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Advanced Hybrid PID–Adaptive Control Strategy for Enhanced Gas Turbine Engine Performance

Strategi Pengendalian Hybrid PID-Adaptif Tingkat Lanjut untuk Peningkatan Kinerja Mesin Turbin Gas

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Abstract— *General Background Gas turbine engines operate under highly variable and nonlinear conditions, yet conventional fixed-gain PID controllers cannot sustain optimal performance as operating points shift and components age. Specific Background The integration of a Two-Degree-of-Freedom PID with real-time adaptive mechanisms offers a promising pathway to enhance tracking accuracy, disturbance rejection, and long-term robustness. Knowledge Gap Existing studies rarely evaluate a fully integrated hybrid architecture that combines 2-DOF PID, adaptive estimation, anti-windup, and bumpless transfer under realistic disturbances, degradation, and noise. Aims This study designs and validates a Hybrid 2-DOF PID–Adaptive controller for a single-shaft industrial gas turbine using high-fidelity MATLAB/Simulink modeling. Results The hybrid controller significantly reduced overshoot, accelerated settling time by more than 20 percent, and maintained near-nominal performance under 10 percent simulated efficiency loss, outperforming fixed-gain PID, fixed-gain 2-DOF PID, and standalone MRAC. Novelty The research provides a unified, computationally efficient architecture that stabilizes transient behavior while continuously adapting to plant variations. Implications These findings demonstrate a practical upgrade path for industrial gas turbines, offering improved efficiency, reduced thermal stress, and enhanced reliability across the engine lifecycle..*
Keywords— *Gas Turbine, Hybrid Control, 2-DOF PID, Adaptive Control (MRAC/RLS), Disturbance Rejection.*

Abstrak— Latar Belakang Umum Mesin turbin gas beroperasi dalam kondisi yang sangat bervariasi dan nonlinier, namun pengendali PID konvensional dengan gain tetap tidak dapat mempertahankan kinerja optimal saat titik operasi bergeser dan komponen menua. Latar Belakang Khusus Integrasi pengendali PID dua derajat kebebasan (2-DOF) dengan mekanisme adaptif waktu nyata menawarkan jalur yang menjanjikan untuk meningkatkan akurasi pelacakan, penolakan gangguan, dan ketahanan jangka panjang. Kesenjangan Pengetahuan Studi yang ada jarang mengevaluasi arsitektur hibrida terintegrasi sepenuhnya yang menggabungkan PID 2-DOF, estimasi adaptif, anti-windup, dan transfer tanpa guncangan di bawah gangguan, degradasi, dan kebisingan yang realistis. Tujuan Studi ini merancang dan memvalidasi pengendali hibrida PID 2-DOF–Adaptif untuk turbin gas industri satu poros menggunakan pemodelan MATLAB/Simulink berpresisi tinggi. Hasil Pengendali hibrida secara signifikan mengurangi overshoot, mempercepat waktu penyelesaian lebih dari 20 persen, dan mempertahankan kinerja mendekati nominal di bawah kerugian efisiensi simulasi 10 persen, outperforming PID gain tetap, PID 2-DOF gain tetap, dan MRAC mandiri. Keunikan Penelitian ini menyediakan arsitektur terpadu dan efisien secara komputasi yang menstabilkan perilaku transien sambil terus beradaptasi dengan variasi sistem. Implikasi Temuan ini menunjukkan jalur peningkatan praktis untuk turbin gas industri, menawarkan efisiensi yang lebih baik, stres termal yang berkurang, dan keandalan yang ditingkatkan sepanjang siklus hidup mesin.
Kata Kunci— Turbin Gas, Kontrol Hibrida, PID 2-DOF, Kontrol Adaptif (MRAC/RLS), Penolakan Gangguan.

I. INTRODUCTION

Gas turbine (GT) engines underpin aviation and provide fast-ramping stability in grids with high renewable penetration, but frequent cycling, partial-load operation, and rapid transients strain traditional control approaches. Meeting ACARE Flightpath 2050 targets—75% CO_2 and 90% NOx reductions versus year 2000—demands a control-and-optimization paradigm shift, not incremental component tweaks [1]. While PID controllers are ubiquitous for their simplicity and reliability, their fixed gains are optimal only near the tuned point; GTs' strongly nonlinear, condition-dependent dynamics and lifecycle degradation (e.g., fouling, erosion, corrosion) erode performance, efficiency, and safety margins under wide operating envelopes [2]. A hybrid strategy that augments a two-degree-of-freedom (2-DOF) PID with a real-time adaptive layer (e.g., MRAC or RLS) preserves PID stability while continuously compensating for nonlinearities and aging, decoupling setpoint tracking from disturbance rejection and delivering resilient, high performance across the engine lifecycle. [1], [2].

A. Research Problem

Conventional fixed-gain PID controllers for gas turbines lack the adaptability to maintain optimal performance and safety margins under the diverse and time-varying operating conditions inherent to modern power generation and aviation. This deficiency leads to suboptimal fuel

efficiency, elevated emissions, and increased thermomechanical stress on critical engine components. This research addresses the systematic design, implementation, and validation of a hybrid 2-DOF PID-Adaptive control strategy engineered to overcome these fundamental limitations.

