ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

CFD-BASED PI/PID CONTROLLER FOR VELOCITY AND HEADING CONTROL OF THE DARPA SUBOFF

M.Sc. THESIS

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<u>İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ</u>

HAD TABANLI PI/PID KONTROL YAKLAŞIMI İLE DARPA SUBOFF DENİZALTISININ HIZ VE ROTA KONTROLÜ

YÜKSEK LİSANS TEZİ

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MAYIS 2025

Duygu ÜNLÜ, an M.Sc. student of İTU Graduate School student ID 508221001, successfully defended the thesis entitled "CFD-BASED PI/PID CONTROLLER FOR VELOCITY AND HEADING CONTROL OF THE DARPA SUBOFF", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family and loved ones who have always supported me.

FOREWORD

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ABREVIATIONS

AFF-8 : Autonomous Free-Floating Target-8
CFD : Computational Fluid Dynamics
DARPA : Defense Advanced Research Projects Agency
DFBI : Dynamic Fluid-Body Interaction
DOF : Degree of Freedom
EFD : Experimental Fluid Dynamics
FVM : Finite Volume Method
GCI : Grid Convergence Index
ITTC : International Towing Tank Conference
MRF : Moving Reference Frame
MPC : Model Predictive Control
PID : Proportional-Integral-Derivative Control
PI : Proportional-Integral Control
RANS : Reynolds-Averaged Navier-Stokes
RBM : Rigid Body Motion
SIL : Simulation-in-the-Loop
SIMPLE : Semi-Implicit Method for Pressure-Linked Equations
SSC : Supervisory Switching Control
SST : Shear Stress Transport (k-ω model)
URANS : Unsteady Reynolds-Averaged Navier-Stokes

SYMBOLS

$\mathbf{A_E/A_0}$	: Blade area ratio	[-]
B	: Breadth	[m]
$\mathbf{D_{MAX}}$	: Maximum diameter	[m]
K	: Nomoto gain constant	[-]
$\mathbf{K_d}$	: Derivative gain	[-]
$\mathbf{K_i}$	: Integral gain	[-]
$\mathbf{K_p}$	: Proportional gain	[-]
$\mathbf{K_Q}$	: Torque coefficient	[-]
$\mathbf{K_T}$	: Thrust coefficient	[-]
$\mathbf{L_{OA}}$	: Length overall	[m]
$\mathbf{L_{PP}}$	: Length between perpendiculars	[m]
n	: Propeller rotation rate	[rps]
P/D	: Pitch ratio	[-]
Q	:Torque	[N·m]
R	: Resistance	[N]
r	: Yaw rate	[rad/s]
S	: Wetted surface area	[m^2]
T	: Thrust	[N]
z	: Number of blades	[-]
α	: Proportional gain constant	[N]
β	: Integral gain constant	[N·m]
δ	: Rudder angle	[deg] or [rad]
Λ	: Scale ratio	[-]
ρ	: Density	[kg/m^3]
ψ	: Heading angle	[deg] or [rad]
$\mathbf{\Psi_t}$	: Target heading angle	[deg]
ζ	: Damping ratio	[-]
$\mathbf{\omega_n}$	: Natural frequency	[rad/s]

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CFD-BASED PI/PID CONTROLLER FOR VELOCITY AND HEADING CONTROL OF THE DARPA SUBOFF

SUMMARY

This thesis presents a control approach developed through Computational Fluid Dynamics (CFD) to maintain the underwater route of submarines in a stable and consistent manner. The main focus of the study is the DARPA SUBOFF model with the E1619 model propeller, a widely used standard hull form in international hydrodynamic research. The study investigates the heading control performance of this model at various velocities and heading angles under free-running conditions. Compared to surface vessels, submerged bodies are exposed to significantly more external influences—such as currents, pressure fluctuations, and vortex structures around the hull—which complicate directional stability. Therefore, more precise and responsive control systems are necessary.

The CFD framework was based on the incompressible Unsteady Reynolds-Averaged Navier–Stokes (URANS) equations discretized using the Finite Volume Method (FVM) to ensure conservation across control volumes. A segregated solver with SIMPLE coupling and the Shear Stress Transport (SST) k–ω turbulence model was employed for stability and near-wall accuracy. The y+ wall treatment ensured proper resolution of near-wall turbulence effects. A Dynamic Fluid-Body Interaction (DFBI) method was employed for maneuvering motions to simulate dynamic interactions and control inputs. Propeller rotation and rudder motion were modeled using the Moving Reference Frame (MRF) and Rotating Body Motion (RBM) methods enabling efficient quasi-steady simulations with reduced computational cost and maintained accuracy. Thus, the adopted CFD setup enabled efficient and accurate prediction of key hydrodynamic phenomena (such as flow separation, vortex shedding, and pressure distribution) essential for maneuvering and propulsion analysis.

This study presents a CFD-integrated classical PID controller for submarine heading control, selected for its proven stability and interpretability in marine applications. Unlike conventional methods that rely on empirical tuning or simplified analytical models, the control gains in this work are systematically derived from high-fidelity CFD-based free-running maneuvering simulations. A custom Java-based macro was seamlessly embedded into the CFD solver, enabling real-time dynamic control and capturing the physical interaction between the vehicle and the surrounding flow field with high fidelity.

To verify the accuracy and reliability of the developed CFD model, a comprehensive Verification and Validation (V&V) study was conducted. The verification process was conducted through free-running self-propulsion simulations, where the Grid Convergence Index (GCI) method was employed to assess mesh uncertainty, resulting in an uncertainty level of less than 1.1%. In the validation step, the computed rotation rate, thrust and torque coefficients at a velocity of 2.75 m/s were compared with

benchmark experimental and CFD data, showing strong agreement and confirming the model's numerical accuracy and predictive capability.

Prior to implementing active heading control, the intrinsic course-keeping ability of the DARPA SUBOFF model was assessed. A free-running simulation without any rudder input (δ=0.0 deg) was performed, and the resulting steady-state yaw rate (r') was measured to be approximately 0.308. The elevated yaw rate indicates limited inherent course-keeping ability of the hull, highlighting the necessity of an active control system to maintain stable and accurate heading under realistic conditions.

The study consists of two main simulation stages. In the first stage, self-propulsion points were determined at three different velocities (2.750 m/s, 6.096 m/s, and 9.152 m/s). These points indicate where propeller thrust balances the hull resistance. A custom-designed Proportional–Integral (PI) controller was implemented to precisely identify the self-propulsion points, ensuring that propeller thrust accurately balanced the hull's resistance forces. This specialized PI controller provided precision, crucial for establishing a stable propulsion baseline. The resulting propeller rotation rates (n) were compared with benchmark experimental and CFD data in the literature, showing a discrepancy of less than 0.22%, thus confirming the reliability and precision of the propulsion model.

In the second stage, 10/10-degree zigzag maneuvers were performed. Parameters such as heading angle (ψ), yaw rate, and rudder angle (δ) were recorded during these tests. These data were used to extract the K (maneuvering gain) and T (hydrodynamic time constant) coefficients of the Nomoto model, which describes the relationship between rudder input and yaw response in submarine steering dynamics. This model is widely used in marine control applications to simplify and quantify the dynamics of course-keeping behavior, including heading control system design, autopilot tuning, and maneuvering performance analysis.

The developed PID control system continuously measured heading deviations and dynamically updated the rudder angle, effectively minimizing deviations from the desired course at target heading angles of 0.0, 5.0, and 15.0 degrees. Even at higher velocities, the controller maintained performance with low overshoot. In the simulation environment, a low-pass filter was applied to the rudder commands, and both rudder angles and rotation rates were constrained within specified physical limits. This ensured both physically meaningful motion and numerical stability.

In conclusion, this thesis demonstrates that PID controllers integrated with CFD can be effectively used for submarine heading control tasks. It enables the determination of control parameters during the design phase, potentially eliminating the need for expensive and time-consuming sea trials. Moreover, it provides a robust, energy-efficient, and environmentally adaptable heading control solution for autonomous underwater vehicles.

A notable contribution of this study is the seamless integration of the control system into the CFD environment via a custom Java-based macro, enabling real-time rudder control without external processing. Furthermore, a key innovation lies in achieving dynamic, physically consistent heading control by directly coupling CFD-derived force responses with the control system. This approach significantly enhances the system's adaptability to varying flow and operating conditions.

For future work, it is recommended to extend this approach to six degrees of freedom (6-DOF) simulations, include environmental effects such as different operating conditions (fully submerged, snorkel, and surface navigation) and ocean currents, and perform comparative analyses with artificial intelligence-based control algorithms. This would contribute to the development of smarter, faster-responding, and more environmentally adaptable autonomous submarine systems.

HAD TABANLI PI/PID KONTROL YAKLAŞIMI İLE DARPA SUBOFF DENİZALTISININ HIZ VE ROTA KONTROLÜ

ÖZET

Bu tez çalışması, denizaltıların su altı rotasını güvenli, kararlı ve enerji verimli bir şekilde koruyabilmesi amacıyla, Hesaplamalı Akışkanlar Mekaniği (Computational Fluid Dynamics – CFD) temelli bir kontrol yaklaşımı geliştirmektedir. Çalışmanın ana hedefi, rota sapmalarını en aza indirgeyerek denizaltının hedef rotasında kararlı şekilde seyretmesini sağlayan, fiziksel gerçekliğe dayalı ve otomatik bir PID (Oransal–İntegral–Türevsel) kontrol modelinin oluşturulmasıdır.

Su altı ortamı, yüzey araçlarına kıyasla daha karmaşık akış koşullarına sahiptir. Akıntılar, basınç değişimleri ve gövde etrafında oluşan girdap yapıları gibi etkiler, denizaltının yönelim kararlılığını doğrudan etkileyen önemli dış kuvvetlerdir. Bu nedenle, klasik açık çevrim kontrol sistemleri yerine, çevresel değişkenlere duyarlı, geri beslemeli ve gerçek zamanlı güncellenebilir kontrol sistemlerine ihtiyaç duyulmaktadır.

Bu bağlamda geliştirilen sistem, hem yön sapmalarını etkin biçimde bastırabilecek hem de farklı hız ve yönelme senaryolarında yüksek kararlılık sağlayabilecek bir çözüm sunmaktadır. Kontrol sistemi, modern bir ticari HAD çözücüsüne Java tabanlı özel bir makro aracılığıyla doğrudan entegre edilmiştir. Bu sayede, sistem harici bir yazılım ya da son işlem adımı gerektirmeksizin gerçek zamanlı dümen komutu üretip uygulayabilmektedir. Geliştirilen PID tabanlı kontrol sistemi, CFD ortamında elde edilen hidrodinamik verilerle doğrudan ilişkilendirilmiş; böylece kontrol kazançlarının sabit değerlerden ziyade fiziksel kuvvet dengelerine göre belirlenmesi mümkün kılınmıştır. Bu çalışmada önerilen yöntem, CFD tabanlı kuvvet verilerinin doğrudan kontrolör tasarımına entegre edilmesi bakımından literatürdeki önceki yaklaşımlardan ayrılmaktadır. Geleneksel çalışmalarda genellikle sabit katsayılar veya ampirik tablolar üzerinden kontrolör tasarımı yapılırken; burada akışa duyarlı, fizik-temelli ve gerçek zamanlı güncellenebilir bir kontrol yaklaşımı geliştirilmiştir. Bu yaklaşım sayesinde sistem, değişen çevresel koşullara gerçek zamanlı olarak adapte olabilen ve akışa duyarlı bir yapı kazanmıştır.

PID kontrolörler, kontrol mühendisliğinde en yaygın kullanılan algoritmalardan biridir. Bu kontrolörler; mevcut hata miktarına (P), geçmiş hataların birikimine (I) ve hatanın değişim hızına (D) dayalı olarak sistem girişini günceller. PID sistemlerinin en önemli avantajları arasında basitlik, düşük maliyet, kolay uygulanabilirlik ve yüksek kararlılık yer alır. Denizcilik sektöründe, özellikle de otonom su altı araçlarında (AUV), bu tarz kontrol sistemleri yön kararlılığı sağlama ve rota sapmalarını önleme amacıyla yaygın şekilde tercih edilmektedir.

Simülasyonlarda kullanılan fiziksel modeller arasında RANS (Reynolds-Averaged Navier-Stokes) tabanlı çözümler ve SST k-ω türbülans modeli yer almaktadır. Denklemler, kontrol hacmi bazında korunum sağlayacak şekilde Sonlu Hacimler Yöntemi (Finite Volume Method – FVM) ile ayrıklaştırılmıştır. Çözümde segregated

(ayrık) akış yaklaşımı benimsenmiş; basınç ve hız alanları, SIMPLE algoritması ile kararlı ve etkili bir şekilde çözdürülmüştür. Yakın duvar bölgesindeki türbülans etkilerinin doğru modellenmesi için y+ duvar bölgesi çözümlemesi (y+ wall treatment) uygulanmıştır.

Manevra hareketlerinin gerçekçi şekilde modellenebilmesi için, hareketli gövde etkileşimleri DFBI (Dynamic Fluid-Body Interaction) yöntemi ile simüle edilmiştir. Pervane hareketi, Hareketli Referans Çerçevesi (MRF) yaklaşımıyla; dümen hareketi ise Rijit Cisim Hareketi (RBM) yöntemiyle modellenmiştir. Pervane dönüş modellemesi için MRF ve dümen hareketi için RBM kullanımı, fiziksel doğruluktan ödün vermeden hesaplama süresini ve maliyetini önemli ölçüde düşüren simülasyonlara olanak sağladı. Bu nedenle, benimsenen CFD kurulumu, manevra ve tahrik analizi için önemli olan temel hidrodinamik fenomenlerin (akış ayrılması, girdap ayrışması, basınç dağılımı vb.) verimli ve doğru bir şekilde tahmin edilmesini sağladı.

Tez çalışması iki ana aşamaya ayrılmıştır. İlk olarak, farklı hız değerlerinde (2.75 m/s, 6.096 m/s ve 9.152 m/s) öz-itme koşulları elde edilmiştir. Öz-itme, denizaltı pervanesinden elde edilen itmenin gövde direnci ile dengelendiği durumları ifade eder ve PI (Oransal–İntegral) kontrol sistemi ile bu denge yakalanmıştır. Bu süreçte denizaltı sadece ileri yöndeki (öteleme – surge) harekete serbestken, diğer hareketlere karşı ise engellenmiştir. Bu analiz, daha sonra gerçekleştirilecek olan manevra analizleri için doğru başlangıç koşullarının oluşturulmasını sağlamıştır. Kullanılan özgün PI kontrolörü, itki ve direnç dengesini yüksek hassasiyetle sağlayarak öz-itme noktasının kesin biçimde tayin edilmesini mümkün kılmıştır. Elde edilen pervane devir sayıları, literatürdeki deneysel ve CFD çalışmalarla karşılaştırılmış ve sonuçlar %0.22’den düşük farkla uyum göstermiştir.

İkinci aşamada, üç serbestlik dereceli (ileri ve yan öteleme, savrulma) 10/10 derecelik zikzak manevraları ile denizaltının yönelme dinamikleri analiz edilmiştir. Zikzak manevraları sonucunda elde edilen rota açısı (ψ), dümen açısı (rudder angle) ve savrulma oranı (yaw rate) verileri, Nomoto modeline uygulanarak—kontrolcü katsayıları olan K ve T parametreleri hesaplanmıştır. Bu katsayılar, PID kontrolörün kazançlarını (K_p, K_i, K_D) belirlemek için doğrudan kullanılmıştır. Nomoto modeli, deniz araçlarının yönelme davranışlarını basitleştirilmiş bir matematiksel yapı ile açıklayan ve denizcilikte sıkça kullanılan bir modeldir. Bu model, PID gibi klasik kontrol algoritmalarının sistemle entegre edilmesinde oldukça etkilidir.

Geliştirilen PID kontrolörü Java tabanlı bir makro aracılığıyla modern bir ticari HAD çözücüsü içerisinde devreye alınmıştır. PID kontrolör, hedef baş doğrultusu ile mevcut baş doğrultusu arasındaki sapmayı sürekli olarak değerlendirerek, dümen açısını otomatik şekilde güncellemektedir. Bu kontrol döngüsünde dümen alçak geçirgen filtre ile yumuşatılmış, maksimum dümen açısı 20 derece ile sınırlandırılmış ve kontrol komutlarının fiziksel gerçekliğe uygun şekilde uygulanması sağlanmıştır. Böylece sistemin ani ve kararsız tepkiler vermesi engellenmiştir.

Doğrulama (verification) sürecinde, GCI (Grid Convergence Index) yöntemiyle üç farklı ağ yoğunluğunda analizler yapılmış ve çözümün ağdan bağımsızlığı %1.1’in altında bir belirsizlik ile sağlanmıştır. Geçerlilik (validation) analizleri ise 2.75 m/s için literatürde yer alan deneysel ve HAD çalışmalarıyla kapsamlı olarak yapılmıştır. Özellikle pervane dönüş hızı, itme (K_T) ve tork (K_Q) katsayıları açısından yüksek düzeyde uyum yakalanmıştır. Bu sonuçlar, kullanılan fizik modellerin doğruluğunu ve güvenilirliğini ortaya koymaktadır.

Aktif rota kontrolünü uygulamadan önce, modelin doğal rota tutma kabiliyeti değerlendirilmiştir. Herhangi bir dümen girdisi olmaksızın (δ=0.0 derece) serbest çalışma şartlarında ilerleyen DARPA modeli rotasını koruyamamış ve belirgin bir dönüş manevrası gerçekleştirmiştir. Bu durumda boyutsuz savrulma oranı (r') yaklaşık 0.308 olarak ölçülmüştür. Bu değer, gövde formunun kendiliğinden kararlı olmadığını ve yönelme eğiliminde önemli bir sapma bulunduğunu göstermektedir. Dolayısıyla, güvenilir ve istikrarlı bir rota tutma performansı sağlanabilmesi için aktif bir kontrol sisteminin uygulanması kaçınılmaz hale gelmiştir.

Aktif rota kontrolünün olduğu durumlarda, geliştirilen PID kontrolörün yönelme sapmalarını başarıyla önlediğini göstermektedir. Özellikle 0.0, 5.0 ve 15.0 derece gibi farklı hedef- doğrultu koşullarında sistemin, hem düşük hızda hem de yüksek hızda hedef rotayı kısa sürede yakaladığı ve yön kararlılığını sürdürdüğü gözlemlenmiştir. Kontrolör aktif olmadığı senaryoda denizaltının rotadan saparak dairesel hareketlere yönelirken, aktif kontrol uygulandığında bu savrulmaların etkin şekilde giderildiği tespit edilmiştir. Bu davranış, geliştirilen PID sistemin dinamik çevresel koşullara etkin biçimde yanıt verdiğini ortaya koymaktadır.

Bu çalışma, CFD ile kontrolör tasarımını kapalı çevrim bir yapıda entegre ederek literatürdeki benzerlerinden ayrışmaktadır. Geleneksel çalışmalar çoğunlukla PID kazançlarını deneysel verilerden veya sabit formüllerden türetirken; bu tez çalışması, kazançları doğrudan CFD ortamında gerçekleştirilmiş zikzak manevraları üzerinden Nomoto modeli sayesinde hesaplamış ve bu verileri simülasyonla doğrulamıştır. Böylece sistem hem fiziksel hem de sayısal düzlemde optimize edilmiştir.

Mühendislik uygulamaları açısından bakıldığında, bu yöntem denizaltı tasarım sürecinde zaman ve maliyet açısından büyük avantaj sağlar. Özellikle deneysel testlerin pahalı ve zaman alıcı olduğu erken tasarım aşamalarında, CFD ile bütünleşik kontrol sistemleri sayesinde denizaltının yönelme karakteristikleri önceden belirlenebilir ve tasarım buna göre optimize edilebilir. Savunma sanayii, araştırma denizaltıları ve otonom su altı araçları (AUV) gibi alanlarda bu tarz gelişmiş kontrol sistemleri büyük önem taşımaktadır.

Bu çalışmanın sonuçları, yalnızca akademik katkılar sağlamakla kalmamış, aynı zamanda sektörel olarak uygulanabilir, sağlam ve güvenilir bir rota kontrol sistemi geliştirme yolunda önemli bir adım atmıştır. Ayrıca çalışmada önerilen yöntem, farklı denizaltı geometrilerine, farklı hız aralıklarına ve farklı çevresel koşullara da kolaylıkla adapte edilebilecek esneklikte bir yaklaşımdır.

