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Integrated Learning of Laminar Boundary Layer Modeling on Flat Plates Using ANSYS Workbench for Ship Machinery Mechanics and Mechatronics Specialists

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***Abstract*—In engineering disciplines such as ship machinery mechanics and mechatronics, the ability to model and simulate physical phenomena is essential for designing and optimizing complex systems. One of the fundamental topics in fluid mechanics is the laminar boundary layer over flat plates, which plays a crucial role in understanding drag forces, heat transfer, and flow behaviour in naval and mechatronic applications. Accurate modelling of the boundary layer is essential for improving the performance of ship propulsion systems, reducing energy losses, and enhancing the efficiency of fluid-based mechatronic devices. This study presents an integrated learning approach that leverages ANSYS Workbench as a computational tool for teaching and understanding the laminar boundary layer modelling over flat plates. The primary objective is to bridge the gap between theoretical knowledge and practical application by incorporating simulation-based learning into engineering education. By integrating computational fluid dynamics (CFD) simulations with classical theoretical models, students develop a deeper understanding of boundary layer development, velocity profiles, and shear stress distribution. The methodology involves a structured learning process where students first study the fundamental equations governing laminar boundary layers, such as the Blasius solution for incompressible flow over a flat plate. They then proceed with hands-on simulations in ANSYS Fluent, where they define boundary conditions, mesh the computational domain, and analyse numerical results in comparison with analytical solutions. The learning approach encourages active problem-solving and enhances critical thinking skills. The findings demonstrate that simulation-based learning significantly improves students' comprehension of boundary layer theory by visualizing complex flow phenomena. Additionally, the integration of CFD tools fosters practical skills in numerical modelling, which are essential for their future careers in ship machinery mechanics and mechatronics. The proposed method enhances student engagement and provides a systematic framework for applying CFD techniques in engineering education, reinforcing the importance of simulation in modern fluid mechanics.**

Keywords— laminar boundary layer, flat plates, ANSYS Workbench, integrated learning, ship machinery mechanics, mechatronics, fluid dynamics.

I. INTRODUCTION

The modelling of laminar boundary layers on flat plates represents one of the fundamental problems in fluid mechanics and finds wide application in engineering practice. This topic is of relevance to the Ship Machinery and Mechanisms and Mechatronics disciplines as it involves the development of solutions for the optimization of the aerodynamic and hydrodynamic performance of structures and machinery used in the marine and industrial domains. This paper discusses an integrated approach for laminar boundary layer modelling training using ANSYS Workbench, a powerful numerical simulation tool.

A. Theoretical basis

Boundary layer theory, a cornerstone of modern fluid mechanics, was introduced by Ludwig Prandtl in the early 20th century and further advanced by researchers such as Hermann Schlichting [1]. It describes fluid flow behavior near solid boundaries, where viscous effects dominate, and velocity gradients are significant. One classical and extensively studied case is the laminar boundary layer over

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a flat plate, where the velocity profile evolves from zero at the wall to the free-stream value away from it.

Schlichting's *Boundary-Layer Theory* [1] and White's *Fluid Mechanics* [2] provide a comprehensive theoretical framework for analyzing such flows. These works explain the derivation and implications of the Blasius solution — a simplified yet fundamental, analytical solution of the Navier-Stokes equations for steady, incompressible, two-dimensional laminar flow over a flat surface.

The importance of this theory extends into practical modeling through Computational Fluid Dynamics (CFD). Anderson's textbook [3] introduces the fundamental principles of CFD and explains how analytical models like the Blasius solution can be validated and extended using numerical techniques.

Cengel and Cimbala [4] elaborate on the physical interpretation of boundary layer formation and offer detailed worked examples, bridging theoretical and applied perspectives.

More specialized CFD references such as Tu et al. [5] and Moukalled et al. [6] present methods for discretizing the governing equations (e.g., using the finite volume method), which are commonly implemented in tools like ANSYS Fluent. These sources offer guidance on constructing computational mesh, setting boundary conditions, and achieving convergence in simulations.

Blazek's volume [7] adds deeper mathematical and physical rigor, providing a robust foundation for those interested in the development of CFD algorithms, including turbulence modeling and advanced solver techniques.

Additionally, Munson et al. [8] provides a broad overview of fluid mechanics fundamentals that support the understanding of laminar boundary layers in both theoretical and experimental contexts.

Given the educational focus of this study, integrating CFD with classroom learning aligns with the principles of inductive teaching described by Prince and Felder [9], where students build theoretical understanding through hands-on simulations.

This theoretical foundation forms the basis for the integrated learning approach developed in this study, combining classical boundary layer theory with numerical modeling through ANSYS Workbench.