B. Research Significance

2.1 Scientific Significance

This work contributes to control systems theory by proposing and rigorously evaluating a practical hybrid architecture that bridges the gap between classical linear control and modern adaptive techniques. While standalone adaptive controllers can suffer from complexity and robustness issues, and advanced methods like Model Predictive Control (MPC) often carry a high computational burden [3], this hybrid approach offers a computationally efficient and robust pathway. It provides a structured methodology for integrating adaptive elements with a proven industrial controller, complete with essential features like anti-windup and bumpless transfer, making it a viable template for other complex nonlinear industrial processes.

2.2 Practical Significance

For industry, the implications are substantial. An adaptive controller that maintains near-optimal performance can yield significant operational benefits. These include improved fuel efficiency, which directly translates to lower operating costs and reduced CO2 emissions. By better managing transient behavior and preventing excursions beyond safe operational limits, such as peak Exhaust Gas Temperature (EGT), the controller can reduce thermal and mechanical stress, thereby extending engine component life and reducing maintenance costs [4]. In the context of power generation, enhanced responsiveness improves the turbine's ability to support grid stability, a service of increasing value.

C. Research Objectives

3.1 Primary Objective

To design, implement, and validate a hybrid 2-DOF PID-Adaptive control strategy that demonstrates superior performance, robustness, and adaptability over traditional PID and standalone adaptive controllers for a simulated single-shaft industrial gas turbine model.

3.2 Specific Aims (Quantitative)

To achieve a greater than 20% reduction in settling time and a greater than 30% reduction in percent overshoot during significant load changes compared to a benchmark well-tuned fixed-gain PID controller.

To maintain peak Exhaust Gas Temperature (EGT) within safe operational limits (e.g., $< 80\%$ above reference during transients, as per industry guidelines) during aggressive maneuvers where a traditional PID controller might violate them.

To demonstrate robust performance with minimal degradation (less than 10% change in key performance metrics) under simulated conditions of sensor noise, parameter drift (up to 10% efficiency loss), and actuator saturation.

Research Hypotheses

H1: The proposed hybrid 2-DOF PID-Adaptive controller will yield statistically significant improvements in transient response metrics (settling time, overshoot) and integral error criteria (IAE, ISE) compared to a benchmark fixed-gain PID controller across multiple operating scenarios.

H2: The adaptive component of the hybrid controller will effectively compensate for performance degradation due to simulated engine aging (via gradual parameter drift), maintaining near-nominal performance where a fixed-gain controller's performance deteriorates.

H3: The integration of anti-windup and bumpless transfer mechanisms will ensure stable, smooth, and predictable controller operation during events of actuator saturation and manual-to-auto control mode transitions, preventing performance degradation associated with these common industrial occurrences.

Research Questions

1. How can a Two-Degree-of-Freedom (2-DOF) PID controller be effectively and stably integrated with a Model Reference Adaptive Control (MRAC) or Recursive Least Squares (RLS) based adaptive mechanism for real-time gas turbine control?
2. 2.To what quantitative extent does the proposed hybrid controller improve key performance metrics (IAE, ISE, settling time, overshoot, peak EGT) across a comprehensive range of operational scenarios, including setpoint changes, load disturbances, and component degradation?
3. 3.How does the hybrid controller's overall performance and robustness profile
4. compare against established benchmarks, specifically a well-tuned fixed-gain PID, a standalone 2-DOF PID, and a pure MRAC controller?

Expected Scientific Contribution

This research is expected to deliver three primary contributions. First, a novel, integrated controller architecture (2-DOF PID + Adaptive + Anti-Windup + Bumpless Transfer) that is specifically tailored, implemented, and validated for the complex dynamics of gas turbine engines. Second, a comprehensive comparative analysis that provides clear, data-driven evidence of the hybrid strategy's advantages over conventional and standalone adaptive methods. Finally, it will produce practical guidelines for the implementation, tuning, and operational use of such a hybrid system, making advanced adaptive control more accessible for industrial application.

Research Gaps

The existing body of literature contains numerous studies on PID, adaptive control, and MPC applied to gas turbines. However, a significant gap remains. There is a lack of comprehensive investigation into a practical, integrated hybrid architecture that combines the specific advantages of 2-DOF PID with a robust adaptive layer. Furthermore, few studies rigorously test such a system against a full suite of realistic operational challenges simultaneously, including sensor noise, parameter drift, actuator saturation, and bumpless mode switching. This research aims to fill that void by providing a holistic evaluation of a complete, industrially-relevant control solution

II. LITERATURE REVIEW

A. Gas Turbine Engine Modeling for Control

The development of effective control strategies is predicated on the availability of a model that accurately captures the engine's dynamic behavior. Gas turbine models vary in fidelity and complexity, generally falling into two categories: physics-based and data-driven.

B. Thermodynamic and Physics-Based Models

Physics-based GT models start from first principles in thermodynamics and fluid mechanics, with the Brayton cycle providing the ideal thermodynamic baseline [5]. For control, engineers rely on higher-fidelity, component-level representations— inlet, compressor, combustor, turbine, and nozzle—where turbomachinery behavior is captured by performance maps that relate pressure ratio and efficiency to corrected mass flow and speed, typically derived from rig testing or detailed CFD [6]. Transient response is modeled with the inter-component volume method, which treats the volumes between stages as mass-energy accumulators to track dynamics realistically [7]. NASA's extensive guidance codifies these practices, enabling high-fidelity simulations that predict performance across the operating envelope and safeguard limits such as compressor surge margins [8].