Gelecek çalışmalarda, bu yapının altı serbestlik dereceli (6-DOF) hareketleri kapsayacak şekilde genişletilmesi, farklı seyir durumları (tamamen dalmış, şnorkel ve satıh seyirleri) ve akıntı gibi çevresel etkilerin modele entegre edilmesi ve yapay zekâ tabanlı kontrol algoritmalarıyla karşılaştırmalı olarak analiz edilmesi önerilmektedir. Ayrıca, deneysel verilerle karşılaştırmalı testler gerçekleştirilerek sistemin gerçek zamanlı uygulamalara entegrasyonu sağlanabilir.

1. INTRODUCTION

1.1 Research Objectives and Scope

Maintaining a submarine's intended course and ensuring stable heading angle are one of the key challenges in underwater navigation. Submarines are constantly affected by external forces such as underwater currents and density variations, which can cause deviations from their intended path. To counteract these disturbances, autopilot systems are used to control the submarine's direction. However, many existing autopilot systems rely on simplified mathematical models that do not fully capture the complex interactions between the submarine and its surrounding water. The primary objective of this research is to enhance heading control performance by integrating Computational Fluid Dynamics (CFD) with advanced control strategies, thereby developing a more accurate and robust autopilot system tailored for submarines with poor natural stability.

The primary objective of this study is to develop a Computational Fluid Dynamics (CFD)-based control model for regulating the underwater trajectory of a submarine. The proposed model employs a Proportional-Integral-Derivative (PID) controller to ensure precise route tracking and maneuverability. By integrating CFD simulations, the study aims to enhance the accuracy of hydrodynamic force predictions and obtain control parameters for improved submarine navigation in varying underwater conditions. A control system has been developed that allows the submarine to make automatic adjustments and maintain its course with minimal deviation.

Beyond its technical contributions, this research also supports the development of autonomous underwater vehicle (AUV) systems. As the maritime industry moves toward automation, more effective autopilot systems are necessary to ensure safe and efficient underwater operations. The outcomes of this work will not only improve existing submarine designs but also provide a foundation for future autonomous underwater navigation. By refining control techniques and utilizing detailed hydrodynamic data, the proposed methodology aims to make submarine steering systems more reliable and adaptable.

The scope of this thesis focuses on heading control rather than general maneuverability. The research presented here is conducted on a specific submarine type to maintain accuracy. However, the developed methodology can be adapted for different submarine designs and operational conditions in future applications.

The PID-based heading controller is integrated into a fully coupled Simulation-in-the-Loop (SIL) environment, where both the submarine dynamics and hydrodynamic forces are resolved through unsteady CFD simulations. This setup enables closed-loop control performance assessment under realistic flow conditions without requiring any physical test platform.

In this study, the applicability of a simpler and more practical control method, compared to other complex control systems, is investigated. Rather than focusing on a single velocity value, the controller is designed to operate effectively over a broad range of velocities.

The control parameters, which vary based on form dynamics, are intended to be determined during the design phase rather than through costly and time-consuming sea trials. This approach aims to eliminate uncertainties related to the hull and propulsion systems at an early stage.

With the increasing computational power and the development of advanced numerical methods, Computational Fluid Dynamics (CFD) has become widely applicable. This study integrates CFD with control system design to enhance the accuracy and robustness of submarine maneuverability predictions.

Unlike surface vessels, submerged bodies are highly sensitive to force imbalances. If a dominant force is not counteracted within the system, maintaining control of the submarine becomes extremely difficult, if not impossible. In this context, the DARPA SUBOFF model was intentionally selected due to its lack of inherent course-keeping ability, making it an ideal benchmark for testing and validating the effectiveness of active control strategies. Forces acting on the body can be balanced through rudder and fin deflections, making it essential to employ a control system that can continuously track motion and generate real-time responses. Therefore, this work focuses on developing a controller specifically aimed at preserving the course of a submerged vehicle. In addition to maintaining heading accuracy, it is essential to ensure that the vehicle operates within predefined limits of acceleration and oscillatory motion to protect crew, equipment, and onboard systems.

In this context, the present study develops a real-time heading control system based on Computational Fluid Dynamics (CFD) simulations and a Proportional-Integral-Derivative (PID) controller. By integrating high-fidelity hydrodynamic modeling with adaptive control strategies, the proposed method enables accurate heading control performance under dynamic underwater conditions, addressing the challenges outlined above.

In alignment with global sustainability frameworks such as the European Green Deal, Sustainable Development Goals (SDGs) and national strategic initiatives like Türkiye’s 12th Development Plan (2024–2028), this thesis supports the advancement of sustainable, efficient, and digitally integrated maritime systems. The CFD-based control model developed in this study reduces the reliance on energy-intensive sea trials by enabling accurate prediction of hydrodynamic behavior during the early design phase, thereby contributing to the reduction of fuel consumption, underwater noise pollution, and greenhouse gas emissions—key environmental targets emphasized in international agreements.

Furthermore, the research directly addresses national priorities by promoting the integration of advanced numerical simulations with autonomous control strategies, in line with objectives to strengthen R&D capacity, foster digital transformation, and advance high-value-added technologies in the maritime and defense sectors. By improving the accuracy and responsiveness of submarine navigation systems, the findings also contribute to the advancement of marine technologies and the sustainable growth of maritime engineering practices.

In summary, from a technical and scientific perspective, this thesis aims to enhance the accuracy and adaptability of submarine control systems through the integration of high-fidelity Computational Fluid Dynamics (CFD) modeling with advanced control algorithms. One of the primary objectives is to develop a real-time control framework that can dynamically respond to environmental disturbances without compromising course stability. By capturing the complex, nonlinear hydrodynamic interactions between the submarine and its surrounding medium, the research addresses the limitations of conventional simplified models. The study also seeks to broaden the operational velocity range of the control system, ensuring robust performance under varying mission conditions. Additionally, by shifting the determination of control parameters to the design phase, the thesis aims to reduce reliance on physical sea trials, streamline development processes, and support the creation of adaptive autopilot systems for next-generation underwater vehicles.

1.2 Scientific and Methodological Contribution

This study introduces an innovative approach to submarine navigation and control by integrating high-accuracy CFD simulations with advanced control strategies. Unlike many previous studies that rely on empirical formulas or experimental data alone, this research directly calculates hydrodynamic coefficients through CFD, ensuring more precise and reliable submarine motion predictions. The integration of these detailed hydrodynamic properties into autopilot systems allows for more adaptive and responsive course control, which marks a significant improvement over conventional method.

One of the key advancements in this study is the comprehensive nature of its CFD analyses. Many earlier studies focus on simplified models or steady-state conditions, often overlooking the complex and dynamic interactions between the submarine and surrounding water. In contrast, this research incorporates unsteady simulations and advanced turbulence modeling to capture real-time effects of underwater currents and rudder movements on submarine stability. By considering these factors in greater detail, this study provides a more complete understanding of the forces acting on a submarine, leading to improved maneuvering predictions and control adjustments.

Furthermore, the control system developed in this study introduces a new perspective on submarine course stability. Instead of relying on predefined response patterns, the system dynamically adapts based on real-time hydrodynamic feedback. This enables the autopilot system to respond more efficiently to environmental changes, reducing unnecessary rudder movements and improving energy efficiency. Additionally, the study explores the influence of different submarine parameters on control performance, offering a more versatile and applicable model for a range of submarine types and operating conditions. An additional innovation is the development of a custom Java-based macro that fully embeds the PID controller within the CFD solver.

This allows real-time rudder actuation directly inside the simulation loop, without external software or co-simulation frameworks, ensuring a seamless and closed-loop control environment.

The findings of this research address critical questions that have not been fully explored in previous studies. In the defense and maritime industry, submarine operators require more accurate and reliable control systems to reduce energy consumption and improve stealth capabilities. This study proposes an optimized method for rudder control, helping naval forces enhance operational efficiency while minimizing detection risks. In academia, the integration of high-accuracy CFD simulations with real-world control applications fills an essential gap in submarine hydrodynamics research. This study presents a novel framework that can support further advancements in autonomous underwater navigation, paving the way for future research on self-steering submarines. Moreover, by implementing a simulation-in-the-loop framework, the study provides a virtual prototyping platform that allows engineers to test and refine autopilot algorithms entirely within a single CFD environment. This eliminates the complexity of multi-platform setups and accelerates the design-validation cycle for advanced control systems.

By addressing these gaps, this study makes a significant contribution to both the naval industry and academic literature. The combination of detailed CFD analyses with advanced control methods enhances current autopilot systems and sets a new benchmark for future research in submarine navigation and maneuverability. The results of this study will help shape the next generation of submarine control technologies, promoting safer, more efficient, and more autonomous underwater operations.

Another important aspect of this study is its contribution to improving operational efficiency in underwater vehicles. The approach supports reduced energy demand by promoting more effective use of control inputs based on real-time hydrodynamic behavior. It aligns with the growing emphasis on sustainable and environmentally friendly maritime practices.

The control framework introduced in this thesis also lays the groundwork for future integration with artificial intelligence and machine learning algorithms. The established macro-based integration also serves as a flexible foundation for incorporating adaptive control algorithms that require continuous feedback from high-fidelity simulations. By creating a high-fidelity, data-rich simulation environment, the study enables the training and validation of intelligent control agents capable of learning optimal maneuvering strategies. This opens new possibilities for adaptive and autonomous navigation systems that continuously improve over time based on operational data.

1.3 Scientific, Industrial and Societal Impact

1.3.1 Scientific and technological contributions

This study significantly enhances the scientific understanding of submarine heading control by integrating detailed Computational Fluid Dynamics (CFD) simulations with adaptive control strategies. Unlike traditional methods relying on empirical data or simplified mathematical models, the proposed approach utilizes high-resolution, unsteady hydrodynamic simulations to directly derive maneuvering characteristics and control parameters. Compared to empirical or linearized models, CFD-based approaches capture the nonlinear and transient effects of hull, propeller, and rudder interactions under dynamic flow conditions, offering a more realistic foundation for control system development. By refining the calculation of hydrodynamic coefficients, the research improves the precision of maneuvering models and strengthens the reliability of CFD applications in submarine navigation studies.

A key advancement of this work lies in its dynamic integration of CFD-derived flow data into real-time control system design. Through the simulation of zigzag maneuvers and extraction of Nomoto model coefficients, the study establishes a framework that allows PID controller tuning within the same transient simulation environment, eliminating the dependency on external empirical tables or static assumptions. The extracted Nomoto model coefficients are systematically processed to calculate PID control gains, which are then directly validated through closed-loop simulations within the same CFD environment. This methodology bridges the gap between hydrodynamic modeling and control design, providing a fully coupled, physics-informed control system validation process.

Moreover, the study offers valuable contributions to the scientific communication of complex fluid-structure interactions. The interactions between hydrodynamic forces, vehicle responses, and control strategies are explained using accessible language and practical examples, making the findings understandable to a broader academic and engineering audience. This accessibility ensures that critical knowledge regarding submarine form optimization and course stability reaches a wider range of researchers and practitioners.

By demonstrating how advanced CFD simulations can be effectively leveraged to improve control system design, the thesis contributes to the development of more accurate and adaptive course-keeping frameworks for underwater vehicles. It also highlights the importance of real-time environmental feedback integration in achieving reliable, stable submarine navigation under dynamic operational conditions.

Ultimately, the methodology presented here serves both as a reference for scientific advancement and as a model for integrating computational hydrodynamics with dynamic control theory.

1.3.2 Industrial and defense sector impact

The findings of this thesis have significant implications for the maritime and defense industries, particularly in the development of advanced underwater navigation systems. In the naval sector, the improved course control methodologies presented in this study can enhance the maneuverability, operational efficiency, and stealth capabilities of both military submarines and surface vessels. By enabling more accurate prediction and real-time counteraction of external disturbances, the proposed control framework supports safer navigation and reduces energy consumption during missions.

Moreover, the research provides a foundational approach for the development of next-generation autonomous underwater vehicles (AUVs). Stability and maneuverability are critical factors for AUV operations in surveillance, reconnaissance, and deep-sea exploration missions. The integration of high-fidelity CFD simulations with adaptive PID-based control strategies enables the design of more intelligent, stable, and responsive unmanned underwater systems. The macro-based automation developed in this study allows engineers to implement control logic directly within the CFD environment, reducing dependence on third-party tools and eliminating the complexity of coupling multiple simulation platforms. This streamlined integration paves the way for virtual prototyping of autopilot algorithms, enabling rapid and cost-effective testing of closed-loop control systems entirely within a single simulation framework. Such an approach offers significant advantages for early-stage design and verification, particularly in fields such as autonomous underwater vehicles (AUVs) and naval defense systems.

The validated CFD-based maneuvering models developed in this work demonstrate the potential to influence new standards and best practices for maritime navigation and automation. By bridging theoretical advancements with practical engineering applications, the proposed methodology aids in reducing the need for extensive sea trials and accelerates the design cycle of both manned and unmanned underwater platforms. Consequently, this thesis contributes to the broader objective of advancing autonomous maritime technologies while strengthening strategic capabilities in the naval and defense sectors.

1.3.3 Future applications

The methodologies and findings of this study have significant applications in academic research. The integration of CFD with adaptive control techniques serves as a foundation for future studies on autonomous submarine navigation, course stability, and maneuvering optimization. Universities and research institutions can build upon this work to develop more advanced simulation tools and experimental validation methods.

Future research should build upon existing control systems—such as the PID-based heading control and velocity control methods demonstrated in this study—to further enhance the autonomy of underwater vehicles. These findings provide a solid foundation for continued advancements in marine robotics. In particular, future efforts should focus on developing six-degree-of-freedom (6-DOF) models and integrating more advanced path-following control strategies, enabling precise and intelligent maneuvering under a wider range of operating conditions.

Looking ahead, CFD technology will continue evolving, enabling more complex and realistic modeling. This research lays the groundwork for future advancements, including higher-resolution turbulence modeling, real-time hydrodynamic data integration, and enhanced simulation accuracy under extreme underwater conditions. By expanding the scope of CFD applications in marine engineering, this study contributes to the ongoing development of advanced, efficient, and autonomous submarine systems.

Ultimately, this research bridges the gap between academic knowledge and engineering practice by providing a comprehensive and validated framework for submarine control. It ensures that the latest developments in hydrodynamic modeling and control theory are both theoretically sound and practically viable. This contribution strengthens scientific understanding while fostering technological progress, paving the way for more reliable, efficient, and intelligent underwater navigation systems.

In conclusion, this study advances submarine hydrodynamics and control systems while offering practical solutions for improving maritime operations. By promoting interdisciplinary collaboration and integrating theoretical insights with real-world applications, this work supports the development of safer, more efficient, and increasingly autonomous underwater technologies.

1.3.4 Scientific communication for general audiences

Submarines operate in a complex and often unpredictable environment beneath the ocean surface. Unlike surface vessels, they are subject to a range of invisible underwater forces, such as changes in water pressure, depth-related effects, and currents. Navigating accurately under such conditions presents a major challenge, requiring both scientific understanding and engineering precision. This challenge has led to the development of increasingly advanced control systems that help submarines maintain their intended paths.

Traditionally, automatic steering systems have relied on simplified mathematical models. While effective under certain conditions, these models often fail to reflect the full complexity of the interactions between the submarine and the surrounding water. In this study, a new approach is proposed that combines two powerful tools: detailed computer simulations of water flow and a real-time automatic control system. These simulations—based on Computational Fluid Dynamics (CFD)—allow for an in-depth understanding of how forces act on the submarine's hull. The control system, which uses a widely accepted technique known as Proportional-Integral-Derivative (PID) control, continuously adjusts the submarine's steering based on current flow conditions. This integration enables the submarine to move more efficiently, smoothly, and safely through dynamic environments.

Unlike traditional methods that assume constant or predictable forces, this model accounts for real-time variations that occur due to changes in velocity, depth, or environmental conditions. By analyzing the flow of water around the submarine with high precision and adjusting its rudder and fin positions accordingly, the control system maintains course stability. Much like a bird instinctively adjusts its wings to stay balanced in flight, the submarine responds to underwater changes in a similar way. This allows it to follow its path with minimal correction, resulting in better energy use and increased navigational safety.

In addition to improving course-keeping performance, this study also considers future applications in autonomous underwater vehicles—submarines that operate without human input. The methods and findings are applicable not only to manually operated submarines but also to intelligent systems used in underwater exploration, construction, or defense. These systems must be able to react to changing conditions without relying on constant human intervention. The approach presented here supports that goal by enabling real-time, adaptive behavior based on environmental feedback.

A further important aspect of this work is safety. Steering systems must not only guide the submarine accurately but also do so within defined limits to ensure the protection of both crew and equipment. Excessive or sudden movements can create risks or discomfort. The developed controller incorporates physical constraints on steering commands—such as maximum rudder angle and rate of movement—to ensure that the submarine’s responses remain within safe and stable ranges.

Overall, this study contributes to narrowing the gap between theoretical hydrodynamics and practical submarine control. By combining CFD-based flow analysis with an intelligent control strategy, it presents a new standard for underwater navigation. The findings offer valuable insights for designing future submarines that are more efficient, adaptable, and capable—whether operated by humans or entirely autonomously. As exploration extends into deeper and more difficult marine environments, the ability to navigate with precision and confidence will be increasingly important. This research represents a significant step toward that future.

1.3.5 Policy alignment and strategic relevance

This study aligns with several national and international policy frameworks that emphasize sustainability, digital transformation, and strategic technological advancement in maritime systems. In the context of the European Green Deal (Fetting, 2020), the proposed CFD-based control methodology contributes to environmentally sustainable marine operations by reducing energy consumption, minimizing the need for resource-intensive sea trials, and promoting smarter, low-emission vessel control strategies. By enabling more efficient underwater navigation with lower operational emissions, the research directly supports the European Union's climate neutrality goals for 2050.

At the national level, the findings of this thesis are consistent with the objectives outlined in Türkiye's 12th Development Plan (2024–2028), as adopted by the the Grand National Assembly of Türkiye (2023), particularly those presented on pages 93, 127, 137, and 138. The plan emphasizes the importance of strengthening research and development (R&D) capacity in critical technology areas such as defense, maritime, and autonomous systems. By integrating advanced numerical simulations with adaptive control techniques, this study contributes to the development of innovative and digitally adaptable control frameworks that can support the design and operation of future autonomous underwater vehicles and naval platforms. Moreover, the study's focus on reducing dependency on empirical testing aligns with national efforts to promote localization, technological independence, and digital transformation across strategic sectors.

Beyond regional and national priorities, the research also resonates with the global vision set forth by Sustainable Development Goals (SDGs) established by the United Nations (2015), particularly Goals 9 (Industry, Innovation and Infrastructure), 13 (Climate Action), and 14 (Life Below Water). The study's emphasis on digital innovation, sustainable maritime engineering, and the reduction of environmental impacts reflects the broader commitment to fostering resilient, environmentally responsible, and technologically advanced marine transportation systems.

Overall, by addressing key themes of environmental sustainability, digital innovation, and technological autonomy, this study makes a meaningful contribution to the evolving landscape of global maritime policies and supports both national and international objectives for the future of marine technology development.

1.4 Literature Review and Evaluation

The development of PID-based control strategies for marine vehicles has evolved from simplified theoretical formulations to highly detailed, simulation-validated implementations. One of the foundational contributions came from Nomoto et al. (1957), who proposed a mathematical model to describe the steering qualities of ships using two key indices: maneuverability gain (K) and response time (T). This so-called Nomoto model became the cornerstone for many subsequent control design approaches. While elegant in its simplicity, the model assumes linearity and small rudder deflections, limiting its applicability for complex or large-angle maneuvers—particularly in submarine operations.

Expanding from this base, early 2000s research introduced enhancements to address nonlinearity and environmental unpredictability. Moradi & Katebi (2001) developed a predictive PID control strategy based on generalized predictive control theory, aiming to improve ship autopilot responsiveness by incorporating future state estimates. In parallel, Jingyi & Yinhai (2001) applied fuzzy logic to the PID control structure, proposing a fuzzy-PID (FPID) system that adjusted parameters based on heuristic rules. While both approaches sought to overcome the rigidity of traditional PID tuning, they diverged in methodology— Moradi & Katebi (2001) focusing on model-based optimization, and Jingyi & Yinhai (2001) emphasizing real-time fuzzy adaptation.

