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UNDERGRADUATE EDUCATION AND RESEARCH IN COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

This paper discusses how United States Naval Academy (USNA) midshipmen, all undergraduate students, are introduced to advanced Computational Fluid Dynamics (CFD) techniques and subsequently participate in state-of-the-art research involving ship air wake impact on rotary wing aircraft and transonic aircraft stores separation analysis. These undergraduate students have shown that they can conduct particularly valuable CFD research normally performed by graduate level students as evidenced by co-authoring numerous invited and peer reviewed conference papers. This paper provides detail of the CFD course content and discuss recent projects and research completed by these students.

INTRODUCTION

In 2008 the USNA Mechanical and Aeronautical Engineering Departments implemented a joint CFD elective to teach advanced numerical techniques, including use of parallel processing, necessary to model complex real world flows. Undergraduate midshipmen, who typically take this elective course during their junior or 3rd year, have previously completed a basic fluid or aerodynamics course and have limited exposure to programming in MATLAB. During the first half of the CFD course they are introduced to basic FORTRAN programming and solve comparatively simple flows (e.g. three-dimensional viscous duct flow) both numerically and analytically. During the second half of the course they are introduced to the NASA Tetrahedral Unstructured Software System (TetrUSS) and USM3d flow solver [15] and the use of parallel processing. Students also complete demanding projects such as modeling an airfoil under transonic conditions (Ma > 0.8). Following the course students are eligible for demanding summer High Performance Computing (HPC) internships at Naval Air Systems Command or at a national HPC Center. During their senior or 4th year the students can then perform independent study work involving advanced CFD simulations. This paper provides details on the CFD course and will discuss examples of the high quality research completed by the midshipmen.

CFD COURSE DESCRIPTION

The joint Mechancial and Aeronautical Engineering Department course syllabus is shown in Figure 1. This syllabus is based upon a 16 week academic semester. Two different textbooks have been used in the course. The original textbook selected, Cebeci et al. [12], was very complete. However, and based upon student feedback, it was determined to be at level beyond the capabilities of most undergraduate students. This textbook was subsequently replaced by Zikanov [7], which has proven to be more appropriate for undergradate students.

As shown in Figure 1, the first eight weeks of the course are devoted to a review of basic conservation equations and an introduction to numerical methods, numerical stability and turbulence. Concurrently the students are also introduced to programming using FORTRAN in a LINUX environment though the completion of six progressively more complex computer labs. (USNA

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midshipmen have limited prior experience with MATLAB operating on Windows based workstations.) During the computer labs the importance of validating simulations against analytical solutions or experimental data is emphasied. An example lab is shown in Figure 2.

During the last eight weeks of the semester the students are introduced to the NASA TetrUSS CFD suite and parallel processing using Message Passing Interface (MPI) on a LINUX cluster. The students then complete a demanding group project, which will be described in the next section. Students have had use of an outdated 48 node AMD cluster to complete their project. Each compute node has two AMD Opteron 248 Processors with 4 GB of memory. Groups are typically assigned 8-12 nodes for their project. A more advanced 48 node AMD cluster (with 4 AMD Opteron 6174 Processors with 128 GB of memory per compute node) will be available to future classes.

Week	**Topic and Lab**	**Reading**
1	Introduction/Conservation Equations	1.1-1.3, 2.1-2.2, 2.4-2.5
2	Conservation Equations *Lab #1: Introduction to Linux, kwrite, gfortran, gnuplot, n!*	2.6-2.10
3	Partial Differential Equations *Lab #2: More Linux, conditionals, n!!, matrices*	3.1-3.3
4	Incompressible Flows	10.1-102
5	Numerical Methods *Lab #3: 2D Duct Flow (2 approaches)*	4.1-4.4.1
6	Numerical Stability/CFL *Lab #4: 3D Duct Flow*	6.1-6.2.1, 6.3, 7.1
7	Shocks/Compressible Flows *Lab #5: Shockwave (Burger's Equation)*	9.1-9.2
8	Turbulence *Lab #6 : Chaotic Behavior (Lorenz Equation); VI Editor*	11.1-11.3.2, 11.4-11.4.2
9	GRIDTOOL	Handout
10	GRIDTOOL	Handout
11	VGRID	Handout
12	USM3D—Flow Solver	Handout
13	EnSight—Flow Visualization	Handout
14	CFD Project	
15	CFD Project	
16	Project Presentations	