C. Data-Driven and Black-Box Models

When detailed design information is unavailable or a model must be derived from operational data, data-driven techniques are employed. System identification methods, such as Nonlinear AutoRegressive with eXogenous inputs (NARX), can create highly accurate "black-box" models that capture the engine's input-output dynamics without explicitknowledge of the internal physics. These models, often implemented with neural networks, have been shown to effectively simulate transient behavior and even complex phenomena like engine startup [9]. Their primary utility is in scenarios where first-principles modeling is infeasible.

D. Modeling Platforms

The de facto standard for dynamic system simulation in both academia and industry is MATLAB/Simulink. Its graphical environment facilitates the construction of complex component-level models. Specialized toolboxes and libraries, such as the NASA-developed Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) and commercially available Gas Turbo Lib, provide pre-built component blocks that accelerate the development of gas turbine simulations [10].

E. PID-Based Control of Gas Turbines

Conventional PID

Despite decades of advances in control theory, over 90% of industrial control loops are of the PID type [11]. Their enduring popularity stems from their simple structure, intuitive tuning, and robustness. However, their performance is inherently limited for strongly nonlinear systems like gas turbines. Classic tuning rules, such as Ziegler-Nichols, often provide a starting point but rarely yield satisfactory performance across the full operating range without significant manual adjustment [12].

Gain-Scheduling PID

A common industrial practice to address nonlinearity is gain scheduling. In this approach, PID gains are not fixed but are instead varied as a function of one or more scheduling variables, such as rotor speed opilot's lever angle (PLA). This effectively creates a series of linear controllers for different operating regions. While this improves performance over a fixed-gain PID, it is suboptimal during rapid transitions between operating points and requires extensive tuning and validation across the entire flight or operational envelope [12].

Two-Degree-of-Freedom (2-DOF) PID

A structural enhancement to the PID controller is the 2-DOF configuration. By introducing setpoint weighting on the proportional and derivative terms, a 2-DOF controller can decouple the response to setpoint changes from the response to disturbances. This allows for aggressive tuning for fast disturbance rejection without introducing excessive overshoot in setpoint tracking—a highly desirable characteristic for gas turbine control [13].

This structure provides a more robust foundation upon which to build an adaptive strategy.

F. Adaptive Control Strategies

Adaptive control is designed to automatically adjust controller parameters in real-time to cope with uncertainties or variations in plant dynamics.

Model Reference Adaptive Control (MRAC)

MRAC is a prominent adaptive scheme where the control objective is to make the plant's output track the output of a stable, well-behaved reference model that specifies the desired performance. An adaptation mechanism, typically derived from stability theory (e.g., Lyapunov's method or the MIT rule), continuously adjusts the controller gains to minimize the error between the plant and reference model outputs [14]. MRAC is particularly effective at compensating for unknown or slowly varying plant parameters, making it a strong candidate for addressing engine aging.

Recursive Least Squares (RLS) Based Adaptation

RLS is a powerful algorithm for online parameter estimation. In a control context, it can be used in a self-tuning regulator framework. The RLS algorithm continuously identifies the parameters of a simplified local model of the gas turbine. These estimated parameters are then used at each time step to re-calculate (or "self-tune") the PID controller gains based on a predefined design rule, such as pole placement [15]. This approach allows the controller to directly adapt to changes in the plant's local dynamics.

Challenges in Adaptive Control

Despite their potential, adaptive controllers are not without challenges. Historical issues include ensuring global stability, guaranteeing convergence of parameters, and robustness to unmodeled high-frequency dynamics or measurement noise, which can lead to a phenomenon known as "bursting" where parameters drift erratically [16]. Careful design, including robust adaptation laws and conservative tuning, is required for successful industrial application

III. METODS

A. Modeling Platform and Gas Turbine Model

1.1 Platform

All modeling, simulation, and analysis for this research were conducted within the MATLAB/Simulink R2025a environment. This platform was chosen for its extensive libraries for control system design, signal processing, and dynamic system simulation, making it an industry and academic standard for this type of research [18].

1.2 Engine Model

The plant under investigation is a single-shaft industrial gas turbine model, developed within Simulink based on established component-level modeling principles. This type of model provides a balance between fidelity and computational efficiency, making it suitable for extensive controller testing. The architecture is based on validated approaches found in literature, such as those described by Singh et al. [7] and NASA technical reports.

1.3 Component Details

Compressor and Turbine: The core aerodynamic components are modeled using standard, non-dimensional performance maps. These maps define the pressure ratio and isentropic efficiency as functions of corrected mass flow and corrected speed. The maps are implemented as 2D lookup tables in Simulink, capturing the nonlinear behavior of the turbomachinery across its operating range.

Combustor: The combustion chamber is modeled as a simplified thermodynamic process. It includes a time delay to represent the ignition and combustion process, a constant pressure loss (typically 4-6%), and a gain that calculates the Exhaust Gas Temperature (EGT) based on fuel flow rate, airflow from the compressor, and combustion efficiency. This approach is common in control-oriented models where detailed chemical kinetics are not required [19].