In a similar vein, Le et al. (2004) proposed an engineering method to design fuzzy autopilots by integrating fuzzy inference systems with classical control theory. However, these fuzzy systems were often sensitive to tuning inputs, prompting a need for adaptive, feedback-based approaches. Skjetne et al. (2004) responded to this with an adaptive maneuvering controller developed for a scaled CyberShip II platform, incorporating nonlinear damping and real-world system identification through towing tests—providing empirical grounding that earlier fuzzy systems lacked.

Fang et al. (2010) advanced this by designing a self-tuning PID controller based on a neural network for roll control in random waves, introducing automated parameter adjustment but encountering limitations in tuning velocity and interpretability. In contrast, Pan et al. (2012) offered a CFD-based solution using RANS to estimate submarine hydrodynamic coefficients, providing a more physical and deterministic input for controller design. These contrasting approaches—model-free adaptation versus physics-based modeling—marked a core divergence that continued through the next decade.

Pathan et al. (2012) used a neural network controller for heading and track-keeping tasks, while Gong et al. (2016) proposed a nonlinear PD-based strategy for underwater straight-line control. Both methods enhanced adaptability under dynamic conditions using model-based feedback, yet neither included real-time hydrodynamic force input derived from physical flow fields—thereby limiting their representational accuracy under complex or unsteady flow conditions. In contrast, Martin et al. (2015) applied 6-DOF maneuvering simulations using a coupled overset mesh and CFD/potential flow solver, capturing submarine responses under complex flow conditions. Although not directly integrating control algorithms into the solver, Martin's work significantly advanced the coupling between control intent and physical behavior—setting a precedent for post-2015 studies.

Chase (2013) provided a dual contribution: one examining overset simulations of the Suboff under various operating conditions, and another analyzing propeller performance using the E1619 model across turbulence models (RANS, DES). His studies demonstrated how solver and turbulence model choice—particularly between RANS and DES—significantly affect the accuracy of wake structure predictions and thrust estimation for self-propelled simulations, which later influenced CFD-based control studies such as those by Carrica et al. (2019) and Zenagui et al. (2025).

Sezen et al. (2018) and Kinaci et al. (2018a) made significant strides by simulating self-propulsion of the DARPA Suboff using RANS-based CFD. While Kinaci et al. implemented virtual disk and BEM coupling, Sezen et al. employed body force and sliding mesh approaches, directly comparing them in terms of thrust efficiency. Both studies demonstrated the limitations of simplified models and stressed the importance of capturing wake–propeller–rudder interaction. Their results showed the limitations of body force methods and emphasized the importance of including full wake–propeller–hull interactions. This physical refinement was supported by Carrica et al. (2019), who examined near-surface propeller behavior under near-surface conditions, both in calm water and head waves, using the REX CFD code, and by Özden et al.

(2019), who conducted rare combined CFD–EFD validation for a self-propelled Suboff. These studies highlighted the necessity of experimental benchmarking and the importance of free-surface and propeller modeling in control-relevant simulations.

In the same period, Dlabač et al. (2019) reintroduced PSO-based PID tuning, offering algorithmic efficiency over traditional gain-scheduling. However, like neural network approaches, it lacked physical integration, making it more suitable for system-level autopilots than for submerged course control. The increased use of 6-DOF RANS simulations, as seen in H. Kim et al. (2018) and Han et al. (2021), provided a middle ground—bridging controller design with predictive flow physics.

Entering the 2020s, the literature embraced full-scale validation, machine learning integration, and reduced-order modeling. Liu et al. (2021) validated full-scale CFD predictions against experimental propulsion data for Suboff, reinforcing Sezen et al. (2021) findings on scale effects. Carrica, Kim, et al. (2021) and Han et al. (2021) refined vertical maneuvering models and validated pitch–yaw dynamics using CFD-derived motion envelopes. Simultaneously, Borase et al. (2021) provided a comprehensive review of PID tuning strategies, documenting the field's transition from static methods toward adaptive and intelligent tuning approaches, including hybrid schemes such as fuzzy-PID and PSO-based controllers. Lin et al. (2021) constructed a semi-autonomous Suboff model with an integrated autopilot system based on a PD controller and LOS algorithm. Unlike earlier CFD-only simulations (e.g., Martin, Han, Pan), Lin coupled motion simulation with control gain tuning and performed zigzag, turning, and spiral tests. His work mirrors later studies like L. Liang et al. (2022) in exploring real-time control performance.

Kinaci et al. (2020) introduced a feedforward velocity control framework that bypassed closed-loop feedback by estimating propeller revolutions based on target velocity and known resistance. Compared to PID-based systems, Kinaci et al.'s method offered a low-cost alternative for commercial AUVs, though it lacked the dynamic responsiveness of adaptive controllers like those proposed by L. Liang et al. (2022).

Ren et al. (2020) used RANS-based CFD modeling to evaluate maneuvering and hydrodynamic force distributions in the Suboff submarine. While earlier works like Pan et al. (2012) and Sezen et al. (2018) also used RANS to derive hydrodynamic coefficients, Ren et al. focused on vertical forces and yaw moments and contributed a deeper understanding of flow-induced asymmetries, providing useful input for realistic control modeling.

Zhang et al. (2020) extended the scope of CFD simulations by modeling submarine surfacing in regular wave conditions, using a 6-DOF solver coupled with overset mesh techniques. His analysis of roll sensitivity, emergence trajectory, and wave interaction complements Carrica et al. (2021), who simulated vertical zigzag behavior, and contrasts with studies limited to calm water assumptions. Zhang et al.'s emphasis on unsteady, surface-breaking behavior highlights complex vertical-plane dynamics that are often overlooked in conventional PID literature.

Assani & Pavić (2020) explored submarine response to course changes using a second-order Nomoto model implemented in MATLAB/Simulink with a PID controller. While the study lacked CFD validation, the study illustrated the fundamental dynamics of ship response under PID control, reaffirming the continued use of Nomoto-based models as a conceptual foundation for early-stage controller testing.

Çoşgun (2021) analyzed self-propulsion across velocity regimes, while Lin et al. (2021) incorporated PID control into an LOS-guided semi-autonomous Suboff platform. L. Liang et al. (2022) proposed a multi-model switching control strategy using SVMs to select among PID, FPID, and MPC structures, demonstrating superior performance compared to conventional fixed-gain PID systems. This move toward adaptive and context-aware control aligns with recent literature trends, as also seen in You et al. (2023)**,** who compared multiple PID tuning strategies, and Q. Liang et al. (2020), who employed CFD simulations to evaluate zigzag maneuvering performance under different rudder configurations—although without explicitly applying a PID controller.

In 2023–2024, empirical and numerical studies became increasingly geometry- and flow-specific, reflecting a broader effort to enhance control-oriented fidelity in simulation-based methodologies. Delen & Kinaci (2023) executed direct CFD simulations of zigzag, pullout, and turning circle tests for the Suboff configuration using MRF and RBM methods to model the propeller and rudder, respectively. The simulations revealed excellent turning ability but poor inherent course stability, paralleling Carrica et al. (2019) and Sezen et al. (2021). Delen & Kinaci's results serve as a rare model scale maneuvering benchmark derived from transient CFD, reinforcing the Suboff's known handling characteristics and supporting its use as a control testbed.

Complementary to this, other recent works addressed specific geometric and dynamic complexities: Kahramanoglu (2023) focused on PMM-based hydrodynamic coefficient validation, while Krishna et al. (2023), Choi et al. (2023), and Mai et al. (2023) explored axisymmetric modeling, large-angle maneuver modeling, and design-parameter–based derivative estimation. Hou et al. (2024) uniquely coupled direct CFD with PID+LOS trajectory control for an underactuated UUV, bridging hydrodynamic modeling, real-time guidance, and control integration in a single simulation loop.

On the control architecture side, Jambak et al. (2023) introduced a cascaded controller based on linearized dynamics for container ships, while MacLin et al. (2024) developed reduced-order models and implemented path-following control in MATLAB Simulink. Both approaches offer alternatives to high-cost CFD simulations, particularly in early-stage design and control testing. D. J. Kim et al. (2024) added depth-dependent coefficient derivation to 6-DOF simulations, identifying exponential decay in surface effects, critical for submarine stealth operations.

Finally, Zenagui et al. (2025) performed a detailed propeller–hull performance assessment for a DREA-type submarine using a seven-bladed design. While not focused on control directly, his findings on thrust offset and efficiency optimization provide valuable guidance for CFD-based controller tuning—particularly in propeller–rudder interaction modeling.

Building on these collective advancements, the present study offers a novel contribution to the field by combining CFD-driven maneuvering simulations with Nomoto-based PID tuning to evaluate heading control performance in a submerged environment. While previous works have explored surface ship control (e.g., Moradi, Dlabač) or AI-enhanced controller tuning (e.g., Fang, Liang), relatively fewer studies have focused on applying high-fidelity, free-running CFD simulations for PID parameter validation in submerged vessels such as the DARPA Suboff. This work directly contributes to bridging that gap.

The research begins by determining self-propulsion points for the Suboff model in surge-only motion using a PI controller, establishing a baseline for realistic hydrodynamic resistance across various velocities. Once the equilibrium thrust condition is met, the degrees of freedom are expanded to include sway and yaw, and the rudder is dynamically actuated through a PID controller whose gains are derived from zigzag maneuvers conducted within the same simulation environment. This approach allows the controller to be tested under fully coupled, non-ideal flow conditions, closely mirroring real-world operation.

Unlike prior studies that used static gain estimations or tuning from empirical zigzag tables (e.g., Kim DJ, Xu You), this work validates its PID gains through a dynamically responsive, transient simulation framework, enabling more accurate prediction of heading recovery, overshoot, and residual yaw rates. Moreover, the study enhances prior findings from Sezen, Coşgun, and Carrica by extending the CFD-based PID evaluation beyond steady self-propulsion and into actively controlled maneuvering, making it one of the few works that closes the loop between CFD, controller tuning, and maneuver verification within a unified platform.

What distinctly sets this study apart from prior work is its fully integrated and dynamically validated control design methodology, which bridges a long-standing gap between idealized PID tuning techniques and realistic, physics-informed simulation environments. While previous studies have either relied on empirical tuning data or decoupled control evaluation from hydrodynamic simulations, this study represents one of the pioneering efforts to integrate controller design directly within high-fidelity CFD simulations through unsteady, free-running maneuver scenarios. By extracting Nomoto-based parameters from zigzag tests and validating them in the same transient CFD domain, the study ensures that control gains are not only theoretically optimal but also empirically robust under realistic flow conditions. Unlike existing methods that compartmentalize propulsion, maneuvering, and control verification across separate tools or assumptions, this approach establishes a unified, closed-loop platform in which rudder actuation, vehicle dynamics, and flow physics interact simultaneously. This methodological coherence enhances predictive fidelity and offers a reusable framework for future research on underwater vehicle autonomy, particularly where physical testing is costly or impractical.

1.5 Thesis Content and Structure

This thesis presents a comprehensive methodology that integrates Computational Fluid Dynamics (CFD) with classical control theory to improve heading control performance in submerged vehicles, using the DARPA Suboff model as a benchmark. This thesis presents a comprehensive methodology that integrates Computational Fluid Dynamics (CFD) with classical control theory to enhance heading control performance in submerged vehicles, using the DARPA Suboff model as a benchmark. The proposed approach leverages high-resolution, time-accurate simulations supported by validated turbulence models, adaptive meshing, and control feedback loops. Through the use of dynamic rudder actuation, coupled flow-structure interaction, and realistic maneuvering scenarios, the study replicates operational conditions that challenge heading stability and maneuverability. By embedding Proportional-Integral-Derivative (PID) control systems directly within transient RANS simulations, the methodology enables high-fidelity analysis of submarine motion in complex hydrodynamic environments, eliminating the need for offline controller tuning or decoupled motion testing.

The structure of the thesis reflects its interdisciplinary nature, combining advanced fluid dynamics modeling with control engineering principles. The integration of SST k–ω RANS turbulence models with Nomoto-based control logic exemplifies the convergence of physics-driven and model-driven paradigms, reinforcing the practical relevance of the simulation results. The study adopts a step-by-step methodology, beginning with the determination of self-propulsion conditions using a Proportional-Integral (PI) controller, followed by a heading control simulation using a Proportional-Integral-Derivative (PID) controller. The PID coefficients are extracted based on Nomoto model parameters, derived from CFD-simulated zigzag maneuvers. This framework enables closed-loop control validation in realistic flow environments without relying on empirical tuning tables or experimental data.

To maintain logical progression and ensure clarity in technical exposition, the thesis is organized into six main chapters. Each chapter targets a specific dimension of the research problem—from physical modeling to control implementation—allowing the reader to trace the full development and validation of the proposed system. The content of the thesis is briefly presented as follows:

- Chapter 1: Introduction

The first chapter outlines the motivation, research scope, and significance of the study. It introduces the challenges associated with maintaining a stable course in underwater vehicles and presents the DARPA Suboff as the selected case model. The chapter also emphasizes the originality of using CFD-derived parameters for real-time control, and how this integration contributes to both academic research and practical applications in autonomous marine systems.

- Chapter 2: Numerical Modeling and Control Framework

This chapter details the numerical and control approaches employed in the study. It begins by describing the setup of the CFD environment, which includes the use of Reynolds-Averaged Navier-Stokes (RANS) equations in conjunction with the SST k-ω turbulence model for accurate prediction of flow behavior around the submerged body. The mesh structure is carefully designed to capture boundary layer effects, and the computational domain is configured with appropriate boundary conditions, including rotating regions defined for the propeller and rudder using Multiple Reference Frame (MRF) and Rigid Body Motion (RBM) models, respectively.

The chapter then introduces the control system framework, focusing on the theory and implementation of Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers. It explains how control parameters are derived through the application of the Nomoto model, using hydrodynamic data collected from simulated 10/10 zigzag maneuvers. This data-driven approach allows for the extraction of Nomoto coefficients, which are then used to compute optimal gain values for the controllers.

- Chapter 3: Submarine Geometry & Test Scenarios

The third chapter presents the geometrical features of the DARPA Suboff and its associated propeller, the E1619. It outlines the test scenarios designed for evaluating the control system, including self-propulsion, zigzag maneuvers, and heading control simulations. These scenarios are conducted at three forward velocities and three different heading targets to examine the robustness and adaptability of the control strategy under varying hydrodynamic conditions.

- Chapter 4: Numerical Verification & Validation

In this chapter, the accuracy and reliability of the numerical models are verified and validated. A grid convergence study is performed using the Grid Convergence Index (GCI) method to ensure mesh independence. The results of self-propulsion simulations are validated against published CFD and experimental data to confirm the fidelity of the numerical approach. This chapter ensures that the simulation results provide a trustworthy foundation for the control system evaluation.

- Chapter 5: Closed-Loop Maneuvering Simulations and Control Performance

The results chapter presents a detailed analysis of the CFD simulations. It begins with the outcomes of self-propulsion simulations and identifies propeller operating points at different velocities. It then analyzes heading behavior and rudder deflections during zigzag maneuvers, highlighting overshoot angles and turning delays. The performance of the PID controller is evaluated under different heading commands, and the rudder angle responses are examined for smoothness and stability. The chapter discusses how the control performance varies with velocity and how the controller mitigates the effects of geometric limitations, such as reduced rudder area. Graphs, tables, and comparative figures are provided to support the interpretation of results.

- Chapter 6: Evaluations and Recommendations

The final chapter critically evaluates the findings and discusses the implications of the developed control system. It reflects on the strengths and limitations of using CFD-informed PID control and proposes directions for future work. These include improving turbulence modeling accuracy, incorporating environmental disturbances like waves and currents, and exploring adaptive or AI-based control systems. The chapter also highlights the importance of validating the model with experimental data or hardware-in-the-loop systems to enhance practical applicability. It concludes by emphasizing the contribution of this study to safer, more efficient, and autonomous underwater navigation technologies.

2. NUMERICAL MODELING AND CONTROL FRAMEWORK

In underwater vehicle research, achieving stable and precise course-keeping is a fundamental challenge due to hydrodynamic complexities and external disturbances. To address this, control strategies such as Proportional-Integral-Derivative (PID) controllers have been widely used in both experimental and computational studies (Fossen, 2011). In recent years, the integration of Computational Fluid Dynamics (CFD) with control algorithms has provided a more detailed and accurate understanding of submerged body maneuvering characteristics. This study applies a CFD-based approach to evaluate the heading control performance of a submerged vehicle using PID control, with a particular focus on the DARPA Suboff model with E1619 model propeller. The Reynolds-Averaged Navier-Stokes (RANS) method, in combination with the SST $k{-}\omega$ turbulence model, was employed to model the flow around the submarine. This approach ensures an accurate prediction of hydrodynamic forces and moments acting on the hull, rudder, and propeller. Unlike traditional experimental methods, CFD allows for a controlled and cost-effective evaluation of different maneuvering scenarios without requiring physical prototypes.

To optimize the control performance, a two-step methodology was applied. First, a Proportional-Integral (PI) controller was used to determine the self-propulsion point, where the thrust generated by the propeller balances the resistance of the hull. This approach significantly reduced the computational cost compared to conventional iterative methods while maintaining accuracy. Once the submarine reached its steady forward velocity, a 10/10 zigzag maneuver was performed to evaluate its maneuvering response. The collected data, including heading angle, rudder deflections, yaw rate, and hydrodynamic forces, were processed to extract the Nomoto model coefficients (Nomoto et al., 1957), which are essential for tuning the PID controller.

The PID controller played a critical role in heading control by dynamically adjusting the rudder angle based on real-time heading deviations. Compared to conventional open-loop control methods, the PID system improved stability by minimizing overshoot and reducing response time, especially at different velocity conditions. The findings of this study demonstrated that while the DARPA Suboff form exhibited significant overshoot angles due to its geometric characteristics and relatively small rudder area, the PID-controlled system effectively compensated for these limitations.

2.1 CFD Solver and Numerical Solution Strategies

In this study, the continuity and momentum equations for fully turbulent, three-dimensional (3D), incompressible flows were employed. These equations form the foundation for the numerical solution of fluid dynamics problems. The continuity equation, which expresses the conservation of mass, is written for incompressible flows as follows:

$$\nabla \cdot V = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = \frac{\partial U_i}{\partial x_i} = 0 \tag{2.1}$$

In turbulent flows, the velocity components (U_i) are separated into mean ($\overline{U_i}$) and fluctuating (u_i') components.

$$U_i = \overline{U_i} + u_i' \tag{2.2}$$

Here, U_i represents the mean velocity components of the fluid. The momentum equations, which express the conservation of momentum, are written for incompressible flows as:

$$\frac{\partial U}{\partial t} + \frac{\partial (U_i U_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \tag{2.3}$$

In these equations:

- V = (u, v, w) represents the velocity vector in Cartesian coordinates,
- U_i is the mean velocity component,
- $\overline{U_i}$ is the time-averaged mean velocity,
- u_i' is the fluctuating velocity component,
- P is the pressure,
- ρ is the fluid density,
- ν is the kinematic viscosity,

- $\overline{u_i' u_j'}$ is the Reynolds stress tensor, which accounts for the effects of turbulent fluctuations.

For turbulence modeling, the SST k-ω (Shear Stress Transport k-omega) turbulence model was used in this study. The SST k-ω model is a hybrid model that combines the strengths of both the k-ε (k-epsilon) and k-ω (k-omega) turbulence models. It is particularly effective for accurately modeling flows near walls and in regions with adverse pressure gradients. This model solves two transport equations for the turbulence kinetic energy (k) and the specific turbulence dissipation rate (ω). The transport equation for turbulence kinetic energy (k) is:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \beta_k \omega k \tag{2.4}$$

The transport equation for the specific turbulence dissipation rate (ω) is:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma \omega}\right)\frac{\partial \omega}{\partial x_j}\right] + \alpha \frac{\omega}{k} P_k - \beta_\omega \omega^2 + 2(1 - F_1)\frac{\sigma_\omega^2}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{2.5}$$

In these equations, ν_t represents the turbulence viscosity ($\nu_t = \frac{k}{\omega}$), P_k is the turbulence kinetic energy production term, and σk, σω, α, β_k, β_ω are model constants. F_1 is a blending function that ensures a smooth transition between the k-ω model near the wall and the k-ε model in the free stream. This model accurate predictions of near-wall turbulence while maintaining robustness in free-stream regions and handling adverse pressure gradients effectively. This makes the SST k-ω model particularly suitable for simulating the complex flow phenomena encountered in fully submerged vessels, where precise modeling of boundary layer effects is critical.