Figure 1: *CFD Course Syllabus. Reading refers to sections of reference [7].*

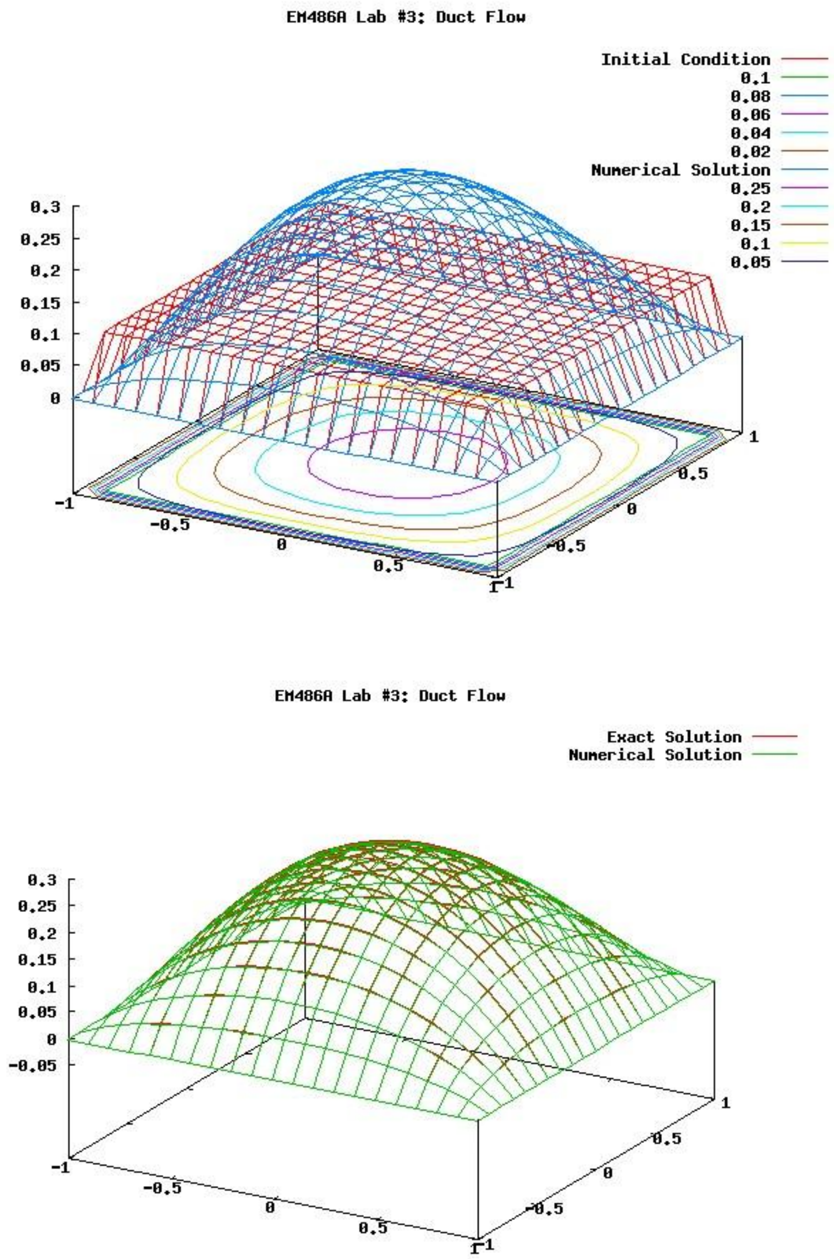

Figure 2*: Three-dimensional viscous duct flow. Initial condition (top) vs. numerical solution and exact analytical solution (bottom).*

STUDENT PROJECTS

Undergraduate students are placed in groups of two to four midshipmen to complete a CFD project. Information on sample CFD projects is provided below.

ONERA Wing

The ONERA M6 wing is a swept, semi-span wing that has a span *b* of 1.19 m. The instrumented wing was tested in a wind tunnel at transonic Ma numbers (0.7, 0.84, 0.88, and 0.92). Pressure, lift and drag coefficients are available in reference [16]. The ONERA M6 wing has become a classic CFD validation case for external flow due to its relatively simple geometry combined with complex transonic flows that include shocks and boundary layer separation. Figure 3 shows the unstructured surface grid for an approximately 2 million tetrahedral simulation performed by midshipmen. Midshipmen were able to get excellent results using TetrUSS as shown in Figure 4, which compares pressure coefficients from CFD and wind tunnel measurement at a span station *y/b* = 0.2 (20% of the span length from the wing root). Students also completed flow visualization using EnSight software (Figure 5 shows shock wave formation at Mach 0.84.)