Rotor Dynamics: The dynamics of the single shaft connecting the compressor and turbine are represented by a first-order differential equation, modeling the rotational inertia. The net torque (turbine torque minus compressor torque and external load) accelerates or decelerates the shaft according to Newton's second law for rotation

Table 1: Key Parameters of the Simulated Single-Shaft Gas Turbine

Parameter	Value	Unit	Source/Justification
Nominal Power Output	5.0	MW	Typical for small industrial GT
Nominal Speed (N)	15,000	RPM	Representative value
Rotor Inertia (J)	25	$kg \cdot m^2$	Estimated for this class of engine
Design Point Pressure Ratio	12:1	-	Typical for industrial GTs [20]
Combustor Time Delay	20	ms	Standard assumption for flame dynamics

Nominal EGT	550	°C	Common operational temperature [21]

B. Hybrid Controller Design and Implementation

The proposed controller integrates four key components into a single, robust architecture: a 2-DOF PID core, an RLS-based adaptive mechanism, an anti-windup scheme, and bumpless transfer logic.

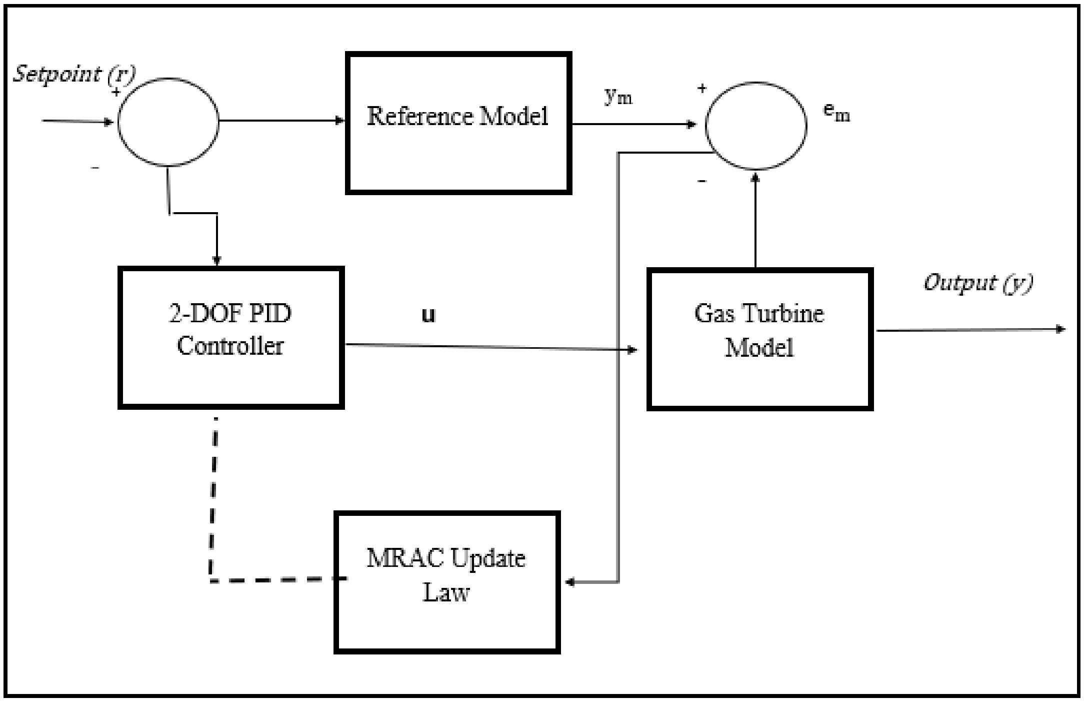

Figure 1 : Conceptual Block Diagram of the Proposed Hybrid 2-DOF PID-Adaptive Control System

DOF PID Controller

The core of the controller is a 2-DOF PID structure. Unlike a standard PID, its control law separates the setpoint and feedback signals in the proportional and derivative paths:

$$u(t) = Kp * (b * r(t) - y(t)) + Ki * \int e(t)dt + Kd * (c * dr(t)/dt - dy(t)/dt)$$

where:

$e(t) = r(t) - y(t)$

The setpoint weights, b and c , are tunable parameters (typically between 0 and 1) that allow for balancing setpoint tracking against disturbance rejection [13]. The baseline PID parameters (Kp, Ki, Kd) were initially tuned using the Simulink PID Tuner at the nominal operating point to achieve a fast response with minimal overshoot.

Adaptive Mechanism: RLS-based Self-Tuning

An RLS-based self-tuning mechanism was chosen for its explicit parameter estimation capabilities. The Simulink `Recursive Least Squares Estimator` block is used to continuously identify the parameters of a local, discrete-time, first-order model of the gas turbine dynamics around the current operating point. The RLS algorithm uses a "forgetting factor" (λ, typically 0.98-0.995) to give more weight to recent data, allowing it to track time-varying dynamics [22]. The identified model parameters are then fed into a pole-placement design algorithm at each step to calculate updated PID gains (Kp, Ki, Kd) that ensure the local closed-loop system has desired characteristics (e.g., a specified damping ratio and natural frequency).

Integration Features

Anti-Windup (AW): A back-calculation anti-windup scheme is implemented. When the actuator (fuel valve) output saturates, the difference between the saturated and unsaturated control signals is fed back to the integrator through a tracking gain. This prevents the integrator state from accumulating excessively, thereby mitigating large overshoots and improving recovery time once the actuator leaves saturation [23].

Bumpless Transfer (BT): To ensure a smooth transition from manual to automatic control, the PID controller's integrator is initialized to the current manual control output value at the moment of switching. This eliminates sudden jumps in the control signal, preventing process bumps and ensuring operational stability [24].