In this study, the flow was assumed to be fully turbulent, aiming to accurately represent the flow characteristics. Three-dimensional modeling allows for a detailed examination of the interactions between the model and the surrounding fluid in all directions. This provides a significant advantage in simulating the model's motion and the surrounding flow. The flow was assumed to consist of only a single liquid phase (water), neglecting the effects of gas or solid phases. It was selected due to its applicability to fully submerged vessels. It simplifies the model and improves computational efficiency.

The incompressible flow assumption is valid when the fluid density remains constant, which is suitable for flows characterized by low velocities. This assumption is particularly accurate for liquids like water at low velocities and constant temperature conditions. In the simulations, the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations were used which describe the conservation of mass and momentum for incompressible, turbulent flow. These equations were discretized using the finite volume method (FVM), a well-established numerical technique that ensures the conservation of fluxes across control volumes. Given the complexity of the problem, the unsteady RANS approach was employed to account for time-dependent variations in flow behavior, particularly for maneuvering simulations (Ferziger & Perić, 2002). This method is widely used in ship and marine vehicle simulations and calculates the mean behavior of the flow by averaging the turbulent flow over time.

The segregated flow approach was adopted as the solution method, in which the velocity and pressure fields were computed separately through an iterative procedure. This method solves the flow equations independently, enhancing computational efficiency. To ensure accurate coupling between pressure and velocity, the Pressure-Implicit with Splitting of Operators (SIMPLE) algorithm was employed, contributing to improved numerical stability and convergence (Patankar, 1980). The governing equations were discretized using the Finite Volume Method (FVM), which divides the computational domain into small control volumes (CD-adapco, 2017). Within each volume, the conservation of mass, momentum, and energy is enforced, enabling accurate modeling of complex geometries and turbulent flow behavior.

The Shear Stress Transport (SST) k-ω turbulence model was selected for turbulence closure, offering a blend of k-ε and k-ω formulations to optimize accuracy in different flow regions (Menter, 1994). Specifically, the k-ω model is applied near the walls to improve boundary-layer resolution, while the k-ε model dominates in the free-stream region to enhance robustness. This hybrid approach provides superior accuracy for ship hydrodynamics simulations, ensuring precise predictions of flow separation, wake structures, and turbulent eddies.

The y+ wall distance approach was used to correctly model the turbulent flow near the wall (Menter et al., 2006)(CD-adapco, 2017). This parameter ensures that the turbulent flow near the wall surface is resolved accurately.

The Dynamic Fluid-Body Interaction (DFBI) model was used to dynamically account for the effects of the ship's motion on the flow (CD-adapco, 2017). This model continuously updates the effects of the ship's motion on the surrounding flow. The Rigid Body Motion (RBM) method was used to model the ship's hull and rudder as rigid bodies. This allows the ship's control surfaces and moving parts to move without deformation, providing a realistic simulation of the control surfaces. The Multiple Reference Frame (MRF) method was used to model the flow around rotating components, such as the propeller (Kinaci et al., 2018b). This method solves the flow around rotating parts in a fixed reference frame, avoiding the need for transient simulations and enabling faster computations. The rotation methodology for the rudder and propeller structures follows the approach proposed by Delen & Kinaci (2023), ensuring an optimal trade-off between computational efficiency and verification robustness. These modeling choices ensured that the mesh could accurately capture both steady-state and transient hydrodynamic interactions, which are critical for evaluating self-propulsion and maneuvering performance. The physics models used are shown in Figure 2.1.

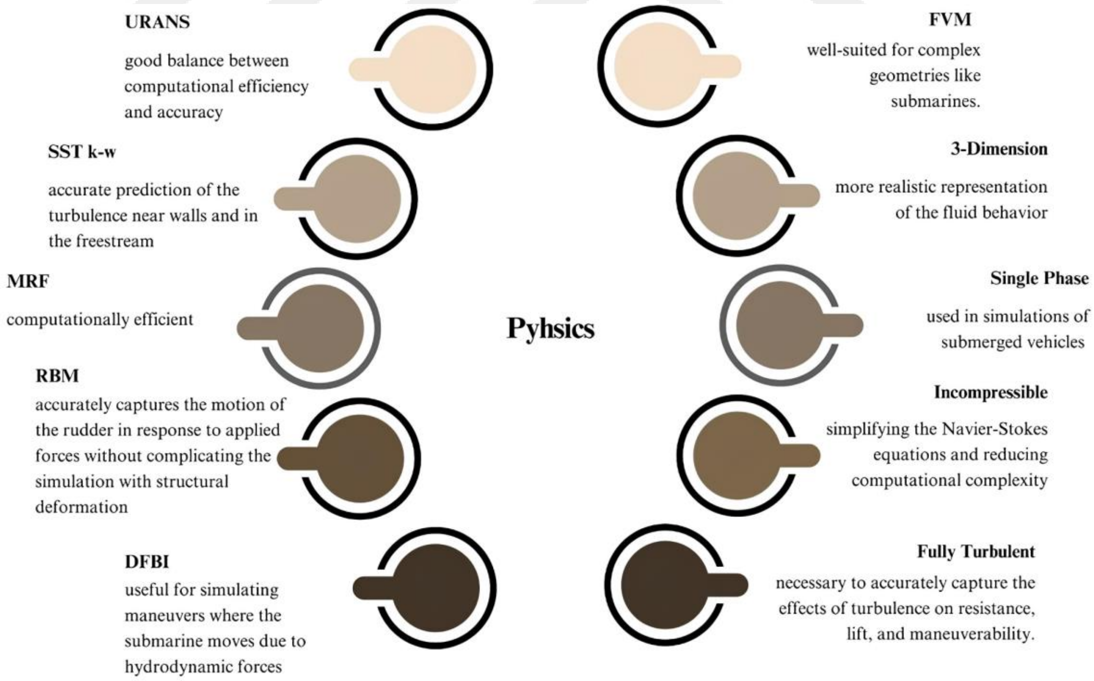

Figure 2.1 : Selected physics models.

2.2 Mesh Structure

The computational grid used in this study was designed to accurately capture the hydrodynamic behavior of the DARPA Suboff submarine while ensuring computational efficiency. A trimmed-cell mesher was employed to generate the volumetric mesh, which consists primarily of hexahedral cells. This approach was chosen due to its ability to handle complex geometries while maintaining high mesh quality and low skewness, particularly around critical areas such as the propeller and rudder (CD-adapco, 2017), (Krishna et al., 2023)).

To enhance the accuracy of the numerical predictions, additional mesh refinement was applied in regions of high flow gradients, including the wake region and near-wall zones. The near-wall resolution was managed using an adaptive meshing approach, along with an all y+ wall treatment, ensuring an appropriate balance between computational cost and boundary layer accuracy. The grid configuration of the DARPA Suboff model is illustrated in Figure 2.2.

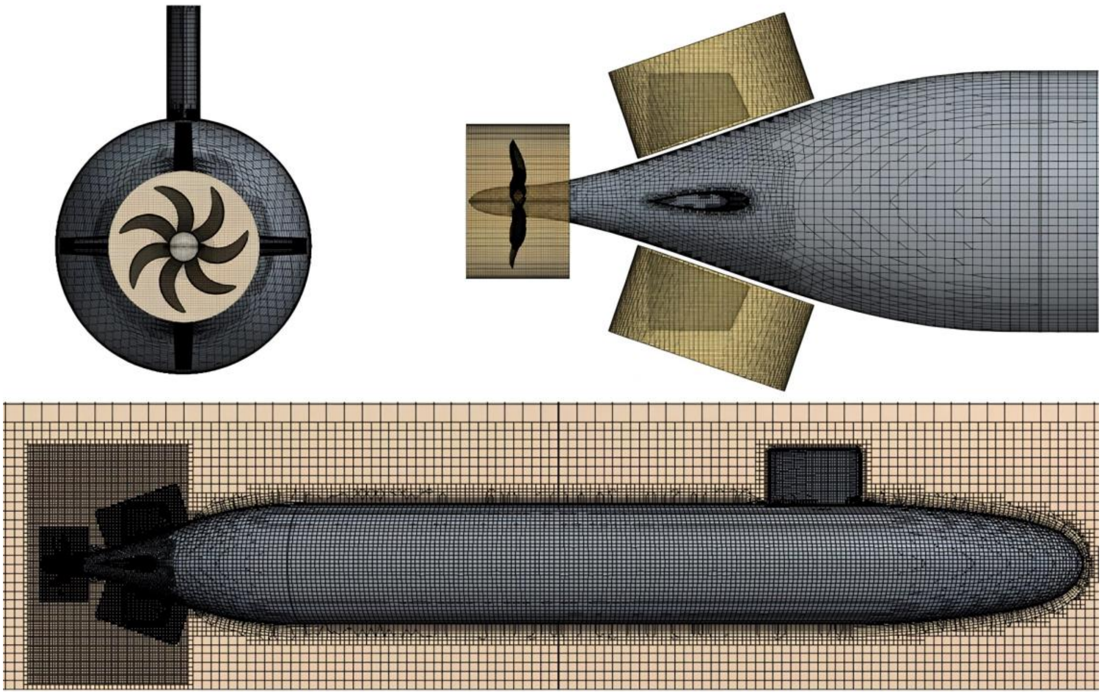

Figure 2.2 : Refined mesh topology around the DARPA Suboff for CFD simulations.

2.3 Computational Domain with Boundary Conditions

The computational domain was carefully designed in accordance with (ITTC, 2011) guidelines, ensuring an optimal balance between computational efficiency and accurate flow representation. Figure 2.3 illustrates the computational domain. A Cartesian coordinate system was used to define the domain, establish boundary conditions, and configure the mesh structure. The origin was positioned at the intersection of the fore perpendicular and the free surface, with the positive x-axis aligned with the inflow direction, the y-axis pointing starboard, and the z-axis directed upward. This configuration facilitated the consistent application of boundary conditions and the interpretation of flow results.

Most of the boundary surfaces were treated as inlet boundaries, but no constant velocity values were assigned, as the simulations focused on self-propulsion and maneuvering rather than prescribed inflow conditions. At the downstream end, a pressure outlet boundary condition was applied, allowing the flow to exit freely at a fixed static pressure, typically set to atmospheric conditions. This setup helped prevent artificial reflections and ensured a more realistic open-water environment.

All solid surfaces, including the submarine hull, were subject to a no-slip wall boundary condition, ensuring zero relative velocity at the walls. This was essential for accurately capturing shear stresses and boundary layer development. The top and bottom boundaries were defined as symmetry planes, assuming negligible vertical flow interactions. This approach reduced computational cost while maintaining solution accuracy.

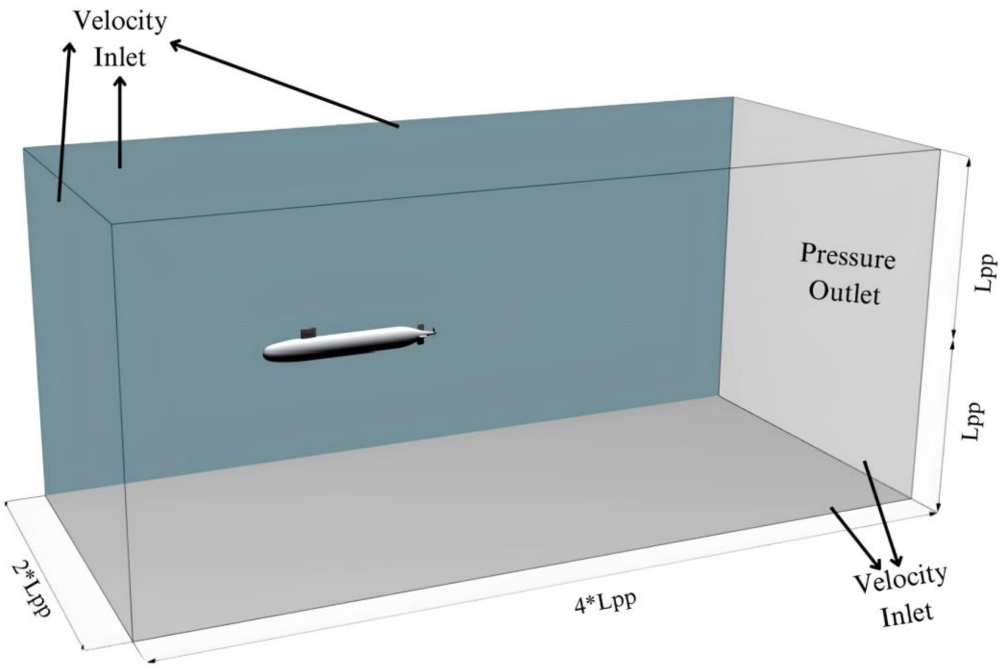

Figure 2.3 : Computational domain with boundary conditions.

To accurately represent the propeller and rudder dynamics, dedicated rotating regions were introduced. Figure 2.4 illustrates the rotating regions. A cylindrical rotating zone was created around the propeller, where the Moving Reference Frame (MRF) method was applied to model steady rotational motion. Similarly, the rudder rotation was simulated using the Rigid Body Motion (RBM) method, enabling dynamic deflections during maneuvering tests.

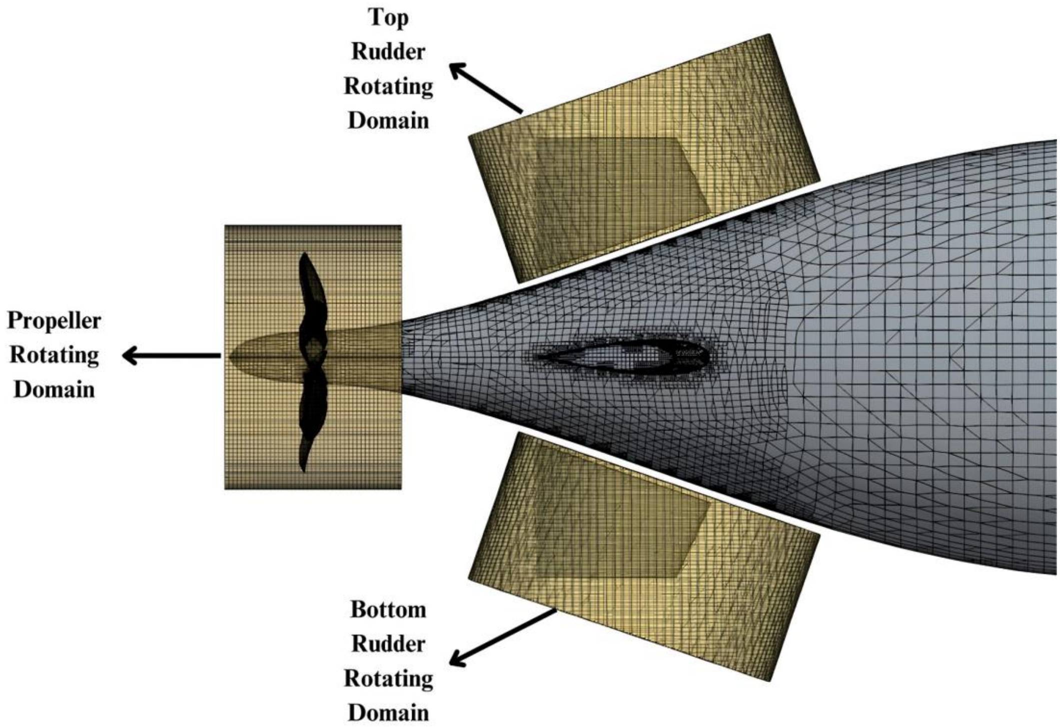

Figure 2.4 : Rotating regions structure.

To further enhance the numerical accuracy, boundary layer refinement was applied around the submarine’s hull, ensuring an appropriate y+ range between 60 and 200 depending on velocity conditions. This refinement was critical for accurately resolving turbulence effects while optimizing computational efficiency.

A fixed time step was selected in accordance with the (ITTC, 2011) recommended practices for maneuvering simulations to ensure numerical stability and temporal resolution. In addition to these guidelines, the time step was carefully adjusted to ensure compatibility with the implementation of the PID controller, particularly for real-time rudder response. Special consideration was also given to minimizing numerical noise in the heading signal, as excessive oscillations in the control loop could adversely affect the controller’s stability and accuracy. The selected time step thus represents a balance between compliance with established best practices and the practical requirements of closed-loop control.

By carefully defining the computational domain and boundary conditions, this study ensured that the CFD simulations provided reliable predictions for self-propulsion and heading control performance while minimizing numerical errors and excessive computational costs.

2.4 Controller Theory

Control methods play a fundamental role in engineering, enabling systems to operate efficiently and adapt to various conditions. These methods are broadly categorized into different approaches based on how they process information and respond to external factors. From classical techniques to modern computational strategies, control systems have evolved to address the increasing complexity of dynamic systems. In this section, key control methods are introduced, highlighting their principles and applications (von Ellenrieder, 2021)

2.4.1 Loop types

2.4.1.1 Open-loop control

Open-loop control adjusts the system based on a predefined set of inputs without considering real-time feedback. For example, in a marine navigation scenario, the steering and throttle positions could be set according to a precomputed trajectory and predicted weather conditions. However, this approach is highly sensitive to errors in the predefined inputs, making it less reliable in changing environments.

2.4.1.2 Closed-loop control

Closed-loop control, in contrast, continuously monitors system outputs and adjusts inputs accordingly. In ship navigation, this means modifying the steering and throttle based on real-time measurements of position and velocity. By incorporating feedback, closed-loop control enables more precise adjustments, reducing errors and improving overall system stability without requiring perfect knowledge of external conditions.

2.4.2 Control methods

Various control methodologies have been developed to enhance system performance, each suited to different types of applications and system dynamics. Below are some of the widely used control methods that also shown in the Figure 2.5.

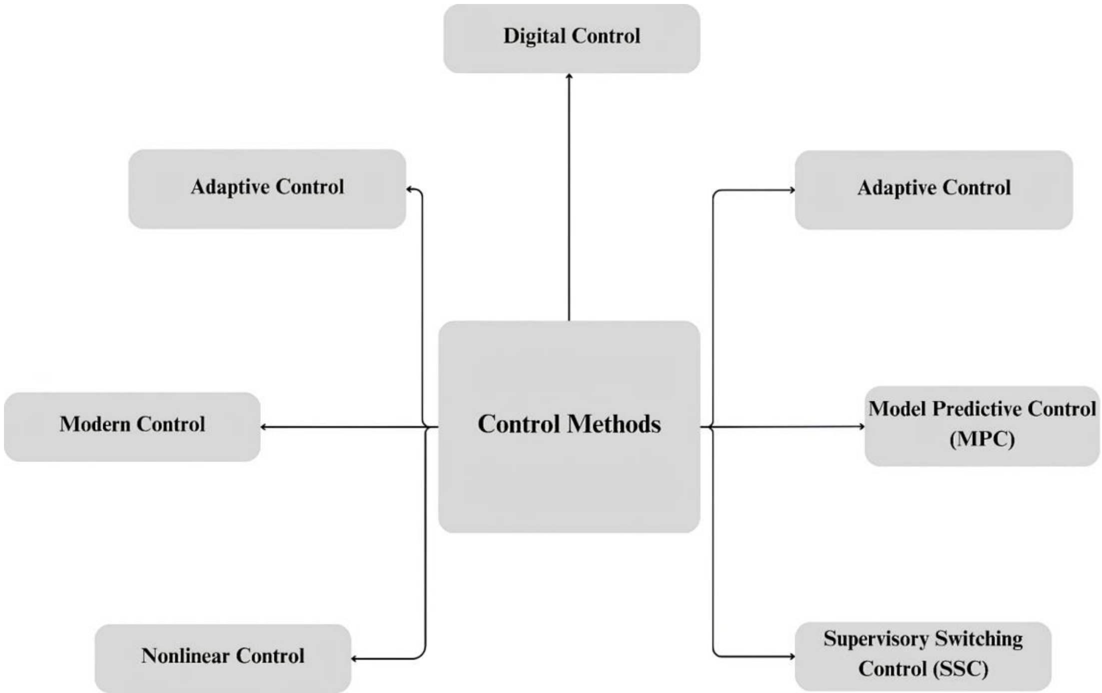

Figure 2.5 : General classification of control methods.