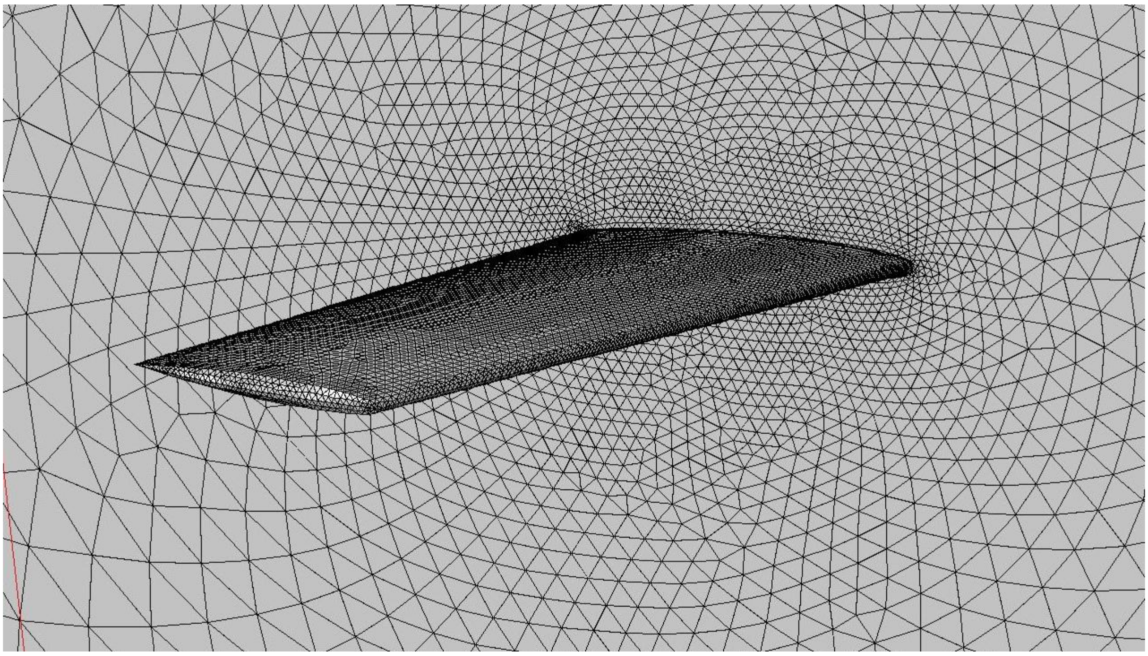

Figure 3: *Unstructured surface grid of the ONERA M6 wing.*

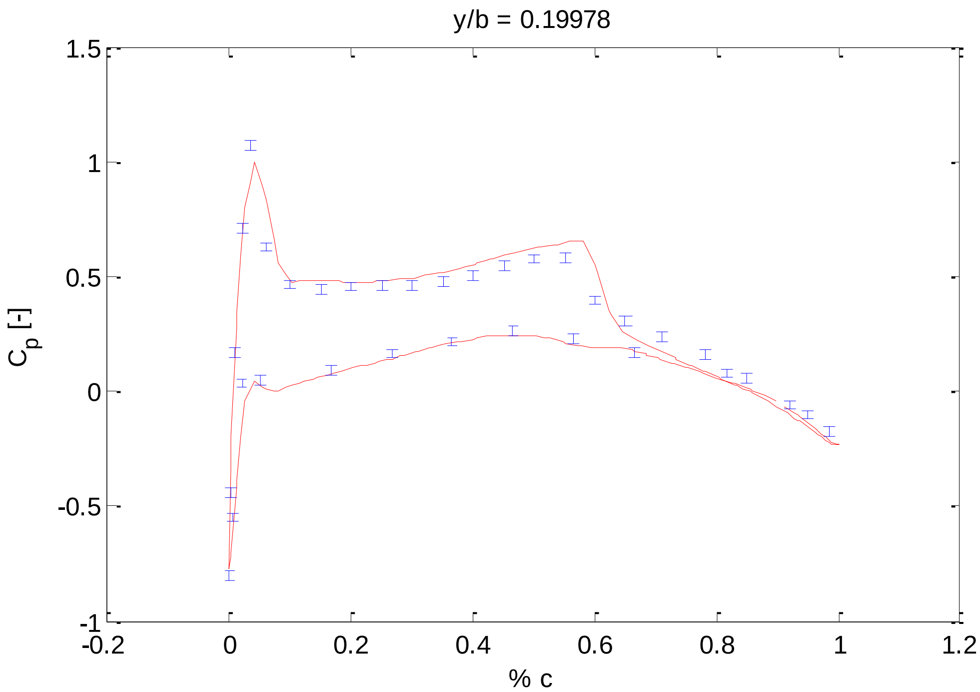

Figure 4: *Coefficient of Pressure comparison between USM3d CFD data (red line) with ONERA test data (blue ticks) for spanstation y/b = 0.2. Abscissa is percent chord.*