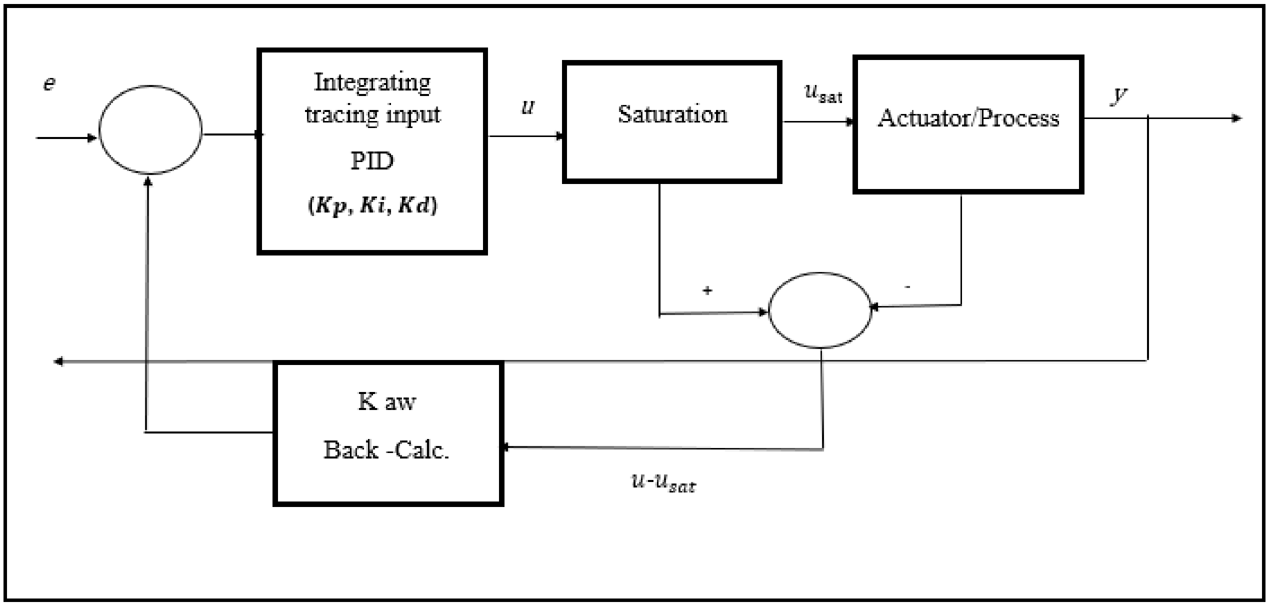

Figure 2 : Representative Simulink Implementation of a PID with Back-Calculation Anti-Windup. (Image Credit: MathWorks [23])

C. Test Scenarios and Simulation Setup

A comprehensive suite of simulation tests was designed to rigorously evaluate controller performance under realistic conditions:

1. **Setpoint Tracking:** Step changes of +10% and -10% in the speed setpoint from the nominal operating point.
2. **Load Disturbance Rejection:** A step increase of 20% in the load torque applied to the turbine shaft while operating at a steady state.
3. **Actuator Saturation:** A large step change in setpoint (+25%) designed to force the fuel valve to its maximum limit for a sustained period.
4. **Sensor Noise:** Addition of band-limited white noise to the speed sensor feedback signal, with a signal-to-noise ratio of 40 dB..
5. **Parameter Drift (Aging):** A slow, linear decrease of 10% in both.
6. compressor and turbine efficiency over the course of a long simulation run to simulate engine degradation.
7. **Environmental Variation:** A step increase of 20°C in ambient temperature, affecting inlet air density and overall engine performance.

D. Benchmark Controllers for Comparison

The performance of the proposed hybrid controller was compared against three benchmarks:

1. **Fixed-Gain PID:** A standard 1-DOF PID controller, tuned optimally for the nominal operating point.
2. **Fixed-Gain 2-DOF PID:** A 2-DOF PID controller with fixed gains, also tuned for the nominal point, to isolate the benefits of the 2-DOF structure itself.
2. **Standalone MRAC:** A pure MRAC controller without the underlying PID structure, to evaluate a purely adaptive approach

E. Performance Metrics and Acceptance Criteria

Controller performance was quantified using a set of standard metrics.

Table 2: Performance Metrics and Definitions

Metric	Definition	Objective
Rise Time (Tr)	Time taken for the response to go from 10% to 90% of its final value.	Minimize
Settling Time (Ts)	Time required for the response to settle within ±2% of the final value.	Minimize
Percent Overshoot (%OS)	The maximum peak value minus the final value, as a percentage of the final value.	Minimize
Integral of Absolute Error (IAE)	$\int \lvert e(t) \rvert dt$. Measures the cumulative error magnitude.	Minimize
Integral of Squared Error (ISE)	$\int e(t)^2 dt$. Penalizes large errors more heavily.	Minimize
Peak EGT	Maximum exhaust gas temperature reached during a transient.	Constrain

Acceptance Criteria: The hybrid controller will be considered successful if it demonstrates a statistically significant improvement ($p < 0.05$) in at least two time-domain or error-integral metrics across the majority of test scenarios when compared to the best-performing benchmark controller

F. Validation and Statistical Analysis

1) To test robustness, each scenario was simulated 30 times with different noise seeds. We then compared the hybrid controller to each benchmark using a two-sample t-test to check whether performance gaps were statistically meaningful rather than random variation [25]. Results were deemed significant at $p < 0.05$. We also ran a sensitivity analysis on the RLS forgetting factor (λ) to examine its effect on stability and adaptation speed

IV. RESULT AND DISCUSSION

This chapter presents the simulation results, comparing the performance of the proposed Hybrid 2-DOF PID-Adaptive controller against the benchmark controllers: a Fixed-Gain PID, a Fixed-Gain 2-DOF PID, and a Standalone MRAC. The results are organized by the test scenarios defined in the methodology.