ANSYS Innovation Space (2023) [11]: The online ANSYS tutorial on flat plate laminar boundary layers offers a practical guide to setting up simulations, defining mesh parameters, and analyzing CFD results.

B. Importance of Engineering Practice

In engineering practice, laminar boundary layer analysis is important for the design of energy efficient systems and devices. In the field of ship machinery and mechanisms, for example, understanding the fluid-structure interaction is critical to reducing hydrodynamic drag and optimizing energy consumption. In mechatronics, on the other hand, boundary layers influence the thermal management and aerodynamic performance of mechanical systems.

Numerical modelling using ANSYS Workbench provides powerful tools to simulate and analyze these complex processes. The software allows the solution of Navier-Stokes equations and the visualization of the results, facilitating both the understanding of the phenomena and their application in the real world.

C. Educational context

Laminar boundary layer training is a valuable element of the curriculum for students in engineering degree programs. Combining theory with practical application through ANSYS Workbench, [10], students can develop critical analysis and design skills. Incorporating realistic projects and simulation-based tasks allows academic knowledge to be linked to industrial applications.

In the specialties "Ship Machinery and Mechanisms" and "Mechatronics" the integrated training includes:

Theoretical background: understanding of the basic principles of fluid mechanics and boundary layer theory.

Practical exercises: using numerical methods to simulate boundary layers on flat plates.

Project-Based Learning: Solve engineering problems using ANSYS Workbench, focusing on visualization and interpretation of results.

D. Objectives of the article

This study aims to develop an integrated learning approach that combines theoretical boundary layer analysis with hands-on numerical simulations using ANSYS Workbench. The key objectives are:

- To introduce students and researchers to theoretical concepts underlying laminar boundary layer formation.
- To provide a step-by-step guide for modeling boundary layer development using ANSYS Fluent.
- To compare analytical solutions, experimental data, and numerical results for enhanced understanding.
- To evaluate the effectiveness of simulation-based learning in engineering education by assessing student engagement and comprehension.

To highlight practical applications in naval engineering and mechatronics, demonstrating how boundary layer modeling contributes to optimizing energy efficiency and system performance. With its interdisciplinary nature and emphasis on practical application, the paper aims to contribute to the improvement of teaching methodologies and to promote the use of modern technologies in engineering education.

E. Importance in Ship Machinery and Mechatronics

- In ship machinery, the drag force on a ship's hull is directly influenced by the boundary layer, affecting fuel efficiency and operational costs. In mechatronic systems, understanding boundary layers can improve the design of fluid-based components, such as actuators and pumps, leading to more efficient and reliable systems

II. Materials and Methods

A. Laminar boundary layer modeling -problem specification

Figure 1 shows Specification of the flat plate laminar boundary layer problem.

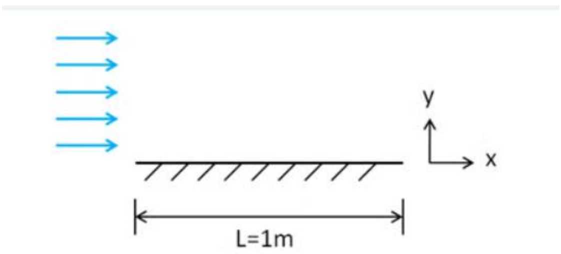

Fig. 1 Flat plate boundary layer problem.

An experimental and theoretical investigation into the development of a laminar boundary layer over a flat plate at a Reynolds number of 10,000 is conducted. Numerical simulations using ANSYS Workbench are employed to determine the velocity and pressure distributions within the boundary layer. The obtained results will be compared with classical solutions for laminar boundary layers. This research is part of a broader project aimed at deepening the understanding of boundary layers and their applications in marine machinery and mechanisms. To accomplish the task of this research, the approach given in the source, [11] was used.

If the steps given in source [11] are followed, before proceeding to drawing the geometry of the flat plate, a preliminary analysis of the problem of this article is made. First, a suitable mathematical model must be specified and it must be seen what boundary conditions will be set. The problem in this present article is solved following the approach [11]. After clarifying the mathematical model, a numerical solution strategy is set. The geometry of the flat plate, which is specified as a domain, is divided into a certain number of control volumes or cells. The problem is optimized by determining the values of the velocities and pressures for each center of the cell. Interpolation of each center of the cell is used to determine the values of the other cells. This step is called discretization, and namely, after drawing the geometry of the model, a computational network is built. Then, following the approach [11], it is discussed analytically how many differential equations are solved, namely the Navier-Stokes equations, in order to clarify the behavior of the velocity profile through the flat plate.