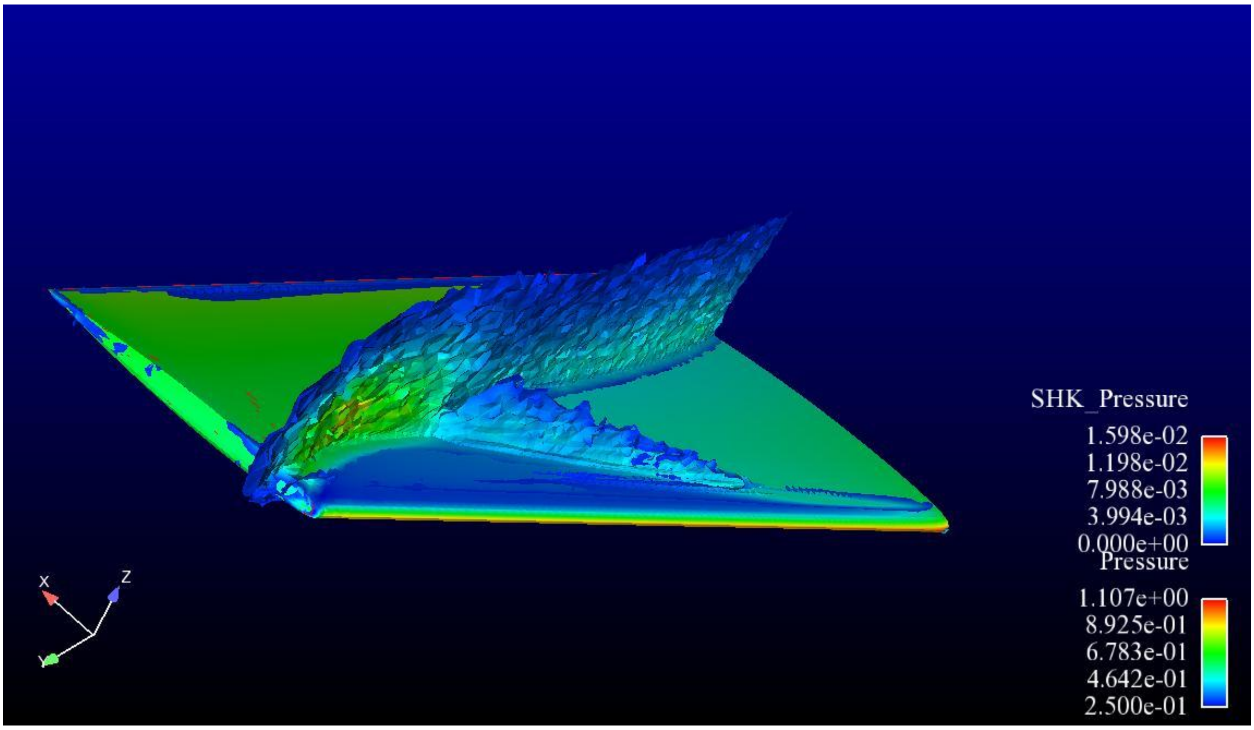

Figure 5: *ONERA wing shock formation at Mach 0.84.*

Mk82 Store with Attached Strut

This project involves modeling a full scale Mk-82 1000 lb gravity bomb mounted on a sting and strut as shown in Figure 6. Comparison is made with a 7.2% (1:13.9) scale model tested in the Aircraft Research Association transonic wind tunnel as discussed in reference [13]. This particular sting and strut design, which reference [13] refers to as a two sting rig, was used for placement of the Mk-82 shape into the store cavity on a model of the British Unmanned Combat Aerial Vehicle. Pitching moment coefficients (Cm_y) on the Mk-82 wind tunnel model were determined by testing the model with sting and strut and then subtracting moments from the sting and strut tested separately. This procedure makes the assumption that the sting and strut have an insignificant effect on Mk-82 moments. Midshipmen completed 4, 6 and 10 million tetrahedral simulations using both a wall function and full viscous boundary layer. Figure 6 shows the surface grid for the simulation with 4 million tetrahedrals.

Figure 7 compares CFD simulation results with wind tunnel data (both for Cm_y on the Mk-82 shape only) for an angle of attack sweep of $-20° < \alpha < 20°$ at Ma = 0.85. The consistent deviation between the simulations and wind tunnel results were investigated further. Flow visualization, see Figure 8, reveals a possible cause for the deviation in the Mk-82 moment coefficient. Specifically, Figure 8 shows a shock wave that forms on the strut and sting interacting with the Mk-82 shape. Such an interaction is not observed in conventional wind tunnel testing since an aft mounted sting would not produce a shock wave that could interact with the Mk-82 shape (or produce a significant moment). These results were reported in reference [6]. Additional investigation will be performed by midshipmen researchers to see if a longer or differently shaped strut would reduce the observed interaction. CFD simulations of the Mk-82 only will also be performed.