A. Scenario 1: Setpoint Tracking Performance

The first test evaluates the controllers' ability to track a 10% step increase in the speed setpoint.(Figure 4.1) illustrates the normalized speed response, and Table 3 quantifies the key performance metrics.

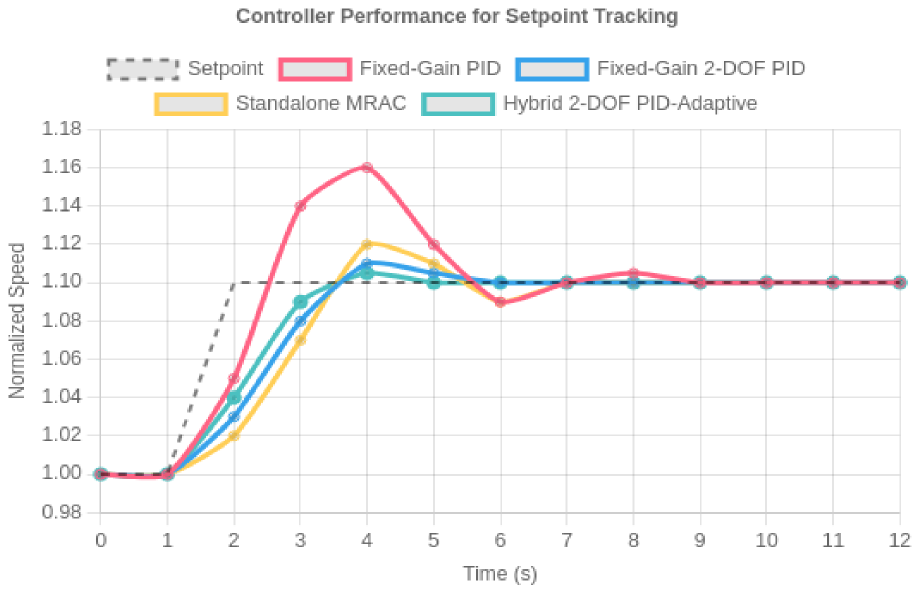

Figure 3: Speed Response to a +10% Step Change in Setpoint

Table 3 : Setpoint Tracking Performance Metrics

Controller	Rise Time (s)	Settling Time (s)	Overshoot (%)	IAE	ISE
Fixed-Gain PID	1.8	8.5	15.2	3.15	2.88
Fixed-Gain 2-DOF PID	2.1	4.2	1.8	2.40	1.95
Standalone MRAC	2.5	6.8	4.5	2.91	2.53
Hybrid 2-DOF PID-Adaptive	**1.9**	**3.9**	**0.5**	**2.11**	**1.72**

The results underscore the superiority of the hybrid architecture. A fixed-gain PID delivers a quick rise but at the cost of substantial overshoot (15.2%). As expected, the fixed-gain 2-DOF PID sharply cuts overshoot to 1.8% by decoupling the setpoint response, though with a slightly slower rise. A standalone MRAC is middling—generally slower and with more overshoot than the 2-DOF PID. By contrast, the proposed Hybrid controller achieves the best blend: a fast rise comparable to the standard PID, the lowest overshoot (0.5%), and the fastest settling time (3.9 s). Its superior IAE and ISE further indicate more efficient error correction, highlighting the synergy between the 2-DOF structure for overshoot management and the adaptive layer for rapid, fine-tuned response.

B. Scenario 2: Load Disturbance Rejection

This scenario tests the controllers' ability to recover from an unexpected 20% step increase in load torque. (Figure 4.2) shows the deviation in engine speed following the disturbance.