Classical control techniques, such as Proportional-Integral-Derivative (PID) control, remain among the most widely used methods for linear time-invariant (LTI) systems. PID controllers adjust system inputs based on the difference between desired and actual outputs, making them highly effective for a range of applications including ship heading control and velocity regulation. However, while PID control offers simplicity and ease of implementation, it may face limitations when dealing with highly nonlinear or time-varying systems.

Digital control methods implement control algorithms in a discrete-time framework, typically on digital computers. These approaches take into account practical issues such as sampling intervals, quantization effects, and computational delays, making them essential for modern automation and embedded control systems, where continuous real-time interaction with hardware components is required.

Modern control techniques extend classical approaches by leveraging more sophisticated mathematical formulations. State-space control, a key modern method, represents system dynamics using sets of first-order differential equations, enabling efficient handling of multi-input, multi-output (MIMO) systems. Additionally, robust control methods are designed to maintain stability and performance even in the presence of uncertainties in system parameters or external disturbances, enhancing reliability in complex environments.

Nonlinear control methods are necessary for systems exhibiting significant nonlinear behaviors, where linear approximations are insufficient. One notable approach is Fuzzy Logic Control (FLC), which manages uncertainty and imprecision through rule-based reasoning rather than exact mathematical modeling. Fuzzy control is particularly effective in complex decision-making environments such as navigation and robotics, and it can be combined with PID strategies (Fuzzy-PID) to enhance system adaptability under varying conditions.

Adaptive control systems offer another solution by dynamically adjusting controller parameters in response to real-time variations in system dynamics. Unlike fixed-gain controllers, adaptive controllers modify their behavior based on observed performance, making them well-suited for applications where system properties change over time, such as marine vehicles operating under varying environmental conditions.

Model Predictive Control (MPC) represents a powerful optimization-based strategy where future system states are predicted over a finite time horizon. At each time step, MPC solves an optimization problem to determine the best control actions, accounting for system constraints and performance objectives. This makes MPC highly effective in applications like chemical process control, automotive systems, and aerospace guidance, where precise trajectory tracking and predictive decision-making are critical.

Finally, Supervisory Switching Control (SSC) is employed in systems operating across multiple regimes, selecting the most suitable controller from a predefined set based on real-time system behavior. Unlike simple gain scheduling, SSC continuously evaluates performance and stability criteria to optimize controller selection, providing robust performance across varying operational conditions.

Each of these methodologies plays a crucial role in contemporary control engineering, with the appropriate selection depending on factors such as system complexity, nonlinearity, environmental variability, and the specific performance requirements of the application.

2.4.3 PI & PID controller theory

PID controllers, despite being classified as classical control methods, offer significant advantages in simplicity, reliability, and cost-effectiveness compared to more modern techniques such as Model Predictive Control (MPC) or AI-based control systems. They are easy to implement and understand, require minimal computational power, and do not depend heavily on detailed system modeling. While modern methods excel in predictive capabilities and are well-suited for handling complex, nonlinear, or multi-variable scenarios, PID controllers remain the preferred choice for straightforward, feedback-driven systems due to their quick deployment, robust performance, and versatility. Owing to these enduring advantages, applications involving both PI and PID control strategies were carried out in this study.

PID (Proportional-Integral-Derivative) control is a widely used feedback control strategy that enhances system stability and accuracy by dynamically adjusting control inputs based on three fundamental components: proportional, integral, and derivative actions. A simplified variant of this is the Proportional-Integral (PI) controller, which omits the derivative component while still effectively addressing steady-state errors and ensuring system stability.

- Proportional (P) control responds to the present error, which is the difference between the desired setpoint and the process variable. It generates an output proportional to the magnitude of this error, helping to reduce deviations from the target value. The time-domain expressions for proportional control are presented as follows:

$$u_c(t) = k_p e(t)(Johnson\ et\ al., 2008) \tag{2.6}$$

- Integral (I) control accounts for past errors by integrating them over time. This component ensures that steady-state errors are eliminated, improving long-term accuracy and preventing persistent offsets. The time-domain expressions for integral control are presented as follows:

$$u_c(t) = k_i \int^{t} e(t)\, d(t) \tag{2.7}$$

- Derivative (D) control predicts future system behavior by considering the rate of change of the error. It counteracts sudden variations, thereby enhancing system stability and reducing overshoot. The time-domain expressions for proportional control are derivative as follows:

$$u_c(t) = k_d \frac{de}{dt} \quad (2.8)$$

While PI controllers are particularly effective in applications where steady-state error elimination is a priority, PID controllers provide additional stability and responsiveness by incorporating the derivative term. Due to their simple structure, ease of implementation, and effectiveness in diverse applications, both PI and PID controllers are extensively employed in industrial automation and motion control (Borase et al. 2021).

2.5 The Nomoto Model

The model developed by (Nomoto et al., 1957) is referred to as a "response model" because it predicts how the ship responds to control actions. In contrast, the Abkowitz model is known as a "force model" as it focuses on the forces and moments acting on the ship. The Nomoto model is straightforward in its structure, and its coefficients are directly related to the ship's maneuvering characteristics. This model has primarily been applied in research on ship maneuvering control and the design of ship autopilots (Gokarn, 2024).

2.5.1 First order Nomoto model

To derive the Nomoto model, the non-dimensional linearized equations governing sway and yaw, can rewritten in the following form:

$$N'_{\dot{v}}\dot{v}' + N'_v \mathrm{v}' = (I'_{zz} - N'_{\dot{r}})\dot{r}' - N'_r r' - N_\delta{}'\delta' \quad (2.9)$$

The first-order Nomoto model is derived under the assumption that the ship's center of gravity is exactly at the midpoint and that the ship has fore-aft symmetry. This assumption allows Y'_r, $Y'_{\dot{r}}$, N'_v, $N'_{\dot{v}}$ derivatives to be set to zero, simplifying the model.

$$K' = -\frac{N'_\delta}{N'_r} \quad (2.10)$$

$$T'_1 + T'_2 = -\frac{(m' - Y'_{\dot{v}})N'_r + Y'_v(I'_{zz} - N'_{\dot{r}})}{Y'_v N'_r} = \frac{m' - Y'_{\dot{v}}}{Y'_v} - \frac{I'_{zz} - N'_{\dot{r}}}{N'_r} \quad (2.11)$$

$$T'_3 = -\frac{m' - Y'_{\dot{v}}}{Y'_v} \quad (2.12)$$

$$T' = T_1' + T_2' - T_3' = -\frac{I_{zz}' - N_{\dot{r}}'}{N_r'} \quad (2.13)$$

Equation (2.9) with $N_v' = N_{\dot{v}}' = 0$ can be written as:

$$-\frac{I_{zz}' N_{\dot{r}}'}{N_r'} \dot{r}' + r' = -\frac{N_\delta'}{N_r'} \delta' \quad (2.14)$$

$$T' \dot{r}' + r' = K' \delta' \quad (2.15)$$

It is often more practical to express the first-order Nomoto equation in its dimensional form.

$$T' \dot{r} + r = K \quad (2.16)$$

As a result, two key parameters that describe the ship's response to rudder input emerge: K and T. These parameters determine how quickly and effectively the ship responds to rudder movements. K represents the rate at which the yaw rate increases in response to a change in rudder angle, while T indicates how this response decays over time. These two parameters are crucial for evaluating the ship's maneuverability.

2.5.2 Nomoto model identification from zigzag simulation

The Nomoto parameters K and T can be ascertained by examining data derived from ship maneuvering experiments or model assessments. (Nomoto et al., 1957) and (Journee & Pinkster, 2002) elucidated a technique for ascertaining K and T based on zig-zag maneuver data.

$$\delta = \frac{\delta_0}{t_0} t \quad 0 \leq t \leq t_0 \quad (2.17)$$

$$\delta = \delta_0 \quad t_0 \leq t \quad (2.18)$$

For $0 \leq t \leq t_0$:

$$\dot{r} + \frac{1}{T} r = \frac{K}{T} \frac{\delta_0}{t_0} t \quad (2.19)$$

Noting that r = 0 at t = 0 , this has the solution:

$$r(t) = \frac{KT\delta_0}{t_0} \left[e^{-\frac{t}{T}} - 1 + \frac{t}{T} \right] \quad 0 \leq t \leq t_0 \quad (2.20)$$

For $t_0 \leq t$:

$$\dot{r} + \frac{1}{T} r = K\delta_0 \tag{2.21}$$

This methodology is purported to yield more reliable outcomes compared to alternative approaches; however, it exhibits a degree of complexity. A more streamlined technique, attributed to (Clarke, 2003), is delineated herein. Upon integrating equation (2.21) from t_2 and t_1, the following expression is derived:

$$T\int_{t_1}^{t_2} \dot{r}\, dt + \int_{t_1}^{t_2} r\, dt = T(r_2 - r_1) + (\psi_2 - \psi_1) = K\int_{t_1}^{t_2} \delta\, dt \tag{2.22}$$

where the subscripts 1 and 2 refer to t1 and t2, respectively. Subscripts 1 and 2 correspond to the time instants t_2 and t_1,respectively. If the time intervals t_2 and t_1, are selected such that $r_2 = r_1 = 0$, as illustrated in Figure 2.6(a), the value of K can be expressed as:

$$K = \frac{(\psi_2 - \psi_1)}{\int_{t_1}^{t_2} \delta\, dt} \tag{2.23}$$

On the other hand, if t_2 and t_1 are chosen such that $\psi_2 = \psi_1 = 0$, Figure 2.6(b)

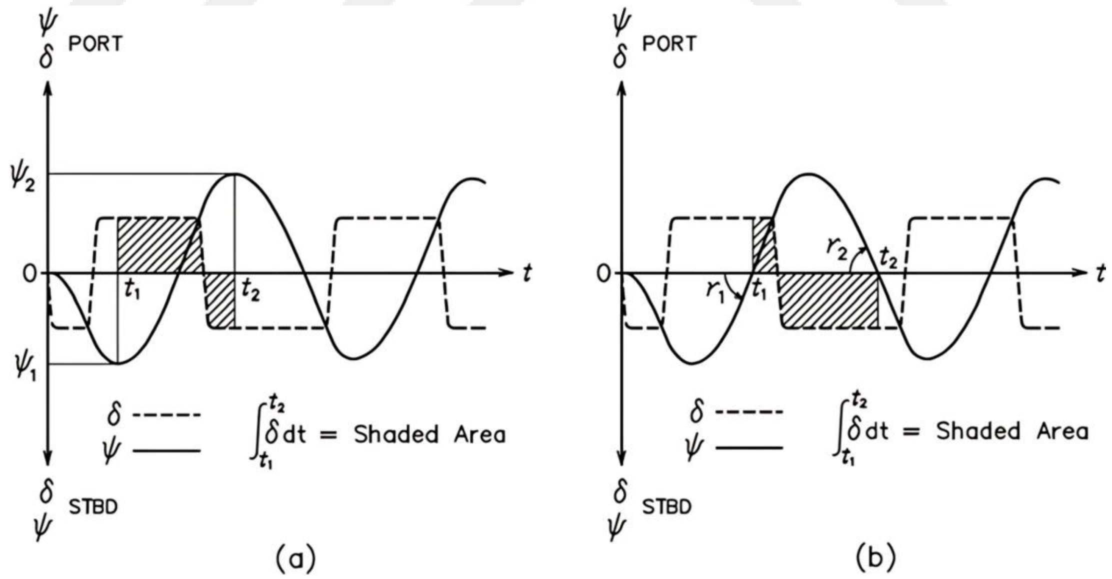

Figure 2.6 : Determination of upper K and upper T from a zigzag maneuver (Gokarn, 2024).

gives:

$$\frac{K}{T} = \frac{(r_2 - r_1)}{\int_{t_1}^{t_2} \delta\, dt} \tag{2.24}$$

It is imperative to acknowledge that, within the first-order Nomoto framework, nonlinear terms and cross-coupled hydrodynamic derivatives (for instance, $\dot{Y}_r$ and $\dot{N}_v$) are disregarded (Gokarn, 2024). The control system can be expressed using the classical PD (Proportional-Derivative) controller formula:

$$\delta = K_p((\psi_d - \psi) - K_d\dot{\psi} \tag{2.25}$$

By applying this equation, the characteristics of the closed-loop system are determined using the first-degree Nomoto model. The dynamics of the control law are represented by the following closed-loop equation:

$$T\dot{\psi} + (1 + KK_d)\dot{\psi} + KK_p\psi = KK_p\psi_p \tag{2.26}$$

In this context, the damping ratio (ζ) and natural frequency (ω_n) are calculated as follows:

$$\zeta = \frac{1 + KK_d}{2\sqrt{TKK_p}} \tag{2.27}$$

$$\omega_n = \sqrt{\frac{KK_p}{T}} \tag{2.28}$$

Accordingly, the values of K_p and K_d can be computed as:

$$K_p = \frac{T{\omega_n}^2}{K} \tag{2.29}$$

$$K_d = \frac{2T\omega_n - 1}{K} \tag{2.30}$$

Additionally, (Skjetne et al., 2004) provides the following recommendation for the integral component:

$$\frac{K_i}{K_d} \approx \frac{\omega_n}{10} \tag{2.31}$$

In this regard:

$$K_i = \frac{{\omega_n}^3 T}{10K} \tag{2.32}$$

2.6 Controller Integration Within CFD Simulation

2.6.1 Implementation of PI controller for straight ahead maneuvering (self-propulsion)

The self-propulsion point (n) is defined as the propeller rotation rate at which the generated thrust precisely offsets the hull's resistance, enabling the submarine to maintain a constant forward velocity. At this stage, all forces acting on the submarine are in equilibrium, resulting in zero net force (Zenagui et al., 2025). A proportional-integral (PI) controller was chosen for its capability to eliminate steady-state errors by addressing both immediate deviations and cumulative discrepancies, enhancing stability and long-term control (Sezen et al., 2021). Figure 2.7 presents the block diagram of the control system, highlighting the relationship between key components: the reference input, the controller, the plant (the system being controlled), and the feedback loop.

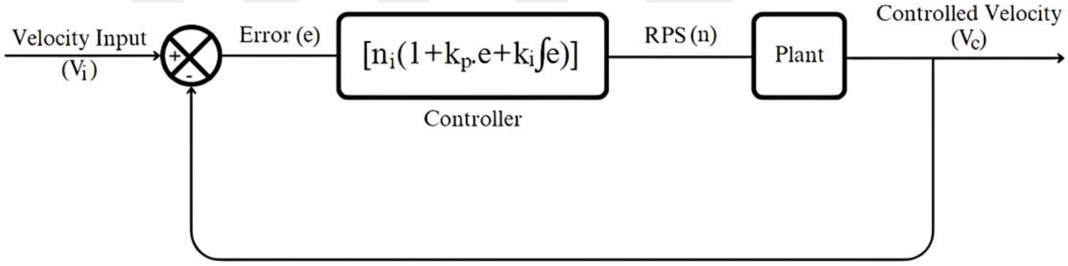

Figure 2.7: The block diagram for PI-Driven self-propulsion test (Ünlü and Delen, 2024).

$$K_p = \frac{\alpha}{\rho {L_{pp}}^2 V^2} \tag{2.33}$$

$$K_i = \frac{\beta}{\rho {L_{pp}}^3 V^2} \tag{2.34}$$

2.6.2 Implementation of PID controller for heading control

PID (Proportional-Integral-Derivative) control is a widely used feedback control strategy that enhances system stability and accuracy by dynamically adjusting control inputs based on three fundamental components: proportional, integral, and derivative control. Due to their simple structure, ease of implementation, and effectiveness in diverse applications, PID controllers are extensively employed in industrial automation, motion control (Borase et al., 2021). In this study, PID-based heading control is applied to a ship maneuvering system. A custom Java-based macro was developed to regulate the hull's rudder angle (δ) and maintain the desired heading (ψ). The unique macro was then executed in simulations to adjust the rudder position based on real-time heading deviations. The PID controller continuously fine-tunes the rudder angle (δ) to ensure smooth and precise heading correction. The proportional, integral, and derivative gains were carefully tuned to achieve optimal response characteristics, minimizing oscillations and overshoot. Figure 2.8 presents the block diagram of the control system. The effectiveness of this approach is demonstrated through simulations, underscoring the advantages of PID control in maritime navigation.

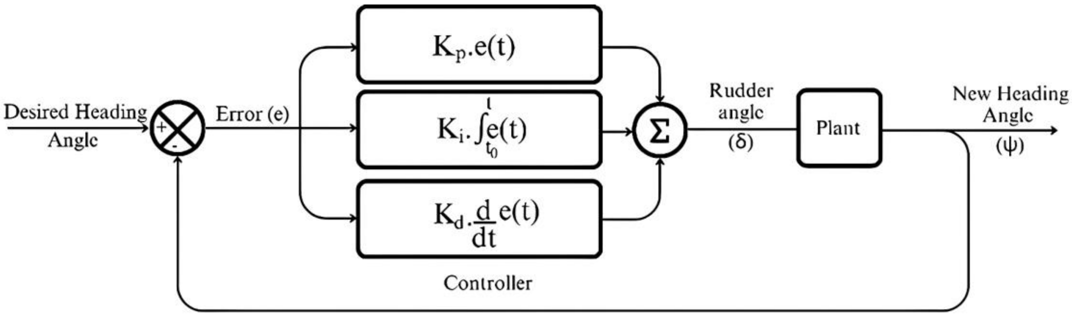

Figure 2.8 : The block diagram for PID-driven heading control.

3. SUBMARINE GEOMETRY & TEST SCENARIOS

The DARPA Suboff model, originally introduced as a benchmark design by (Groves et al., 1989), is a widely acknowledged reference in underwater vehicle research and open-access computational fluid dynamics (CFD) analyses. It has been frequently utilized in various validation studies, serving as a foundation for assessing hydrodynamic performance and control system behavior in self-propulsion investigations ((Sezen et al., 2018),(Delen & Kinaci, 2023), (Liu et al., 2021)). A three-dimensional representation of the DARPA Suboff is depicted in Figure 3.1, while Table 3.1 outlines the key characteristics of the E1619 propeller and Table 3.2 outlines the principal specifications of the DARPA Suboff (AFF-8) model.

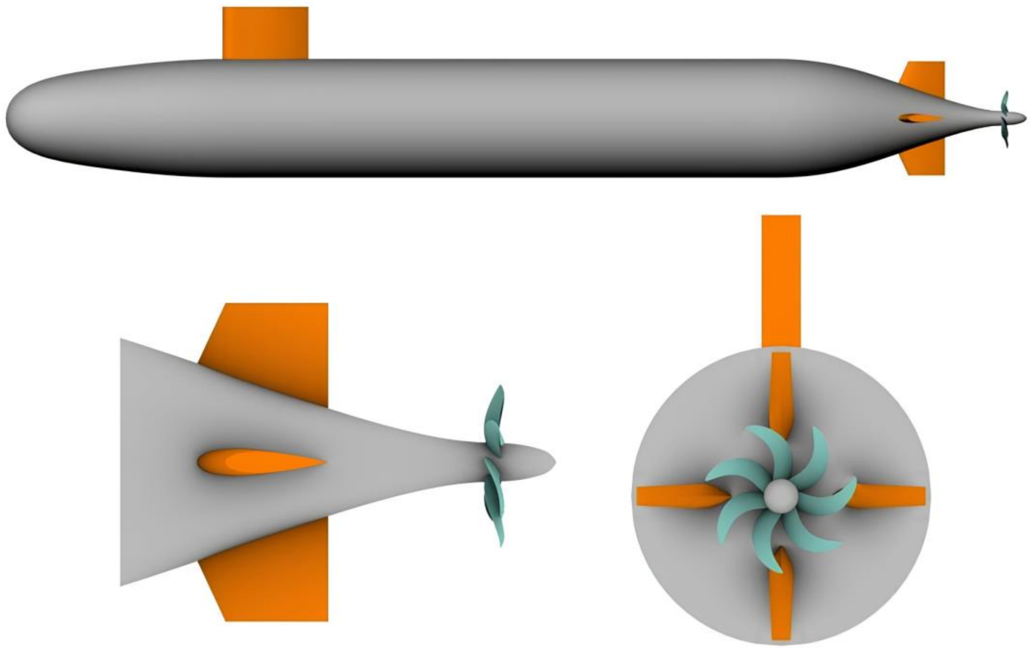

Figure 3.1 : The profile view of DARPA Suboff (AFF-8) with E1619 propeller.