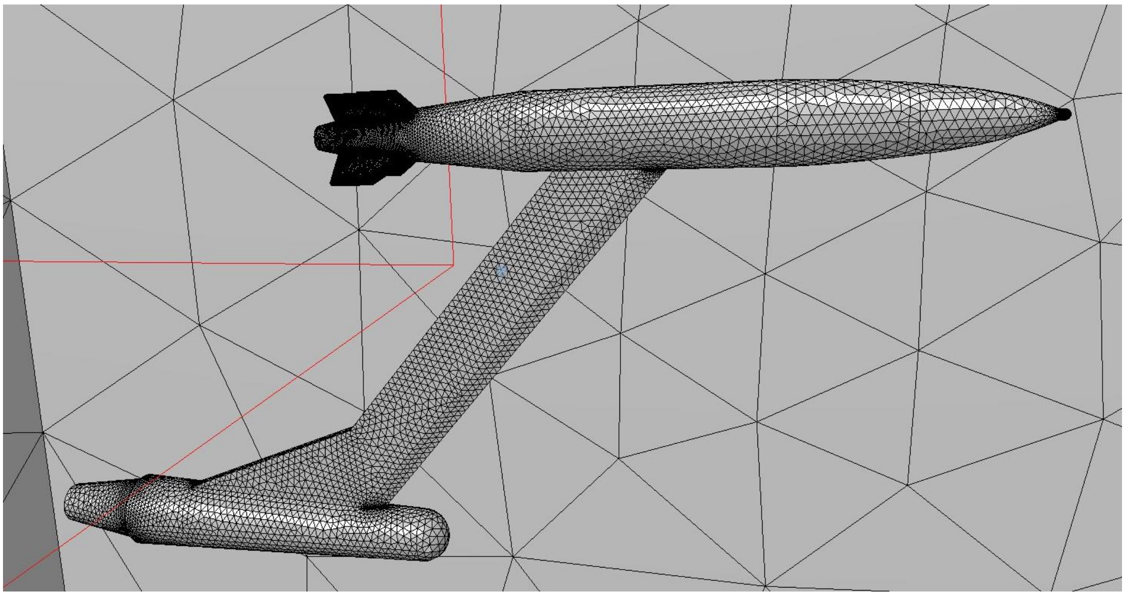

Figure 6: *Surface grid for simulation with 4 million tetrahedrals.*

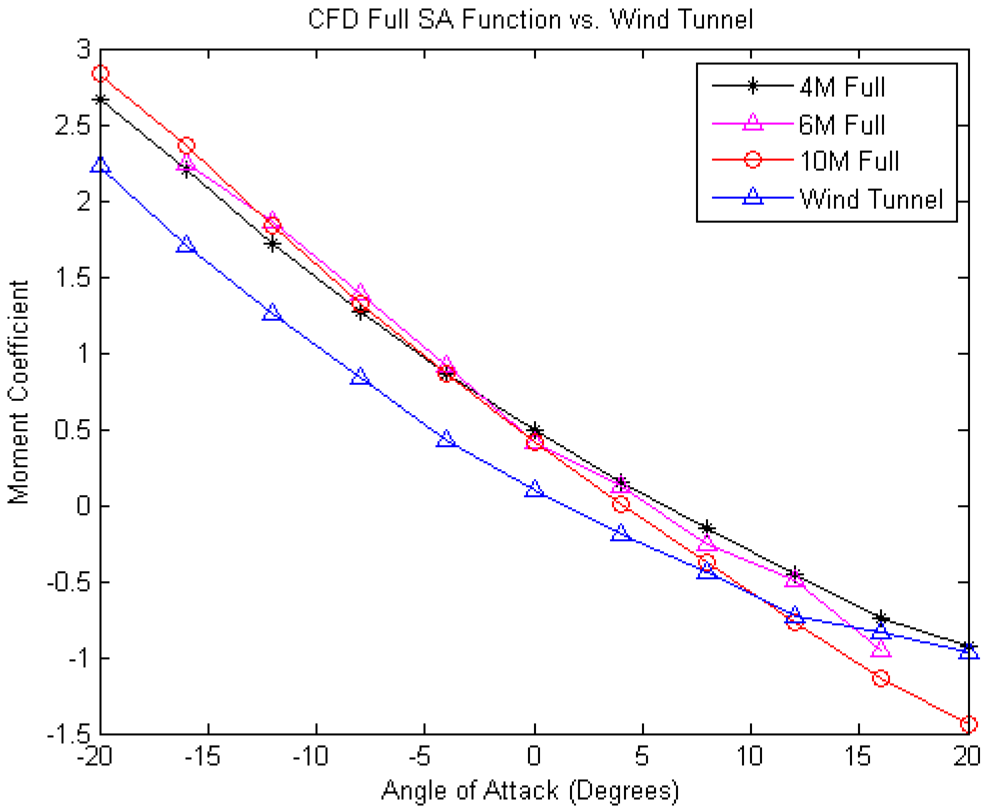

Figure 7*: Pitching moment coefficient vs. angle of attack for Mk-82 (without strut or sting) at Ma 0.85.*