After a preliminary analysis of the modeled object has been performed, including clarification of the mathematical model, the numerical solution strategy, and hand calculation, the next step is drawing the geometry of the object.

B. Flat plate geometry

Fig. 2 shows the drawn geometry of the object-flat plate into environment Space Claim into ANSYS.

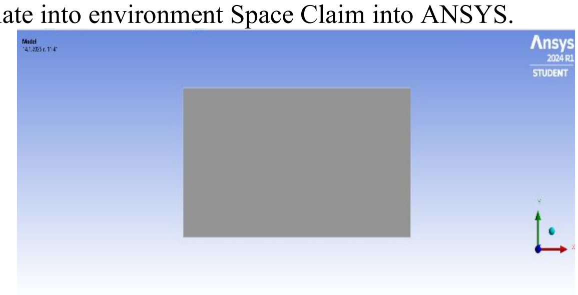

Fig. 2 geometry of flat plate

The geometry is drawn following the approach [11]. The study deals with conducting laminar boundary layer modeling over the flat plat.

C. Numerical mesh

In order to achieve the goal of the present study, namely the successful modeling of a laminar boundary layer around a flat plate and following approach [11], a procedure for creating a hex mesh around the object was performed. Fig. 3 shows the numerical mesh created around the object.

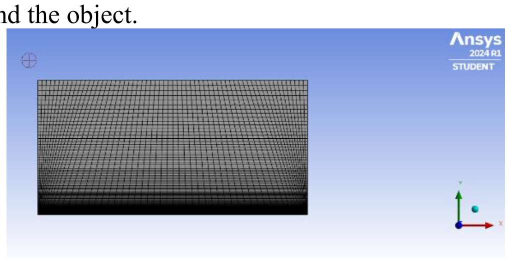

Fig. 3 Mesh around the flat plate

To capture flow behavior near the flat plate, the mesh must be refined near the boundary. Folling the approach [11] and as can be seen from Fig. 3 the mesh is refined at the flat plate boundary using edge biasing control. According to statics given in ANSYS the mesh consists of 6200 elements.

D. Physical Setup

After the successful construction of the computational mesh, a physical setup of the model was performed, [11]. Laminar flow was chosen as the viscous model and the following assumption was made that the modeled fluid flow is two-dimensional, steady, incompressible and Newtonian.

E. Numerical Solution

Folling the procedure according to source [11] the next step to fulfill the purpose of that study is to run the solution of the problem into ANSYS Fluent and to set up the residual criteria.

III. Results and Discussion

Convergence is crucial for modeling laminar boundary layer. As the iterations go on, the key parameters are expected to stop changing. At this point, the simulation is considered converged. For modeling the behavior of laminar boundary layer over the flat plate the key parameters for convergence that must be monitored are velocity vectors, velocity magnitude contours, pressure contours and velocity profile.

Fig. 4 and Fig. 5 show from afar and up-close velocity vectors after formulation and development of the laminar boundary layer around the flat plate.

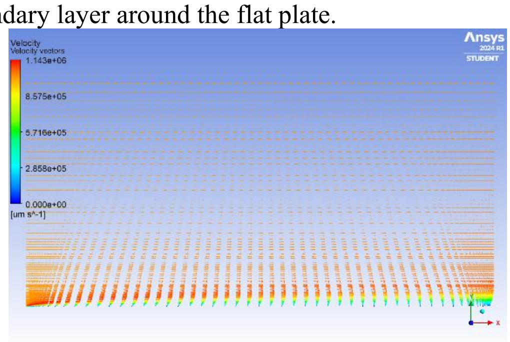

Fig. 4 Velocity vectors afar.

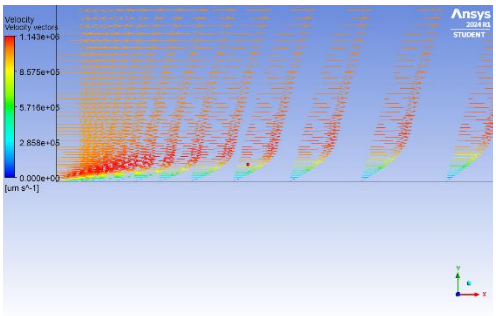

Fig. 5 Velocity vectors up-close.

Observing Fig. 4 and Fig. 5 velocity vectors show a nice view of the boundary layer development and if we go over the range the velocities go from zero to a little over one, which is what we expected. The closer look of a boundary layer over the plate shows that in the beginning the boundary layer is uniform then quickly it gets established and then it grows slowly.

Fig. 6 shows the velocity magnitude contours.