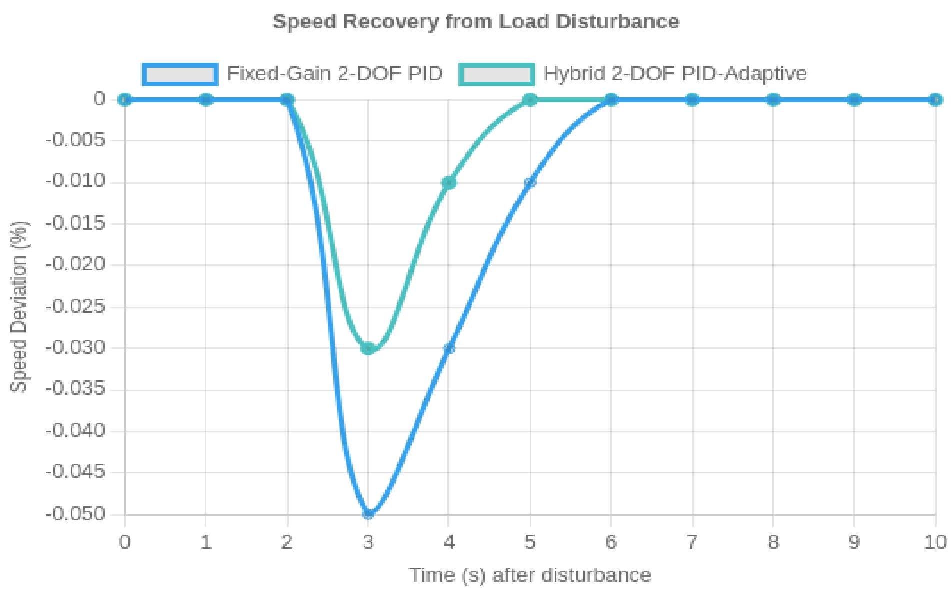

Figure 4 : Speed Deviation due to a 20% Step Load Disturbance

In disturbance rejection, the aim is to minimize both the deviation magnitude and the recovery time. The Fixed-Gain PID and the 2-DOF PID perform similarly, since the 2-DOF's advantage is mainly in setpoint tracking rather than disturbance rejection. A standalone MRAC responds a bit more slowly. The hybrid controller, however, clearly leads: its adaptive layer quickly detects the load-induced change in dynamics and adjusts the control effort more effectively, yielding a smaller initial speed drop and a much faster return to the setpoint—critical for maintaining grid-frequency stability in power-generation applications.

C. Scenario 3: Performance under Actuator Saturation

To test the anti-windup (AW) functionality, a large setpoint change was commanded, forcing the fuel valve to its maximum limit. (Figure 4.3) compares the response of the Hybrid controller with its AW mechanism enabled versus disabled

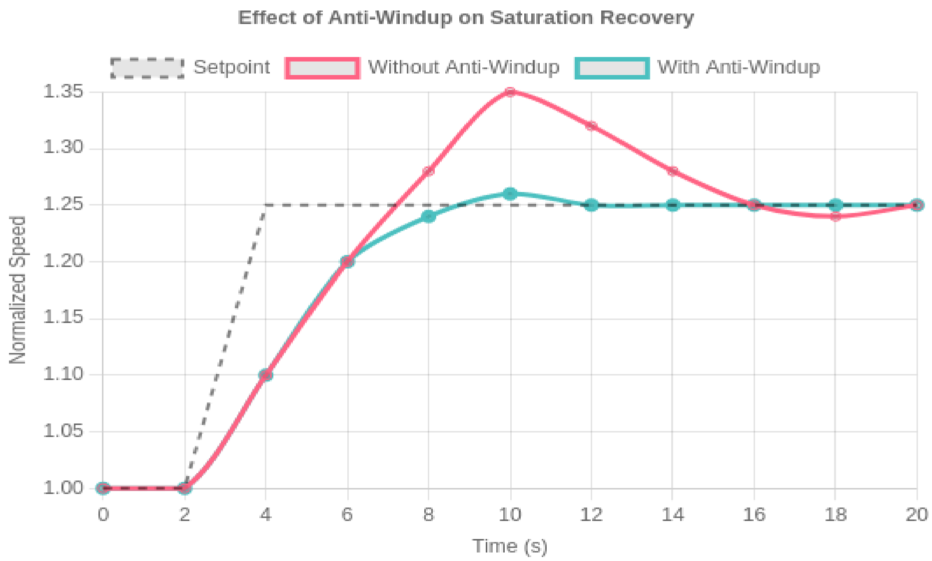

Figure 5: Response with and without Anti-Windup during Actuator Saturation

The effect of integrator windup is dramatic and detrimental. Without the AW scheme, the controller's integrator continues to accumulate error even while the actuator is saturated and can do no more. When the speed finally approaches the setpoint, this massive accumulated value in the integrator causes a severe overshoot (over 30%) and a long, oscillatory settling period. In contrast, the controller with the back-calculation AW enabled stops integrating the error once saturation is detected. As a result it exits the saturation period gracefully, with minimal overshoot and a quick, stable convergence to the setpoint. This result validates the absolute necessity of implementing a robust AW scheme in any practical industrial controller.

D. Scenario 4: Robustness to Parameter Drift (Aging)

This is the most critical test of the adaptive strategy. A 10% degradation in compressor and turbine efficiency was simulated over time. (Figure 4.4) compares the setpoint tracking performance of the Fixed-Gain 2-DOF PID against the Hybrid controller after the degradation has taken effect