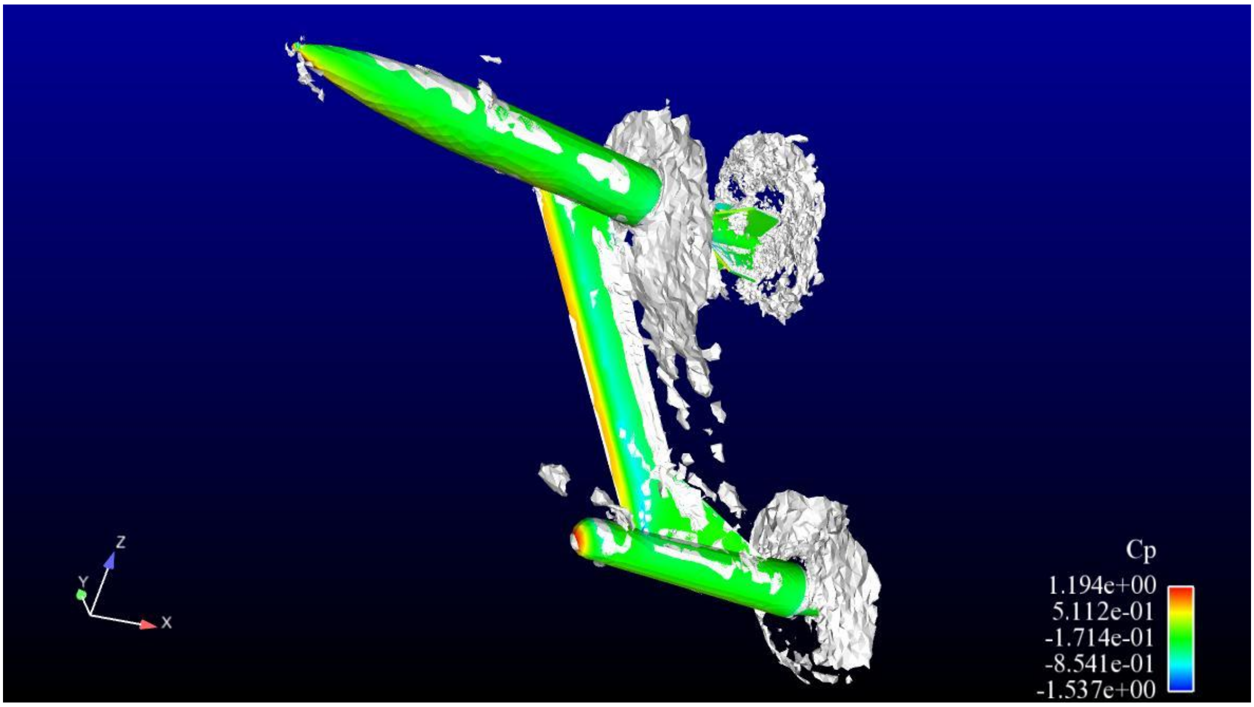

Figure 8: *Shock formation at 20° angle of attack.*

STUDENT RESEARCH

Following completion of the CFD course the students have the opportunity to perform CFD research during internships or through an independent study in their senior or 4th year. Student researchers have been extremely productive as evidenced by co-authoring numerous invited and peer-reviewed conference papers [3]-[6], [8]-[11]. Examples of the high quality work done by these undergraduate researchers are discussed below.

Ship Air Wake Program

The objective of the USNA Ship Air Wake Program is to validate and improve CFD tools that will be useful in determining ship air wake impact on naval rotary wing vehicles. Currently, ship launch and recovery wind limits and envelopes for helicopters are primarily determined through at-sea *in situ* flight testing that is expensive and frequently difficult to schedule and complete. The time consuming and potentially risky flight testing is required, in part, because computational tools are not mature enough to adequately predict air flow and wake data in the lee of a ship with a complex superstructure. The top-side configuration of USNA YPs (Patrol Craft, Training) is similar to that of a destroyer or cruiser, and their size (length of 32.9 m and above waterline height of 7.3 m) allows for collection of air wake data with a Reynolds number that is the same order of magnitude as that of modern naval warships, an important consideration in aerodynamic modeling. A dedicated YP has been modified to add a flight deck and hangar structure to produce an air wake similar to that on a modern destroyer. Three axis acoustic anemometers, fog generators and an inertial measurement unit have been installed. Repeated testing on the modified YP is being conducted in the Chesapeake Bay, which allows for the collection of data over a wide range of wind conditions. Additionally, a 4% scale model of the modified YP has been constructed and tested in the 107×152×305 cm USNA wind tunnel. Examples of CFD modeling completed by student researchers, in support of this project, are provided in Figures 9 and 10. References [1]-[3], [8]-[9] provide details and results of this unique research program.

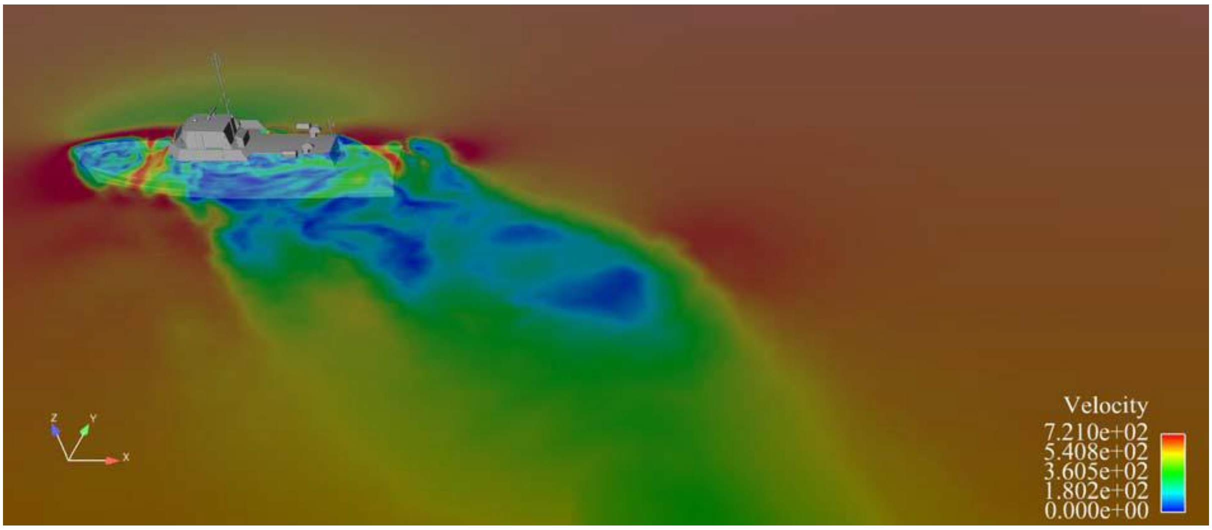

Figure 9: *Simulated ship air wake for Naval Academy training vessel. Air flow coming from 60° off the starboard bow. Velocity in inches/sec.*