Table 3.1: Main parameters of E1619 propeller.

Parameters (Unit)	Propeller (E1619)
D (m)	0.262
P/D (-)	1.15
Z (-)	7
Dh/D (-)	0.226
Ae/A0 (-)	0.608
Rotation (-)	Clockwise

Table 3.2 : Main parameters of DARPA Suboff (Groves et al., 1989)

Parameters (Unit)	Hull (AFF-8)
λ	24.000
L_{OA}(m)	4.356
L_{PP} (m)	4.261
D_{max} (m)	0.508
S (m^2) (fully appended)	6.348
∇ (m^3)	0.706
LCB (m) (from aft)	2.347
KG (m) (from center)	0.002
K_{xx}/B	0.175
K_{YY}/L_{OA}	1.032
K_{ZZ}/L_{OA}	1.031
Time step	0.04

Self-propulsion points were identified under straight-ahead motion using PI control, allowing movement exclusively in the surge direction. In the subsequent simulations, sway and yaw motions were introduced, and 10/10 zigzag maneuver test was conducted. This study examined heading control performance at fundamental velocities of 2.750, 6.096, and 9.152 m/s. To assess the controller's ability to maintain a desired heading, three distinct target heading angles were defined (ψ = 0.0, ψ = 5.0, and ψ = 15.0 degrees). This setup was designed to investigate the limits of the control system under varying combinations of velocity (V) and heading angle (ψ). The test cases are summarized in Table 3.3.

Table 3.3 : Summary of CFD-based maneuvering test cases.

Case	Maneuver Type	ψ (deg)	V (m/s)	DOF	Controller type
1	Zig-zag	10	2.750	3-DOF (Surge, sway, yaw)	-
2	Straight-ahead	0	2.750	1-DOF (surge)	PI
3			6.096		
4			9.152		
5	Heading control	0	2.75	3-DOF (Surge, sway, yaw)	PID
6		5			
7		15			
8		0	6.096	3-DOF (Surge, sway, yaw)	
9		5			
10		15			
11		0	9.152	3-DOF (Surge, sway, yaw)	
12		5			
13		15			

4. NUMERICAL VERIFICATION & VALIDATION

In CFD studies, numerical models often include several assumptions and simplifications, which can introduce uncertainties in the results. To reduce and better understand these uncertainties, both verification and validation processes are essential. Verification ensures that the numerical model is solving the equations correctly, while validation evaluates how accurately the model represents real-world physical behavior. As part of the verification process, it is important to test different mesh sizes and simulation settings to examine the sensitivity of the results.

4.1 Verification Study of Straight-Ahead Maneuvering Simulation

In this study, the Grid Convergence Index (GCI) method was employed in all CFD analyses to evaluate the impact of grid resolution and verify the consistency of the numerical model. This method, originally introduced by Roache (1998), is based on Richardson (1911) extrapolation and provides a way to measure the errors introduced by the mesh resolution. Celik et al. (2008). later outlined a detailed procedure for applying the method. GCI was selected in this study due to its ability to systematically quantify grid convergence and provide an objective measure of numerical uncertainty, thereby enhancing the robustness and reliability of the simulation results.

The GCI method requires simulations to be performed with at least three different grid densities**,** typically referred to as coarse, medium, and fine grids. The values of a key output parameter (e.g., velocity, resistance, pressure) are recorded from each grid and used to evaluate the rate of convergence and numerical uncertainty. Here is an outline of the main steps in the GCI methodology:

1. **Grid Setup**: Simulations are performed using three progressively refined grids. Let $\phi_1, \phi_2, and\ \phi_3$be the solution values from the coarse, medium, and fine grids, respectively.
2. **Refinement Ratio Calculation**: The refinement ratio between grids is calculated using:

$$r_{21} = \sqrt[3]{\frac{N_1}{N_2}}, \quad (4.1), \qquad r_{32} = \sqrt[3]{\frac{N_2}{N_3}} \quad (4.2)$$

where N_1, N_2, N_3 are the number of cells in each grid.

3. **Solution Difference and Convergence Ratio**: The differences in solution values between successive grids are defined as:

$$\varepsilon_{32} = \phi_3 - \phi_2 \quad (4.3), \qquad \varepsilon_{21} = \phi_2 - \phi_1 \quad (4.4)$$

The convergence ratio R is then computed as:

$$\mathrm{R} = \frac{\varepsilon_{21}}{\varepsilon_{32}} \quad (4.5)$$

This helps to determine whether the solution is converging smoothly (monotonically), diverging, or oscillating. If the value of R lies between 0 and 1, it indicates that the numerical solution of the model converges monotonically.

4. **Observed Order of Accuracy**: The observed order of accuracy p is calculated to evaluate how the numerical solution improves with mesh refinement. First, define:

$$s = 1 * sgn\left(\frac{\varepsilon_{21}}{\varepsilon_{32}}\right) \quad (4.6)$$

$$q(p) = ln\left(\frac{r_{21}^{p} - s}{r_{32}^{p} - s}\right) \quad (4.7)$$

Then, the observed order p is approximated by:

$$p = \frac{1}{ln_{(r_{21})}} \left| ln\left|\frac{\varepsilon_{21}}{\varepsilon_{32}}\right| + q(p)\right| \quad (4.8)$$

5. **Extrapolated Solution:** An extrapolated solution value between the coarse and medium grids can be computed as:

$$\phi_{21}^{\mathrm{ext}} = \frac{r^{p}\phi_1 - \phi_2}{r_{21}^{p} - 1} \quad (4.9)$$

6. **GCI and Estimated Error**: The following error estimates are used to quantify the numerical uncertainty. The approximate relative error,

$$e_a^{21} = \left|\frac{\phi_1 - \phi_2}{\phi_1}\right| \tag{4.10}$$

The extrapolated relative error,

$$e_{ext}^{21} = \left|\frac{\phi_{ext}^{12} - \phi_1}{\phi_{ext}^{12}}\right| \tag{4.11}$$

The **Grid Convergence Index (GCI)** is computed for the fine grid to quantify the relative discretization error:

$$\mathrm{GCI}_{fine}^{21} = \frac{1.25\, e_a^{21}}{r_{21}^{p} - 1} \tag{4.12}$$

These steps provide a quantitative assessment of discretization error and verify the grid independence of the solution.

Table 4.1: Grid Convergence Index (GCI) results for verification study.

Parameters	Values
N_1, N_2, N_3 (x 10^6)	2.71, 1.31, 0.66
ϕ_1, ϕ_2, ϕ_3	9.314, 9.365, 9.443
r_{21}, r_{32}	1.275, 1.256
R	0.650
p	2.105
q(p)	8.08 x 10^{-2}
ϕ_{ext}^{21}	9.239
e_a^{21}	0.543
e_{ext}^{21}	0.818%
GCI_{fine}^{21}	1.015%

Numerical uncertainty results for the DARPA SUBOFF case are presented in Table 4.1. The values of $\phi_1, \phi_2, and\ \phi_3$ represent the self-propulsion values obtained at a velocity of 2.75 m/s using a PI controller. The Grid Convergence Index (GCI) parameter, which quantifies numerical uncertainty, is also shown in Table 4.1.

To perform the uncertainty analysis, three significantly different grid sets were generated, referred to as fine, medium, and coarse, corresponding to the cell numbers $N_1, N_2, and\ N_3$, respectively. The convergence ratio R was calculated as 0.650, which falls within the range [0–1], indicating that the solution is monotonically convergent. The uncertainty for the fine grid was estimated to be approximately 1.015%, indicating that the solution is within an acceptable uncertainty level. Therefore, the fine grid was selected for the subsequent simulations.

4.2 Validation of Straight-Ahead Maneuvering Simulation

Validation of the numerical model is necessary to ensure the accuracy and reliability of the simulation results. In this study, validation was performed by comparing the self-propulsion rotation rate (n) values obtained at a velocity of 2.75 m/s with those reported in other reference studies. These reference rotation rate (n) values were also determined for the same velocity using experimental or validated numerical methods. Additionally, the thrust and torque coefficients ($K_T\ and\ K_Q$) were examined to support the comparison. By evaluating the consistency between the computed rotation rate (n), $K_T, and\ K_Q$ values and those from the literature, the accuracy of the developed numerical approach can be assessed. This comparison serves as a critical step in confirming the validity of the model before conducting further analyses. (Sezen et al., 2018)

Under free-running conditions, the propeller's rotational rate (n) required to maintain the desired velocity of 2.75 m/s was determined to be 9.315 rps through the control of the implemented PI controller. A comparison with values reported in previous studies for the same target velocity indicates a strong agreement. Additionally, the thrust and torque coefficients were found to be $K_T = 0.240\ and\ K_Q = 0.046$, as shown in Table 4.2, further supporting the reliability of the simulation. These values align well with both reference data and the expected mean values.

Table 4.2: Validation study results at 2.75 m/s

Self-Propelled Cases	Type	n (rps)	K_T	K_Q
Present study	CFD	9.315	0.240	0.046
Chase et al. (2013)	CFD	–	0.234	0.047
Kinaci et al. (2018a)	CFD	–	0.231	0.046
Sezen et al. (2018)	CFD	9.360	0.234	0.045
Özden et al. (2019)	CFD	9.258	0.242	0.046
Özden et al. (2019)	EFD	8.969	0.275	0.056
Sezen et al. (2021)	CFD	–	0.234	0.045
Çoşgun (2021)	CFD	–	0.232	0.045
Lungu (2022)	CFD	9.780	0.234	0.046
Delen & Kinaci (2023)	CFD	9.330	0.240	0.046
Average		**9.335**	**0.240**	**0.047**

5. CLOSED-LOOP MANEUVERING SIMULATIONS AND CONTROL PERFORMANCE

5.1 PI-Based Velocity Control for Straight Ahead Simulation

This section presents the implementation of a Proportional–Integral (PI) controller to regulate the forward velocity (surge velocity) of the DARPA Suboff model during self-propulsion simulations. The objective is to achieve a steady cruising velocity by automatically adjusting the propeller's rotational velocity until the net axial force acting on the hull approaches zero. This process ensures that the submarine reaches its target velocity without external input and provides a consistent hydrodynamic baseline for subsequent maneuvering and control tests. The controller gains are tuned based on system response, and the resulting equilibrium operating points are used to initialize further simulations involving lateral motion and heading changes.

The controller parameters, K_p and K_i, were calculated using the equations (2.33) and (2.34)(Song et al., 2020), with constant values of α and β set to 100 to improve computational efficiency. The K_p and K_i, parameters are calculated as $K_p = 7.005137 \times 10^{-4}$ and $K_i = 1.610376 \times 10^{-4}$.

The Straight Ahead Simulation (self-propulsion) of the DARPA submarine form were conducted at three different velocities using the CFD method and PI control. As a result, the propulsion parameters, including thrust, torque, and propeller rotation rate, were estimated for various velocity values as illustrated in Figure 5.2.

Through these simulations, the corresponding propeller rotation rates for each velocity were determined. Furthermore, the force balance on the submarine form was investigated. The analysis of the results indicates that at each velocity, the generated thrust matches the total resistance encountered, confirming that the submarine is in a self-propelled state. All results are presented in the Table 5.1.

The self-propulsion points computed with the PI gains that determined before were overlaid on Sezen et al. (2018) model scale rpm–velocity curve in Figure 5.1 revealing discrepancies under 1.3 % at 2.75 m/s and 6.10 m/s, and rising to only 2.4 % at 9.15 m/s. Such close agreement across a three-fold velocity range confirms that our PI loop accurately compensates hull resistance with minimal tuning. Overall, these results demonstrate that the developed PI controller achieves the desired self-propulsion condition at minimal computational and operational cost, without sacrificing the essential engineering tenets of robustness, precision, and energy-efficient operation.

Table 5.1 : Calculated self-propulsion characteristics with PID controller

V [m/s]	Q [N.m]	T [N]	R [N]	n [rps]	K_Q [-]	K_T [-]
2.75	4.93	97.98	98.00	9.31	0.046	0.24
6.096	22.09	433.97	434.15	20.04	0.045	0.23
9.152	47.15	921.19	921.38	29.58	0.044	0.22

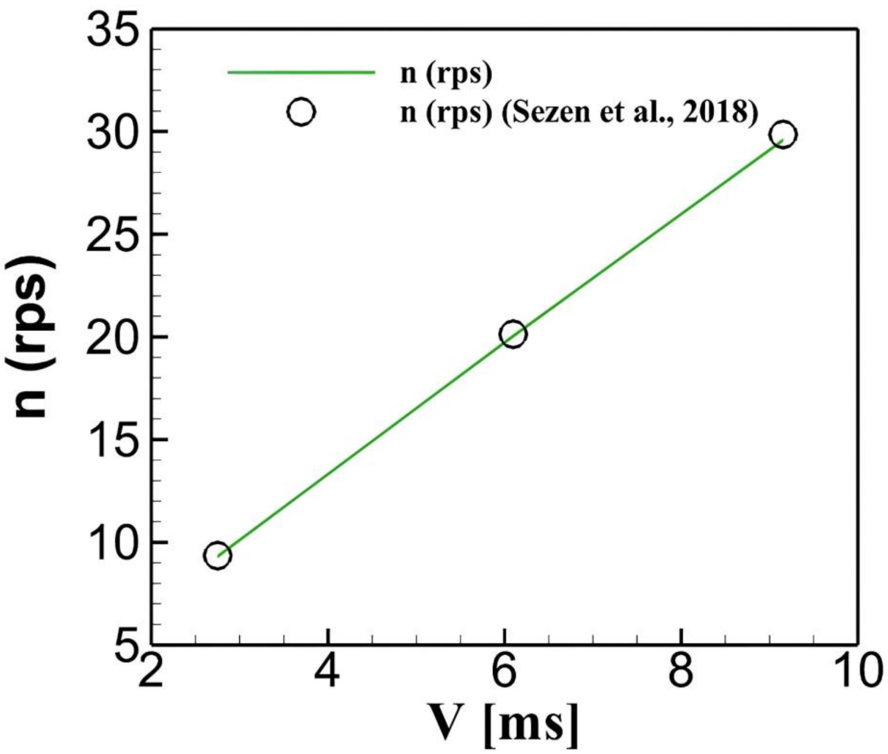

Figure 5.1: Self propulsion point at various velocities compared with Sezen et al. (2018)

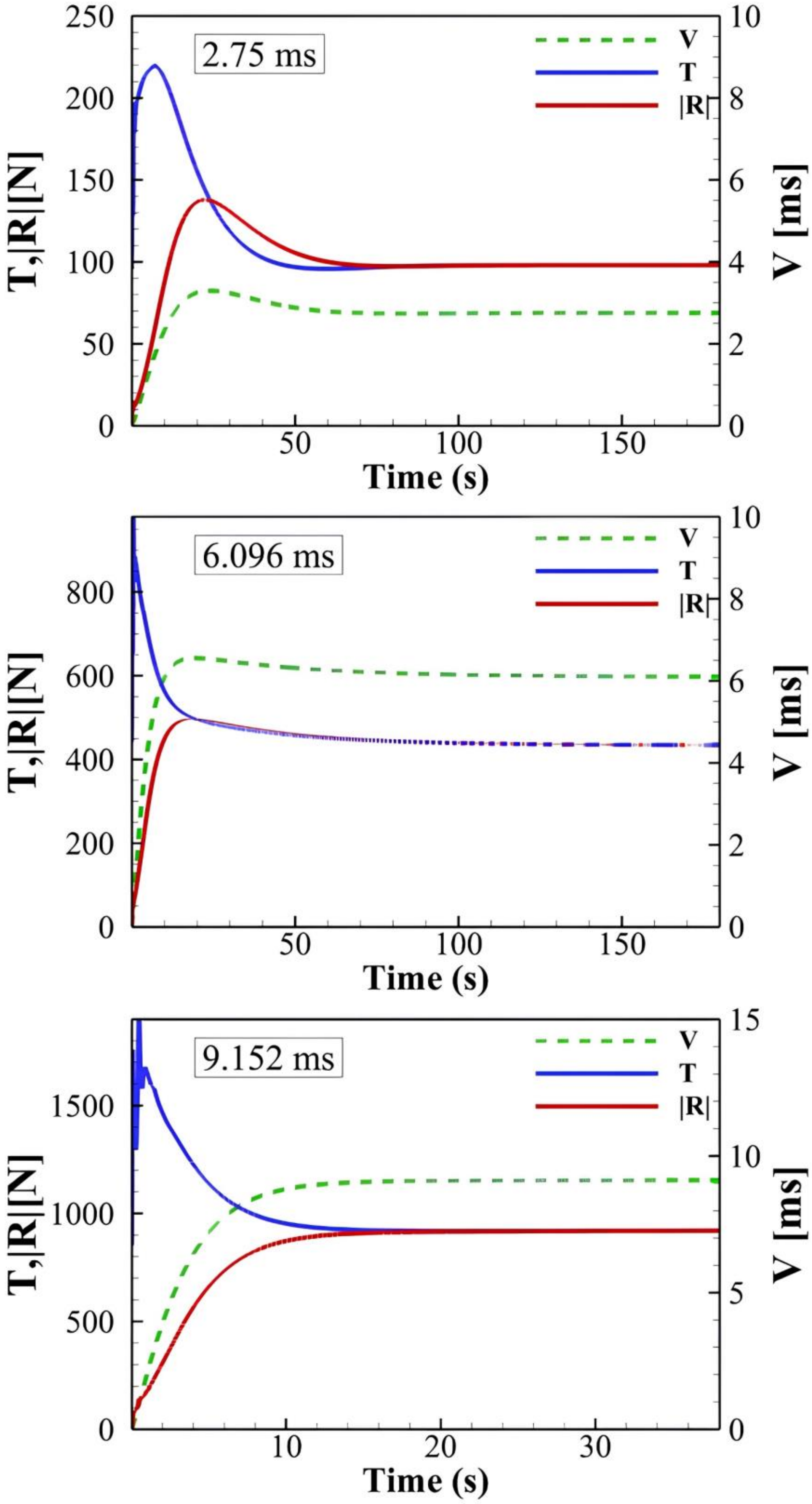

Figure 5.2 : The Time histories of velocity (V), resistance (R), and thrust (T) during self-propulsion simulations at 2.75 m/s (top), 6.096 m/s (middle) and 9.152 m/s (bottom)

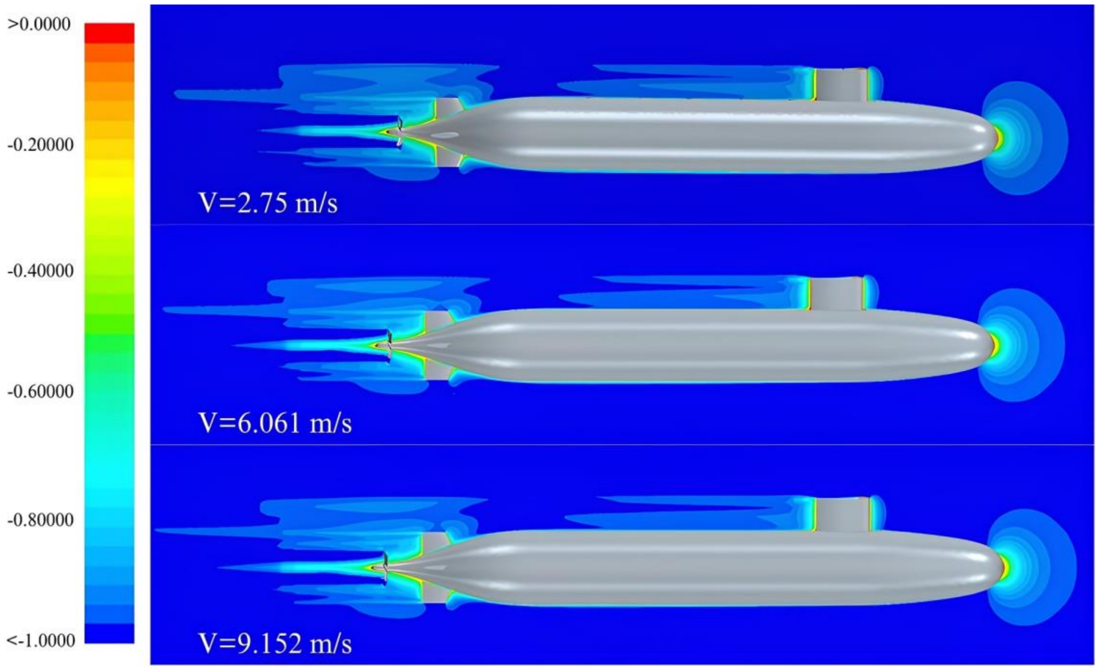

Figure 5.3: Dimensionless velocity contours at various velocities (2.75 m/s, 6.091 m/s, 9.151 m/s)

Figure 5.3 illustrates the dimensionless velocity contours around the Suboff hull at 2.75, 6.06 and 9.15 m/s. As velocity increases, the low-velocity wake behind the stern and sail, both deepens and elongates downstream, reflecting greater momentum loss and pressure drag. This growing wake deficit correlates with the drop in thrust coefficients at Table 5.1 and indicates why higher rotational rate (n) and is required to maintain heading stability at high Froude numbers.