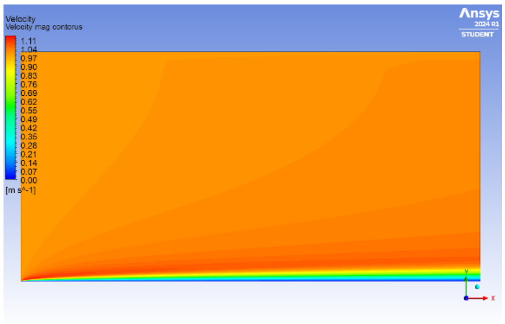

Fig. 6 Velocity mag contours.

Velocity mag contours, Fig. 6 show the development of boundary layer and, we can see thickness of the boundary layer that is much smaller than the length of the plate which is what we expected. We can also probe values of velocity using probe command from ANSYS. From the right side of the plate where we see the red contours, the boundary layer transitions into the outer flow. The velocity is around 1 which is what we expected. Near the farfield 1 and farfield 2 the velocity value is close to one and then near the plate it is at zero which is what we expect.

Fig. 7 shows the pressure contours after modeling laminar boundary layer over the flat plate.

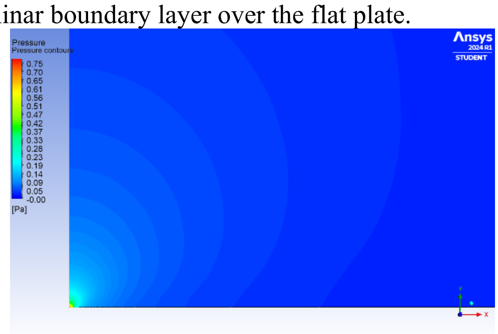

Fig. 7 Pressure contours.

Into the pressure contours we see the variation of pressure. If we come to leading edge, we see that we get relatively high pressures here now boundary layer theory breaks down over here and fluent solution is valid in the leading edge, but we get very rapid boundary layer development over here. Away from the left corner of the graph we can see that the gauge pressure is almost zero and so we go through the boundary layer and since the pressure is not very much the partial derivative of pressure by y is very close to zero and that is what we expect and that matches with our expectations from boundary layer theory. If we look at the range of gauge pressure, we should compare it to the free stream dynamic pressure which has half density goes infinity squared which is equal to 0.5. Path blue regions indicated the gauge pressure variation is very low which meets with our expectations from boundary layer theory. The gauge pressure, especially as you get closer to the plate, deviates from zero to 0.17. Fig. 8 shows the comparison between the pressure contours and the velocity magnitude contours.

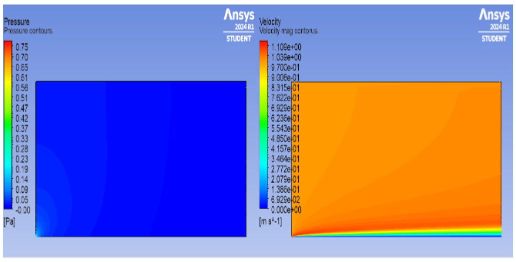

Fig. 8 Pressure contours versus velocity magnitude contours.

Pressure contours & velocity mag contours from here you can see that the boundary layer does not have much effect on the pressure whereas it has a big effect on velocity where velocity is going from 0 to 1.

Fig. 9 shows the velocity profile at the flat plate. Velocity profile at the plate is zero and then it increases as we move away from the plate in the Y direction. From boundary layer theory we expect it to go to 1 here it's overshooting by about 10% and then it decays to one. The overshooting is an artifact of the displacement thickness of the boundary layer it's a finite Reynold number of fact as you increase Reynold number this overshoot becomes smaller and smaller.

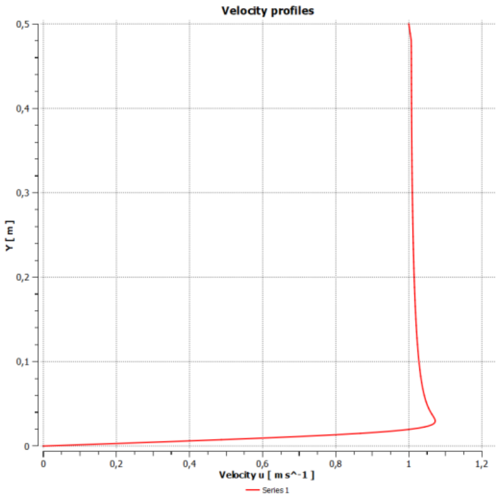

Fig. 9 Velocity profile at the flat plate.