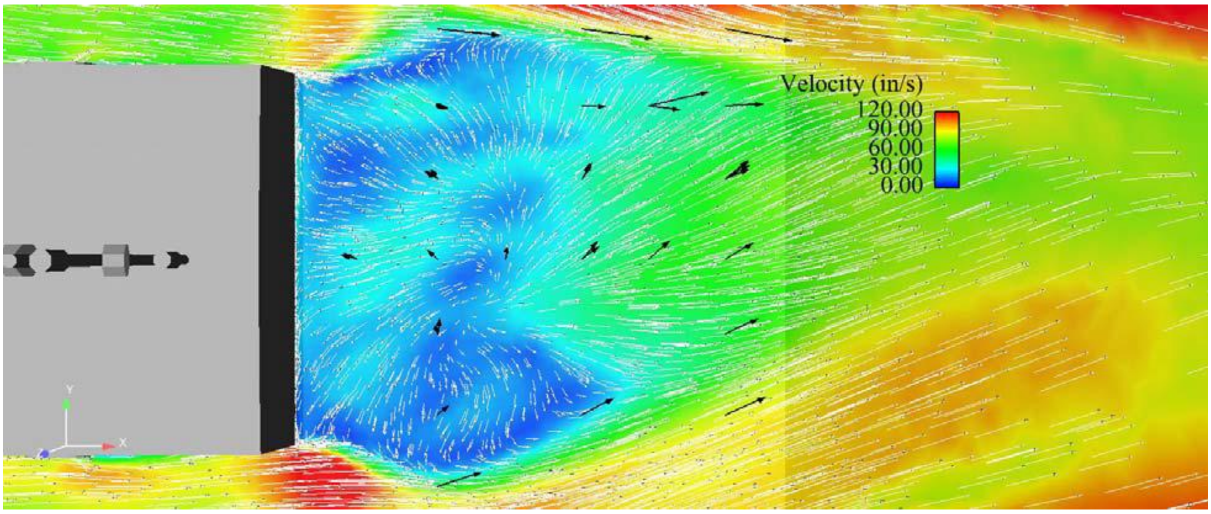

Figure 10: *Experimentally collected flow data (black arrows) vs. advanced CFD simulation (white arrows and color background) for air flow over the flight deck of the Naval Academy training vessel. Air flow from 15° off the starboard bow.*

Modification of Litening External Targeting Pod.

This CFD project involved four separate midshipmen researchers over an 18 month period and investigated the impact of moving an air cooling intake scoop on the Litening external targeting pod mounted on an F/A-18C aircraft [5]. Specifically, it was investigated if moving the location of the cooling air intake scoop could create more favorable store separation characteristics for the Mk-83 1000 lb gravity bomb. Previous research [10], [11] has shown that small changes to the geometry of external targeting pods may result in adverse moments on the smaller Mk-82 gravity bomb. These adverse moments can result in the released bomb striking the aircraft. For this study the Litening Pod, which is used on many Allied aircraft, is mounted on the starboard side of the F/A-18C fuselage adjacent to a pylon carrying a Mk-83 bomb. The air scoop is an approximately rectangular inlet on the side of the Litening Pod that collects ram air to cool internal electronics. This study showed that rotating the air scoop reduced adverse moments on the released store.[5] This conclusion was supported by visualization of generated shock waves as shown in Figure 11.

