S = D^2$	$Re > 10^4$	1.05
		$S = D^2$	$Re > 10^4$	0.8
Solid hemisphere		$S = \pi D^2 / 4$	$Re > 10^4$	$\rightarrow$ 0.42 $\leftarrow$ 1.17
Hollow hemisphere		$S = \pi D^2 / 4$	$Re > 10^4$	$\rightarrow$ 0.38 $\leftarrow$ 1.42
Thin disk		$S = \pi D^2 / 4$	$Re > 10^3$	1.1
Circular disk		$S = \pi D^2 / 4$	$Re \leq 1$ $Re > 10^4$	20.4/Re 1
Sphere		$S = \pi D^2 / 4$	$Re \leq 1$ $1 < Re \leq 2\times10^5$ $Re > 2\times10^5$	24.0/Re 0.45 0.2
Streamlined body		$S = \pi D^2 / 4$	$Re > 10^5$	0.04

Table 5: Typical drag coefficients for objects of interest

Type of body		Reference area	Drag coefficient C_D	
Parachute		$S = \pi D^2 / 4$	1.4	
Empire State Building		Front area	1.4	
Fluttering flag		$S = l D$	$l / D = 1.0$	0.07
			$l / D = 2.0$	0.12
			$l / D = 3.0$	0.15

Tree		Front area	V_0 = 10 m/s	0.43
			V_0 = 20 m/s	0.26
			V_0 = 30 m/s	0.20
Thin rectangular plate		S = l D	l / D = 1.0	1.05
			l / D = 2.0	1.10
			l / D = 4.0	1.12
			l / D = 8.0	1.20
			l / D = 10.0	1.22
			l / D = 12.0	1.22
			l / D = 17.8	1.33
			l / D > 17.8	1.90
Dolphin		Wetted area	0.0036	
Large bird		Front area	0.40	
Six-car passenger train		Front area	1.8	
Tractor-trailer truck		Front area	0.96	
SUV		Front area	0.8	
Sedan		Front area	0.45	
Car (theoretical minimum)		Front area	0.15	

5. Conclusions

The rapid development of Internet technologies in combination with dramatic improvements in the processing power of personal computers is increasingly making interactive distance education a reality. In this paper, we have presented an online wind tunnel laboratory, which combines a virtual laboratory with a remote laboratory. Computer-based student laboratories provide a range of versatile tools that allow experiments to be performed and learning to be achieved more efficiently than in a laboratory limited to the use of traditional instrumentation. The online laboratory presented in this paper allows the students to explore the air flow patterns around various objects, and the associated virtual laboratory expands the scope of the remote experiments.

In the future, we plan to extend the online fluid mechanics laboratory to additional experiments. Remotely controllable implementations of an air flow rig experiment and an air flow jet experiment are currently under development. The undergraduate fluid mechanics laboratory with the facilities described here will greatly enhance the mechanical engineering curriculum at SIT and provide the means necessary to improve the professional preparation for all of our undergraduate graduates, thus allowing them to compete more effectively in the marketplace.

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