Fig. 10 shows again the velocity profile with some changes and improvements.

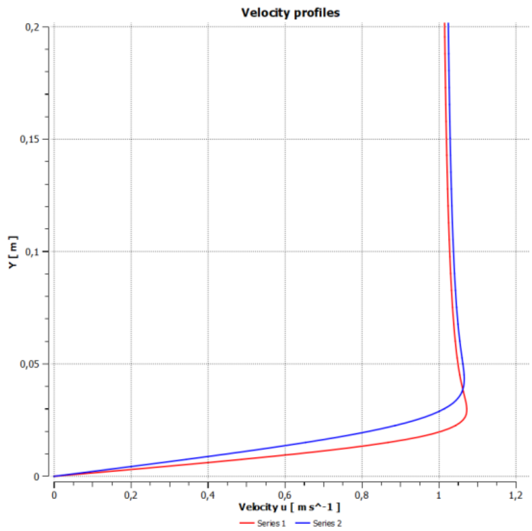

Fig. 10 Velocity profile 2.

Velocity profile 2, Fig. 10 shows the effect of the boundary layer thickening, the boundary layer ends approximately equal to close to 0.05 so that is the same ballpark as our estimate for the boundary layer thickness at the end of the plate using boundary layer theory. From the graph of velocity profile 2 we will discuss velocity profile overshoot, including why the velocity at the boundary layer edge is on the higher side of that free stream. Overshoot in the velocity profiles that we see on the graph is a real effect that you get by solving Navier-Stokes equations with fluent that is missed by boundary layer theory. Boundary layer theory splits the flow into an inner flow and outer flow. The inner flow is where the boundary layer equations are valid in the outer flow. The boundary layer theory assumes that the boundary layer is very thin so it's just a flow past flat plate. However, if you think about the outer flow as it's getting displaced as it's moving along the fluid it's going to accelerate. So, the velocity profile is zero at the wall and then it increases and at the edge of the boundary layer it's not one it's slightly higher than one because of the acceleration effect.

IV. Conclusions

This study presents an integrated approach to modeling laminar boundary layers over flat plates by combining theoretical analysis with numerical simulations in ANSYS Workbench. The results demonstrate the effectiveness of using Computational Fluid Dynamics (CFD) tools in engineering education, providing students and researchers with a deeper understanding of boundary layer development and its implications in practical applications.

A. Theoretical Applications

- From a theoretical standpoint, the study validates the classical boundary layer theory, particularly the Blasius solution, which describes the velocity profile and boundary layer growth for an incompressible, steady laminar flow over a flat plate. The numerical results closely match the expected boundary layer behavior, including:

- The gradual formation and thickening of the boundary layer along the plate.
- The velocity profile's transition from zero at the wall to its free-stream value, with an overshoot due to displacement effects.
- The near-zero pressure gradient in the boundary layer, aligning with theoretical predictions.
- These findings confirm the accuracy and reliability of classical fluid mechanics principles, reinforcing their continued relevance in modern engineering analysis. Additionally, by comparing analytical and numerical solutions, students gain a quantitative understanding of fluid behavior and numerical approximations.

B. Practical Applications

The practical significance of laminar boundary layer modeling extends to multiple engineering fields:

C. Naval Engineering and Ship Machinery

- Understanding boundary layer effects is crucial for reducing hydrodynamic drag on ship hulls, leading to improved fuel efficiency and lower operational costs.
- CFD simulations help in designing more hydrodynamically efficient hull structures by optimizing surface smoothness and shape.

D. Mechatronics and Fluid-Based System

- In mechatronic applications, boundary layer phenomena influence thermal management, lubrication efficiency, and aerodynamics of mechanical components.
- CFD modeling provides insights for optimizing fluid-based actuators and pumps, ensuring efficient operation and reduced energy losses.

E. Aerospace and Automotive Engineering:

- Although not the primary focus of this study, similar boundary layer principles apply in airfoil design, drag reduction strategies, and heat transfer optimization in various engineering sectors.

F. Educational Impact and Future Prospects

- This integrated learning approach enhances engineering education by fostering:
- Active problem-solving skills through hands-on CFD simulations.
- A deeper conceptual understanding of boundary layer physics beyond textbook learning.
- Improved computational proficiency, preparing students for advanced CFD applications in industrial settings.
- Future research could extend this approach to turbulent boundary layers, explore 3D flow effects, or integrate experimental validation with laboratory tests for further verification of CFD models.

In conclusion, the combination of theoretical foundations and numerical simulations in engineering curricula significantly enhances both learning outcomes and practical competencies, bridging the gap between academic knowledge and real-world engineering applications.

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