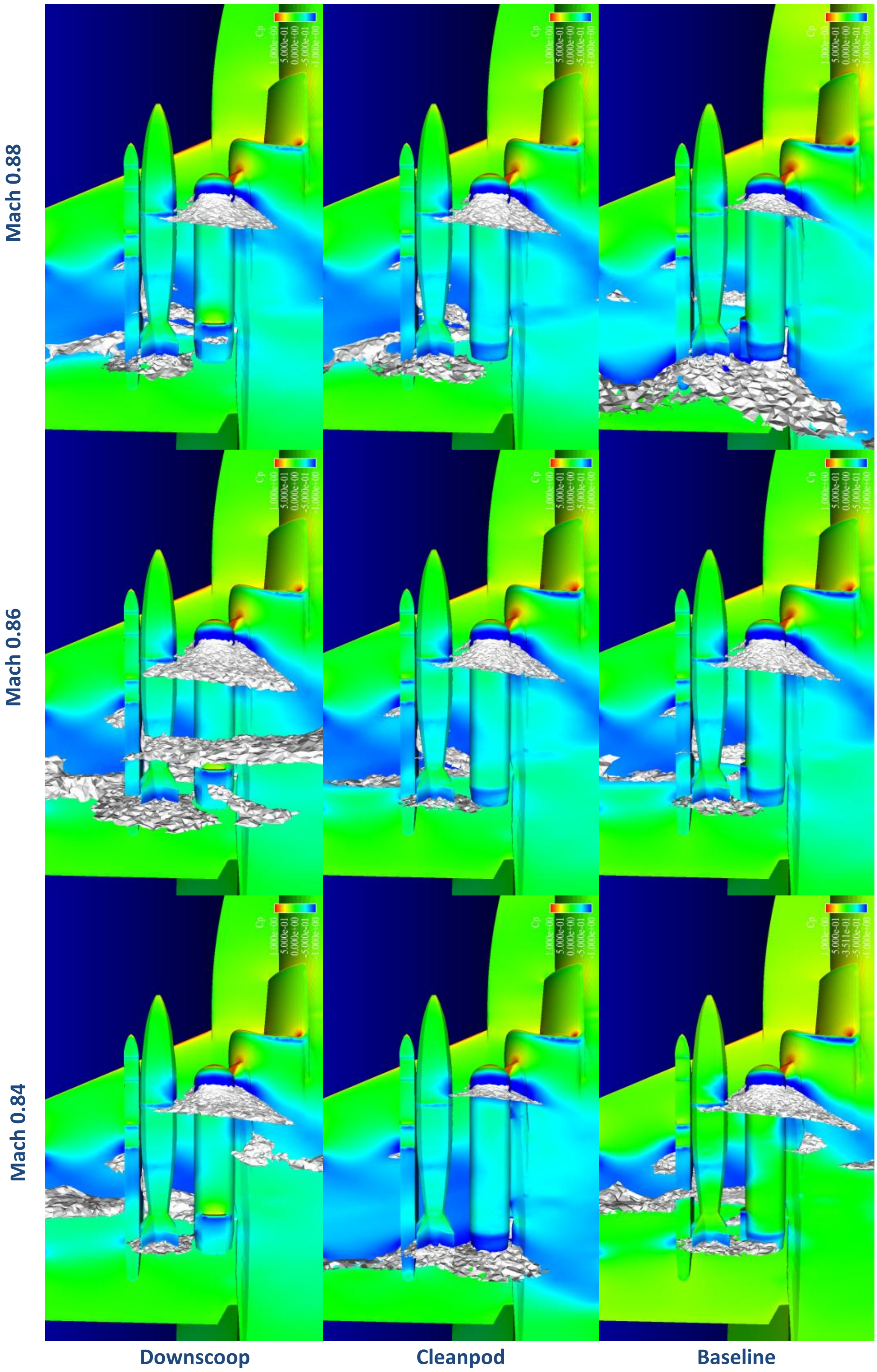

Figure 11: *Shock wave interactions for with Mk-83 gravity bomb for Litening Pod with downscoop (left column), no scoop (center column) and original configuration (right column) vs. Ma. The air intake scoop is on the very aft end of the Litening Pod.*

Figure 12 shows the miss distances vs. time for the released Mk-83 and the F/A-18C with Litening Pod for the original configuration and for the downscoop configuration. These miss distances were calculated using the US Navy Generalized Separation Package [14] for an F/A-18C flying at Ma 0.94 at 11,400 ft in a 60° dive. Review of Figure 12 indicates that the downscoop configuration offers significantly more initial standoff or miss distance than the original scoop configuration due to the rotation of the air scoop away from the store. After store release, the downscoop configuration offers no additional incremental adverse store displacement towards the aircraft than the baseline configuration. The minimum miss distance for the downscoop configuration is approximately 15 cm (6 in) while that for the original configuration is approximately 7.6 cm (3 in).

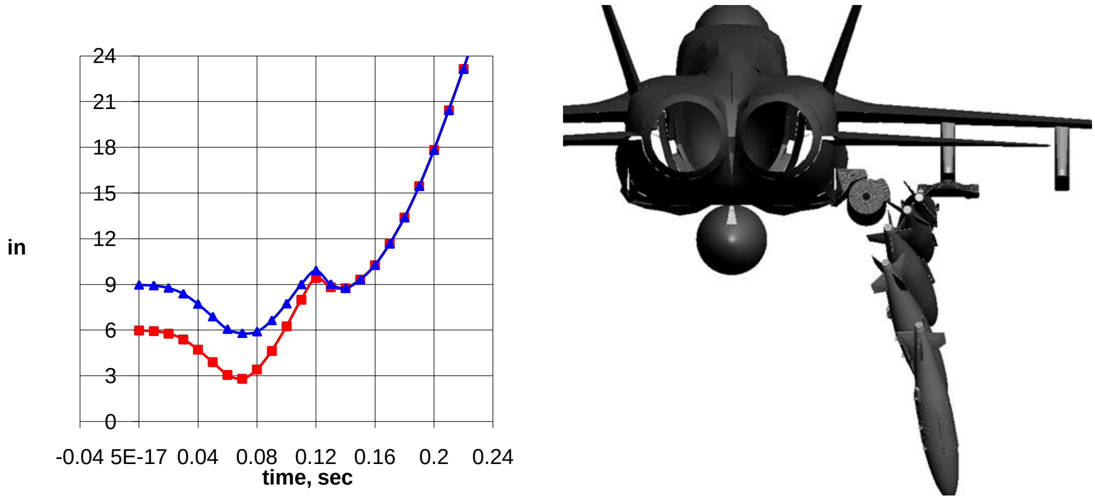

Figure 12: *At left-miss distance (in) vs. time (sec) for Litening Pod with original configuration (red) and with downscoop configuration (blue). At right-computed Mk-83 trajectory with Litening Pod with original air scoop configuration.*

CONCLUSIONS

This paper discusses how advanced CFD simulation methods can be successfully included in an undergraduate engineering curriculum. Furthermore, undergraduate students have been shown to be capable of completing advanced flow simulations normally done by graduate students or degreed engineers.

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