5.2 Zigzag Maneuvering Test for Heading Controller Design

The zigzag maneuvering simulations performed in this section serve as the foundation for estimating the Nomoto model parameters that govern the heading dynamics of the DARPA Suboff model with E1619 model propeller. The 10/10 zigzag test yielded time-domain responses from which the maneuverability gain (K) and time constant (T) were extracted with high temporal resolution. These parameters were subsequently used to derive the PID controller coefficients, enabling more accurate heading control in subsequent simulations.

5.2.1 10/10 Zigzag maneuver simulation results

The 10/10 degree zig-zag maneuver was carried out using the model. Before starting the test, the submarine was brought to its target velocity using PI control. The results are presented in Table 5.2 and visualized in Figure 5.4. In this context, Ψ represents the heading angle, r represents the yaw rate, and δ_{Rudder} represents the rudder angles.

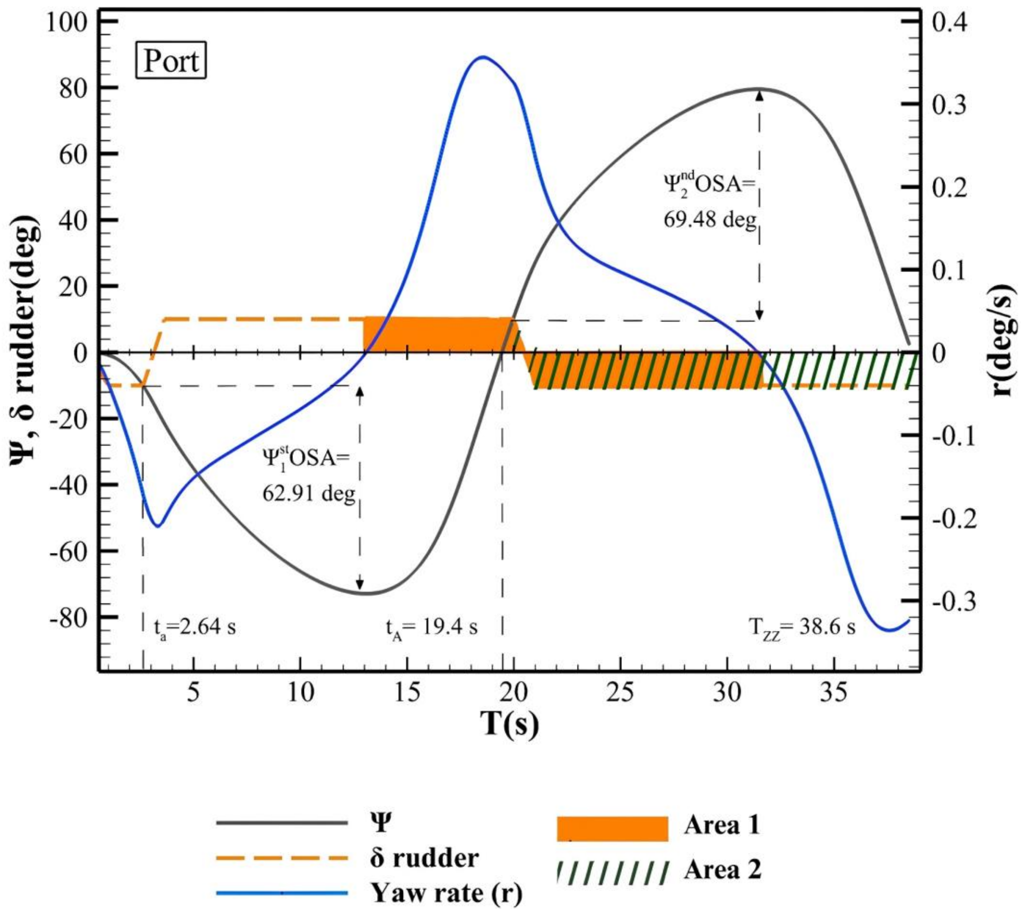

Figure 5.4 : 10/10 Zig-Zag maneuver results.

Table 5.2 : 10/10 Zig-Zag maneuver results.

Case	Ψ_1st OSA	Ψ_2nd OSA	Initial Turning Time t_a	Reach t_A	Period T_{ZZ}
10/10	62.91 deg	69.48 deg	2.64 s	19.4 s	38.6 s

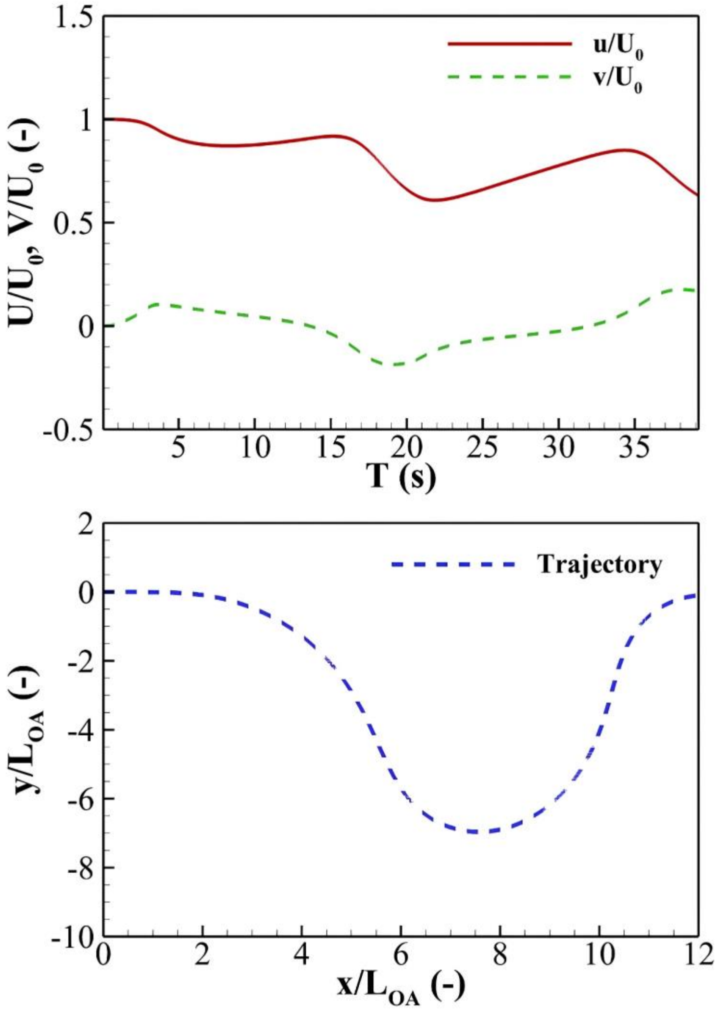

Figure 5.5: The velocity loss (top) and trajectory (bottom) responses of DARPA Suboff for 10/10 zig-zag maneuver.

Figure 5.5 presents the results of the 10-degree zigzag test, showing both the velocity response and the trajectory of the vehicle. The velocity graph displays the surge (u/U_0) and sway (v/U_0) components over time. The surge velocity shows small fluctuations during the maneuver due to changes in heading and rudder action, which slightly affect the forward velocity. The sway velocity remains near zero but shows oscillations, indicating lateral motion as the vehicle turns. The trajectory graph shows how the vehicle first moves to one side and then back, creating an S-shaped path. This reflects the typical response of the vehicle as it changes course and corrects its heading during the zigzag maneuver.

The results provide insights into the submarine's maneuverability and control performance. The first and second overshoot angles (Ψ_1= 62.91 degrees and Ψ_2= 69.48 degrees) are quite high, indicating that the submarine tends to exceed the intended course significantly during maneuvers. This suggests that its course-keeping ability may be limited, likely due to its geometric design and relatively small rudder area. These findings highlight the need for an advanced control system to improve stability.

The submarine's response to rudder rotations requires careful control, as high overshoot angles indicate significant deviations during sudden maneuvers, affecting heading stability and course-keeping. This behavior stems from the submarine's geometry and relatively small rudder surface. The DARPA Suboff form thus requires a dedicated control system for stability. The initial turning time of 2.64 seconds reflects a quick response to rudder commands, enhancing maneuverability. However, the 19.4 second reaching time suggests a prolonged settling period, emphasizing the need for control system refinement. These findings highlight the necessity of optimizing the rudder and control systems for improved course stability and maneuvering efficiency.

In conclusion, the zigzag maneuvering test successfully provided both qualitative and quantitative insight into the submarine's inherent maneuvering characteristics. The data obtained offer a physically grounded basis for controller tuning, bridging the gap between high-fidelity CFD simulations and classical control theory.

5.2.2 PID coefficient estimation by Nomoto method

The (Nomoto et al., 1957) was applied to determine the PID coefficients. The recorded data for heading angle (Ψ), yaw rate (r), and rudder angle (δ_{Rudder}) were processed to generate Figure 5.4, which was used to calculate the values of K and T. In equation (2.23) the integral $\int t_1 t_2 \delta \mathrm{dt}$ represents the area under the curve in section of the Figure 5.4(a). This integral is essential for deriving K, as it reflects the cumulative influence of the rudder angle (δ) over a specific time interval. When both r_1 and r_2 are set to zero, the equation simplifies, isolating the effect of the rudder angle on the change in heading angle (ψ). This relationship highlights how rudder inputs influence heading changes in the absence of external disturbances, offering insight into the submarine's maneuvering behavior.

Similarly, in equation (2.24), when t_1 and t_2 are chosen such that $\psi_1 = \psi_2 = 0$, the equation further simplifies. In this case, the integral $\int t_1 t_2 \delta \mathrm{dt}$ represents the area under the curve in section of the Figure 5.4(b). and is used to determine the ratio of K to T, where K is the maneuvering gain and T is the time constant. When that $\psi_1 = \psi_2 = 0$, the yaw rates (r_1 and r_2) are used to evaluate the system's response to rudder inputs, providing key parameters for assessing the submarine's dynamic stability and maneuverability. The coefficients K and T were computed using equations (2.23) and (2.24). Once these values were obtained, the PID controller coefficients K_p, K_i and K_d were calculated using equations (2.29), (2.30) and (2.32). The final values of the coefficients are presented in Table 5.3.

Table 5.3 : PID controller coefficients derived from CFD-based zigzag maneuver simulations.

Parameters	Value
K	-4.3297
T	-5982.7
K_p	13.8177
K_i	0.1382
K_d	276.585

5.2.3 Integration of PID control via custom Java-based macro

An original contribution of this thesis is the development and integration of a custom Java-based macro within the CFD environment to enable real-time heading control during the simulation, as illustrated in Figure 5.6. This macro allows the CFD solver to operate in a fully closed-loop configuration, where rudder angle is dynamically adjusted at each timestep based on the submarine's instantaneous heading error. The PID control law is implemented directly inside the CFD solver, eliminating the need for external co-simulation tools or middleware, which are commonly used in similar studies.

The control loop begins by defining a target heading angle as the reference input. At each timestep, the macro retrieves the current heading angle from the simulation and calculates the heading error. This error is then processed using a classical PID algorithm, where proportional, integral, and derivative components are computed to determine the required rudder adjustment. The macro applies real-time rudder commands as boundary condition updates within the CFD solver, ensuring that the control input directly influences the hydrodynamic response of the submarine in the next timestep.

To ensure numerical stability and realistic actuator behavior, the rudder commands are passed through a first-order low-pass filter, which smooths sudden changes and prevents non-physical oscillations. Additionally, both the rudder angle and its rate of change are constrained within predefined physical limits, mimicking the performance characteristics of actual submarine steering systems.

This simulation-in-the-loop framework ensures tight coupling between hydrodynamic forces and control actions, enabling immediate feedback and adjustment during the simulation run. The approach not only enhances the physical realism of the heading control simulations but also offers a practical engineering solution for virtual prototyping of autopilot systems. The seamless integration of control logic within the CFD solver environment provides a significant advancement over traditional methods, paving the way for faster, more robust testing of closed-loop control systems in maritime applications.

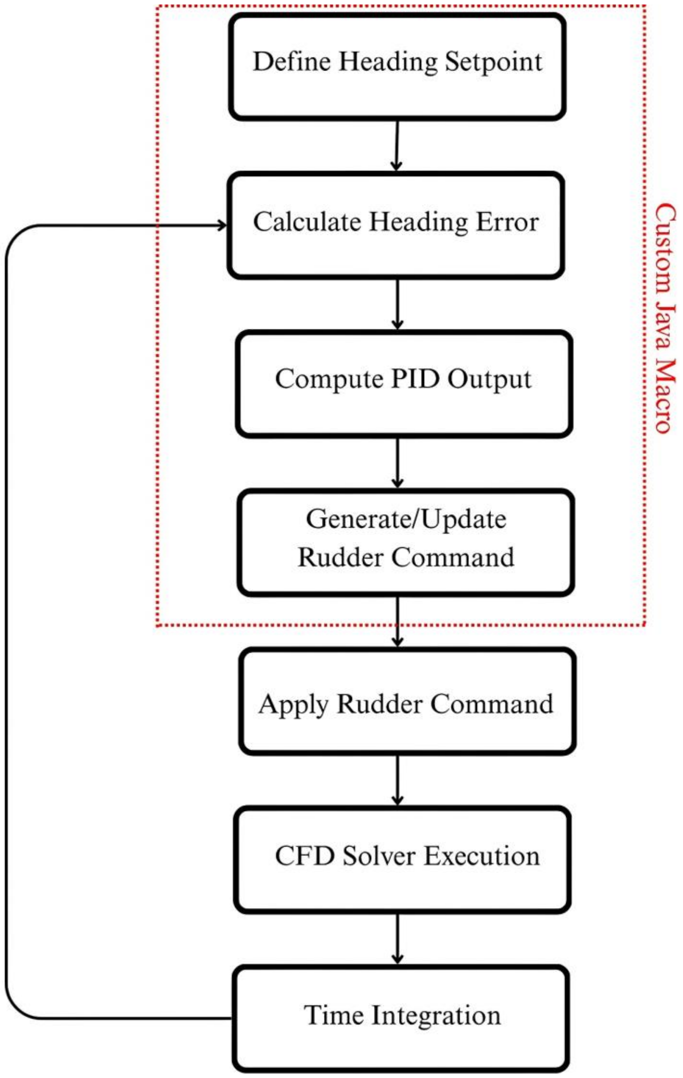

Figure 5.6: Flowchart of closed-loop heading control implementation using a custom Java macro integrated into the CFD solver

5.3 Assessment of Intrinsic Course-Keeping Ability

In this section, the intrinsic course-keeping ability of the DARPA Suboff model is evaluated without any active heading control. The aim is to investigate whether the submarine can maintain a straight-line trajectory under constant forward velocity, solely based on its geometric configuration and hydrodynamic characteristics. By observing the evolution of heading angle and yaw rate during passive motion, the study assesses the natural directional stability of the hull form. The findings serve as a baseline reference to compare with controlled scenarios, helping to quantify the effectiveness of the PID-based autopilot introduced in subsequent sections.

To investigate this behavior, a set of simulations was conducted under self-propulsion conditions at constant forward velocity, while disabling any rudder-based actuation or feedback control. In the absence of an active heading controller, the submarine's dynamic response was governed purely by its form-induced stability characteristics and flow-induced disturbances.

The results, presented in Figure 5.7, clearly indicate that the submarine failed to maintain its initial heading. Over time, a gradual yet continuous yaw motion developed, eventually leading the submarine into an unintended turning circle trajectory. This behavior demonstrates a lack of inherent directional stability—also known as open-loop instability—which is typical in axisymmetric hulls with low natural restoring moments in yaw. To further emphasize this instability, the dimensionless yaw rate was found to remain significantly greater than zero with a value of 0.3085 (r'>0) during the simulation. This sustained non-zero yaw motion quantitatively indicates that the submarine lacks natural course-keeping ability, as any inherent stability would have gradually reduced r' back toward zero over time. The absence of a stabilizing hydrodynamic moment allowed small asymmetries or numerical imperfections to grow over time, resulting in cumulative heading deviation. Although the turning circle test provides clear evidence of this behavior, it is worth noting that pull-out maneuvers are commonly used in literature to more directly quantify a submarine's ability to return to its original course after an initial heading disturbance. In this context, Delen & Kinaci (2023) demonstrated via CFD-based pull-out simulations that the DARPA Suboff exhibits poor intrinsic heading stability, supporting the findings presented in this study. These combined insights underline the necessity of implementing an active control system to ensure reliable course-keeping performance.

These findings underline the necessity of implementing an active heading control system to maintain a straight course during submerged operations. Without such a system, even minor disturbances or model asymmetry can cause significant long-term deviations, rendering autonomous navigation impractical. Therefore, the following sections will introduce a PID-based autopilot system designed to mitigate these effects and restore heading stability under varying operating conditions.

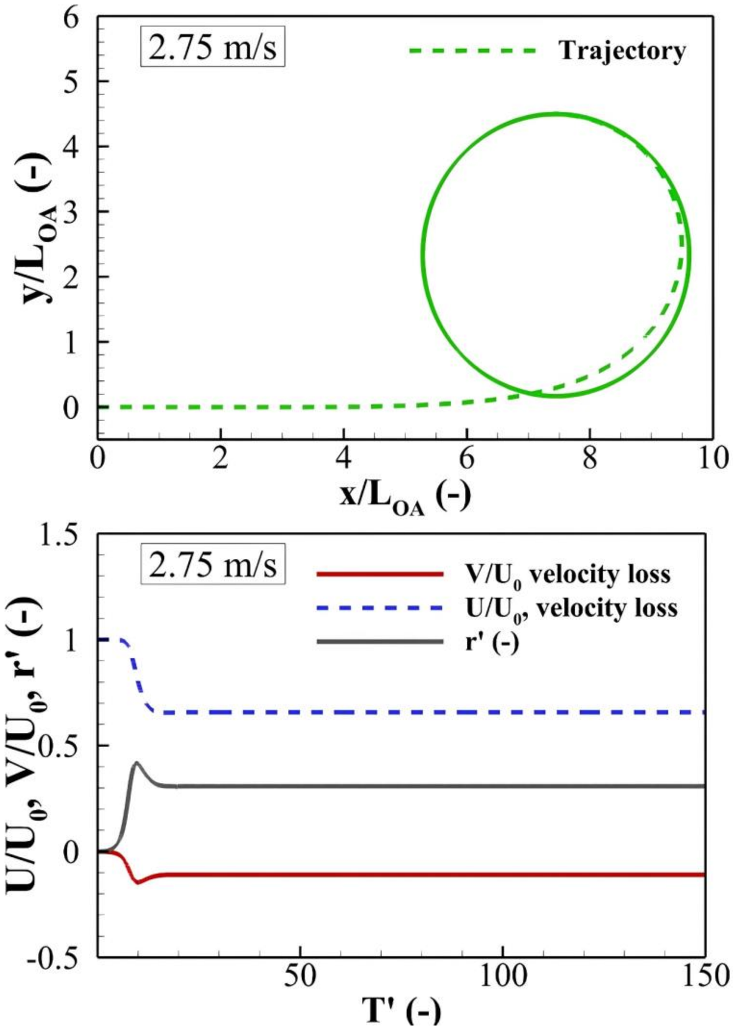

Figure 5.7: Free-running submarine trajectory (top) and velocity loss and yaw rate (bottom) motion without heading control (δ=0.0 deg)

5.4 Heading Control with PID-Based Autopilot

To evaluate the performance of the heading controller, a series of controlled simulations were conducted at three different forward velocities (2.75 m/s, 6.096 m/s, and 9.152 m/s) and for three distinct target heading angles (ψ_t = 0.0, 5.0, and 15.0 degrees). In all scenarios, the PID-based controller effectively steered the submarine toward the intended heading and maintained stable heading behavior throughout the maneuver. As illustrated in Figure 5.7, Figure 5.8, and Figure 5.9, the submarine consistently aligned with the target heading angle regardless of velocity or commanded course, demonstrating the robustness and reliability of the control system.

The results show that the controller adjusted the rudder deflection efficiently to correct heading deviations. Importantly, the submarine reached the target heading within a reasonable timeframe without inducing oscillatory behavior, meeting key criteria for effective control performance. As forward velocity increased, larger rudder angles were required to counteract stronger hydrodynamic forces acting on the hull and control surfaces—an anticipated outcome of the system dynamics. This adaptive rudder response ensured that the submarine stayed on desired heading angle even under varying dynamic conditions.

During the analysis of the heading control responses, it was observed that even when the target heading angle was zero (ψ_t = 0.0°), the rudder angle (δ) did not symmetrically alternate but instead predominantly acted in one direction. This behavior is attributed to the intrinsic directional tendency of the DARPA Suboff hull, which naturally yaws to port (positive δ) under free-running conditions due to asymmetric hull forces and hydrodynamic moments. To counter this bias and maintain the desired heading, the PID controller persistently commands rudder deflections toward the port side. This one-sided rudder actuation serves to stabilize the vehicle and nullify the cumulative influence of asymmetric inertia and hydrodynamic forces.

To safeguard the vehicle's stability and prevent abrupt or excessively aggressive maneuvers, rudder deflection angles were constrained to a maximum of 20 degrees, and the rudder rate (rate of change of rudder angle) was limited. Furthermore, before transmitting rudder commands to the CFD solver, a low-pass filter was applied to smooth the control signals and eliminate high-frequency noise. This filtering step was crucial to avoid non-physical rudder actuation and reduce potential numerical instabilities, while also contributing to a smoother and more realistic control response.

The overshoot and settling behavior observed across the simulations were minimal and remained consistent at different heading targets. For instance, the overshoot values at ψ_t = 5.0 degree and ψ_t = 15.0 degrees were nearly identical across all tested velocities, underscoring the controller's stability, responsiveness, and capability to minimize heading deviation. The resulting trajectories exhibited smooth convergence between the commanded and actual heading angles, free from sustained oscillations or instability.

These findings validate the effectiveness of the developed controller, which leverages the Nomoto model with coefficients derived from CFD-based hydrodynamic analysis rather than relying solely on empirical methods. The control system's ability to achieve the target heading promptly, minimize oscillations and deviations, and avoid unnecessarily aggressive rudder inputs highlights its suitability for practical underwater navigation applications. Collectively, these results confirm that CFD-informed PID control offers a reliable, robust, and adaptable approach for submerged vehicle guidance under various operational conditions.

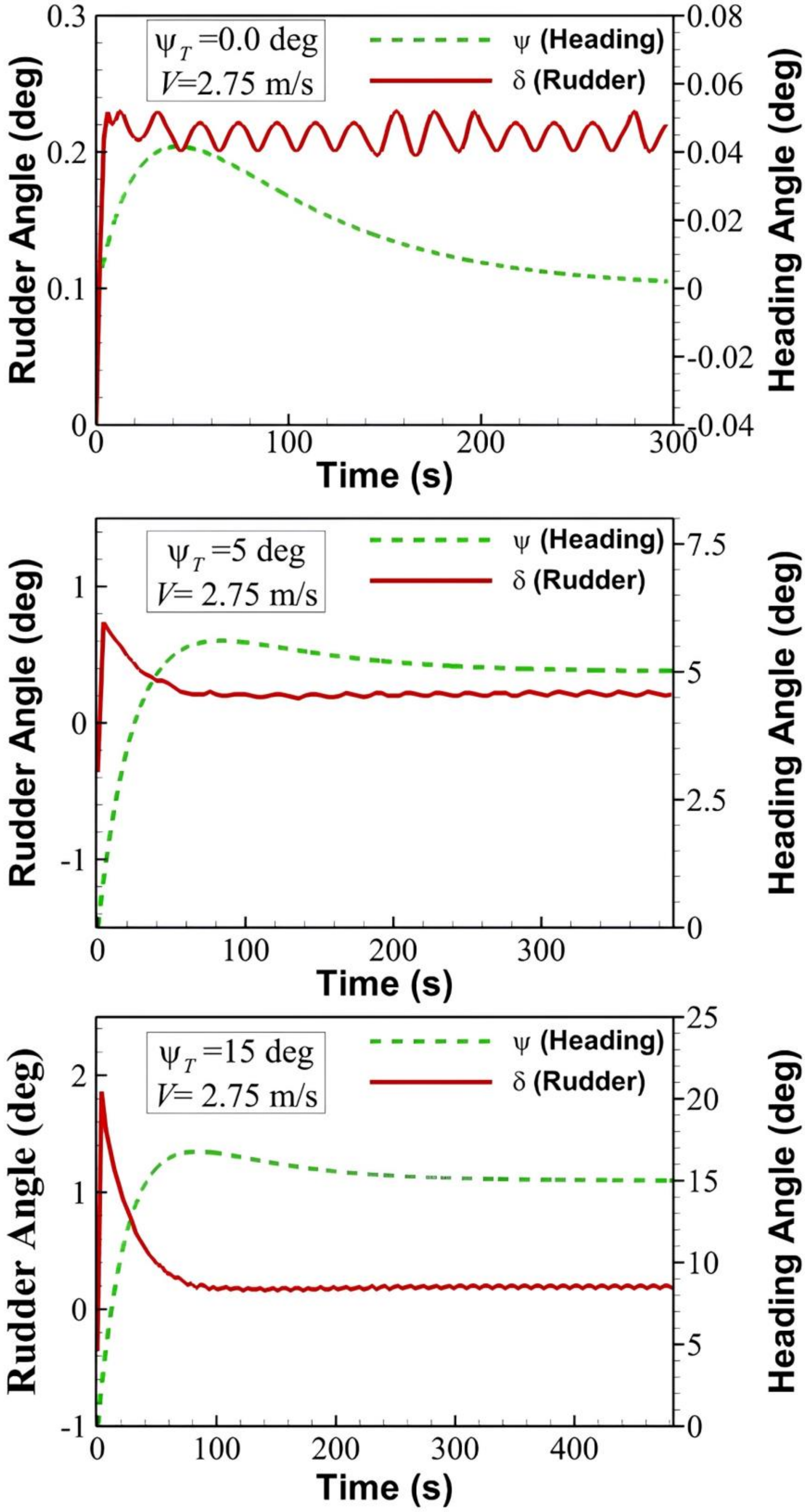

Figure 5.8: Rudder and heading angle responses with PID controller at 2.75 m/s for target heading angles of ψ_t = 0.0 deg (top), ψ_t = 5.0 deg (middle), ψ_t = 15.0 deg (bottom).

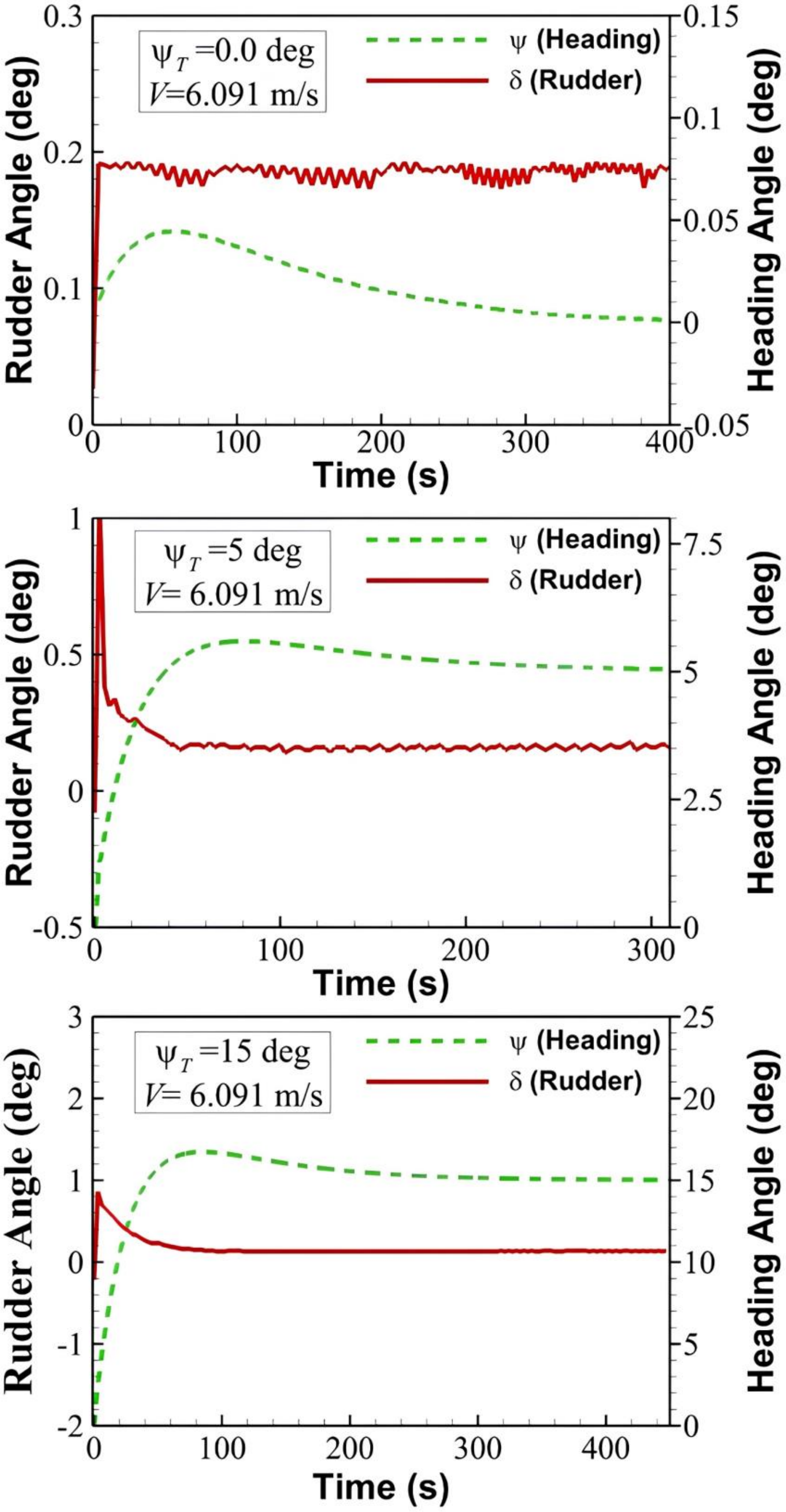

Figure 5.9: Rudder and heading angle responses with PID controller at 6.091 m/s for target heading angles of ψ_t = 0.0 deg (top), ψ_t = 5.0 deg (middle), ψ_t = 15.0 deg (bottom).

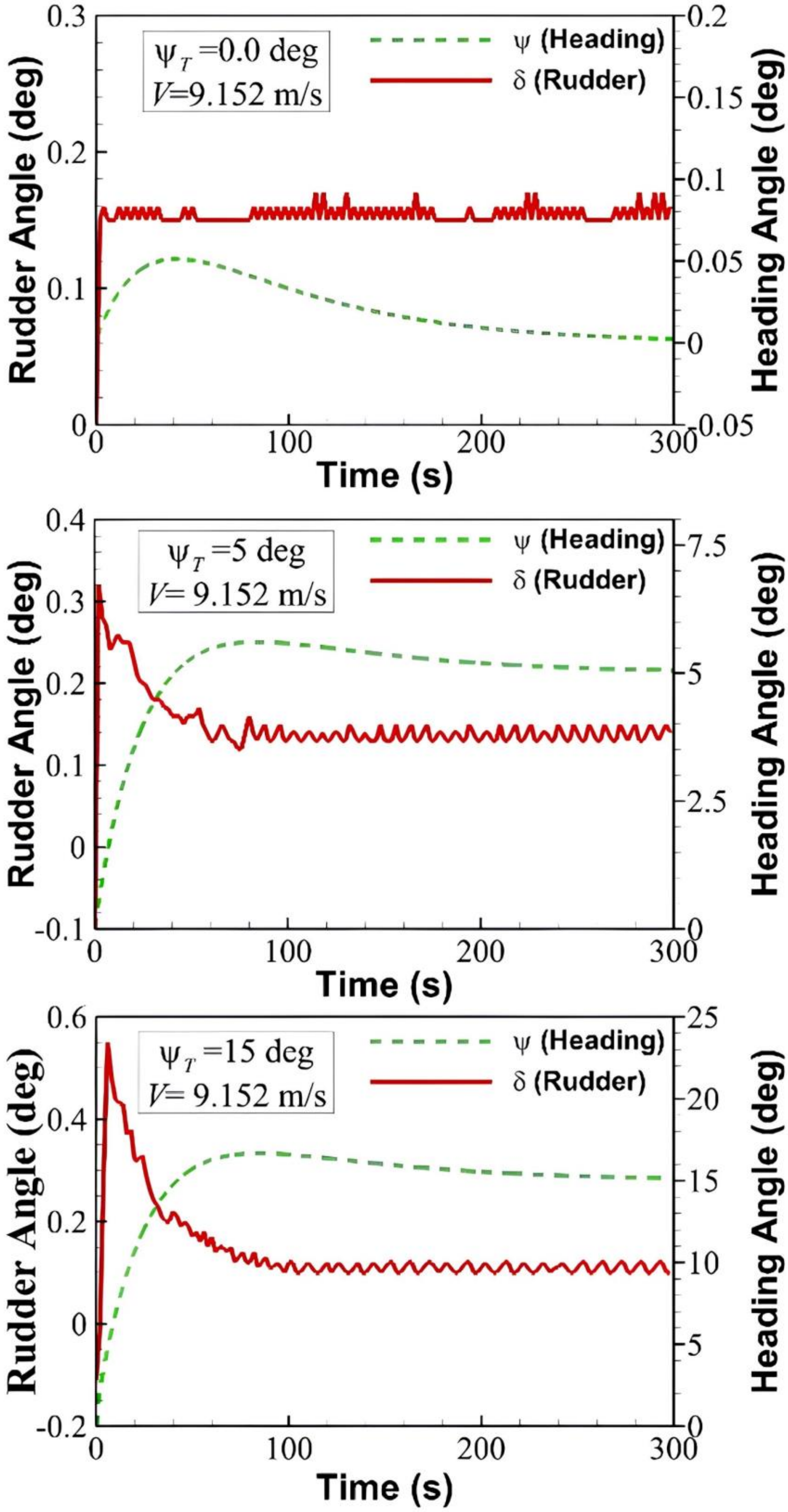

Figure 5.10: Rudder and heading angle responses with PID controller at 9.152 m/s for target heading angles of ψ_t = 0.0 deg (top), ψ_t = 5.0 deg (middle), ψ_t = 15.0 deg (bottom).

6. EVALUATIONS & RECOMMENDATIONS

In this study, a comprehensive CFD-based control methodology was developed to maintain the underwater heading control of a DARPA SUBOFF submarine model with E1619 model propeller through a PID controller. The primary objective was to accurately determine control parameters using high-fidelity CFD simulations without relying on empirical approximations or extensive physical trials. To enable seamless integration between the control logic and the flow solver, a custom Java-based macro was developed. This macro allowed the PID controller to operate directly within the CFD environment, enabling real-time rudder command generation without requiring external tools or post-processing.

The CFD modeling framework played a pivotal role in achieving these reliable results by solving the incompressible URANS equations with the Finite Volume Method. A segregated flow approach and the SIMPLE algorithm ensured stable convergence, while the SST k–ω turbulence model provided a balance between near-wall and free-stream predictions. The use of y^+ wall treatment ensured adequate near-wall resolution, enabling accurate simulation of hydrodynamic forces, pressure fields, and wake dynamics critical for maneuvering predictions. The SST k–ω turbulence model was selected not only for its predictive capabilities but also for its balance between accuracy and computational efficiency, making it particularly suitable for extracting control parameters within the scope of this study. Although higher-fidelity approaches such as DES exist, the selected method sufficiently addressed the simulation requirements without introducing additional numerical complexity.

The verification and validation study focused on self-propulsion simulations conducted at three distinct velocities (2.750 m/s, 6.096 m/s, and 9.152 m/s), corresponding to operating points where propeller thrust balances total hull resistance. A custom-designed Proportional–Integral (PI) controller was implemented to precisely determine these points by dynamically adjusting propeller rotational speed, ensuring a stable thrust–resistance equilibrium critical for establishing a reliable propulsion baseline. Verification was performed using the Grid Convergence Index (GCI) method, confirming mesh independence with a numerical uncertainty below 1.1%. For validation, the resulting propeller rotational rates (n), along with thrust and torque coefficients, were compared against benchmark experimental and CFD data from the literature. The comparisons revealed a maximum deviation of less than 0.22% for self-propulsion points, demonstrating strong agreement and confirming the accuracy and robustness of the selected turbulence model, boundary conditions, and solver strategy.

An evaluation of the results revealed that the DARPA SUBOFF form inherently exhibits poor open-loop course-keeping ability due to its geometric features and limited rudder area. In the absence of active control, the model failed to maintain a straight trajectory and deviated into turning motions. However, once the PID-based heading control was activated, significant improvements in directional stability were achieved. Rudder deflections remained within physically meaningful limits, and oscillations were minimized even at higher forward velocities, indicating that the PID system could dynamically compensate for flow-induced disturbances. The Java-based macro played a key role in enabling this dynamic compensation by allowing the control algorithm to adjust the rudder input at every iteration, directly responding to transient flow behavior within the CFD solver.

The results demonstrated that the developed control methodology successfully maintained heading stability at various target angles (0.0, 5.0, and 15.0 degrees) and velocities (2.750 m/s, 6.096 m/s, and 9.152 m/s), validating the effectiveness of the proposed method under different operational conditions. These findings align well with the initial hypothesis that a CFD-derived PID controller could replace traditional tuning methods and provide more adaptive, physics-based control solutions. Moreover, the study demonstrated that control parameters extracted directly from CFD-based zigzag maneuvers could be used effectively for real-time heading stabilization without requiring empirical input or sea trials.

While the controller successfully guided the submarine toward the desired heading in all scenarios, it was observed that the time required to reach the target heading could be further optimized. Future studies may focus on tuning and optimizing the controller coefficients to reduce response time without compromising stability or safety. Such improvements would enhance the system's responsiveness, particularly for applications requiring rapid maneuvering or real-time path correction.

From an engineering and industrial perspective, the results underscore the advantages of integrating CFD with control system development during the early design stages of submarine projects. This approach offers significant time and cost savings by minimizing the need for expensive experimental campaigns. Additionally, the ability to predict and optimize heading control performance through simulation contributes to safer and more efficient autonomous underwater vehicle (AUV) designs, supporting advancements in defense, research, and commercial sectors.

Based on the findings of this study, several recommendations for future work are proposed. Although a PID controller was successfully implemented in this study, its performance depends on fixed gains and may be limited under highly nonlinear or time-varying flow conditions. Future research may explore adaptive and intelligent control techniques—such as gain-scheduled PID, fuzzy logic controllers, or model predictive control (MPC)—to achieve enhanced robustness and optimality in real-time submarine navigation. It is important to note, however, that the PID controller employed here already fulfilled its intended objective by providing a simple, fast, and reliable solution suitable for the scope of this study, without necessitating more complex algorithms at this stage.

Future studies may also broaden the evaluation of control system effectiveness under dynamic and nonlinear hydrodynamic conditions. Environmental factors such as waves, currents, and stratified water conditions should be incorporated into simulations to assess the robustness of control performance under realistic sea states. Lastly, integrating artificial intelligence and machine learning techniques with CFD models represents a promising direction for developing intelligent and autonomous navigation systems capable of adapting to changing underwater environments.

In conclusion, this thesis establishes a solid foundation for CFD-integrated control system design in underwater vehicles by bridging high-fidelity hydrodynamic simulation with practical heading control implementation. A key innovation of the study is the use of a custom Java-based macro, which enabled the real-time execution of the PID controller directly within the CFD environment. This native integration eliminated the need for external coupling or post-processing and enhanced the responsiveness and physical realism of the control system.

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- **Ünlü, D.** and Delen, C. (2024) *Prediction of Course-Keeping Control Coefficients of DARPA Suboff*. Proceedings of the 8th EAI International Conference on Robotic Sensor Networks, Istanbul, Turkey. (In press)
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