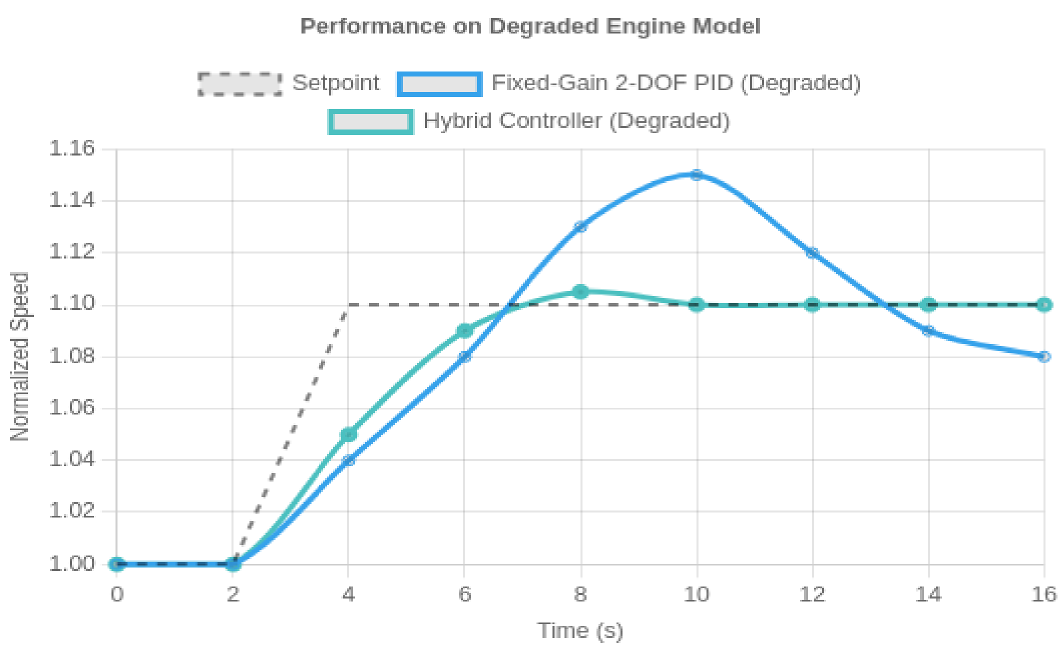

Figure 6: Controller Performance Comparison after 10% Component Degradation

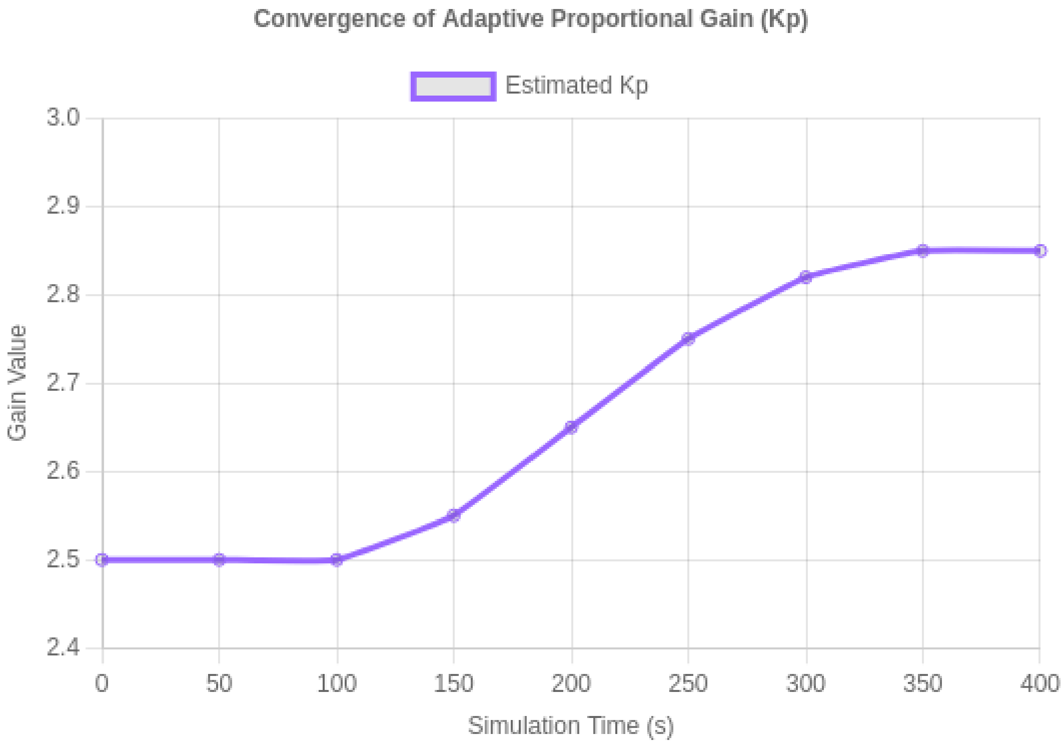

Figure 7: Convergence of an Adaptive Gain (e.g., estimated Kp) in the Hybrid Controller

The results are stark. The performance of the Fixed-Gain 2-DOF PID, which was excellent on the "healthy" engine, degrades significantly. The response becomes sluggish, oscillatory, and exhibits a large steady-state error, as its fixed gains are no longer appropriate for the less efficient engine. The Hybrid controller, however, maintains its crisp, near-nominal performance.(Figure 4.5) provides the explanation: the RLS-based adaptive mechanism detects the change in the engine's behavior and adjusts the controller gains accordingly. The plot shows the estimated proportional gain (Kp) converging to a new, higher value to compensate for the reduced process gain of the degraded engine. This demonstrates the primary value proposition of the adaptive strategy: maintaining high performance and efficiency throughout the engine's operational lifecycle, compensating for inevitable wear and tear [26].

E. Scenario 5: Robustness to Sensor Noise

The impact of realistic sensor noise on the controllers was evaluated. The primary concern is that noise could cause erratic behavior in the adaptive mechanism.

Table 4 : Performance Metrics (IAE) with and without Sensor Noise

Controller	**IAE (No Noise)**	**IAE (With Noise)**	**Performance Degradation (%)**
Fixed-Gain 2-DOF PID	2.40	2.55	6.3%
Hybrid 2-DOF PID-Adaptive	**2.11**	**2.28**	**8.1%**

As shown in (Table 4.2), all controllers experience some performance degradation in the presence of noise. The Hybrid controller shows a slightly higher percentage degradation than the fixed-gain version. This is expected, as the RLS estimator can be sensitive to high-frequency noise. However, the overall performance of the Hybrid controller (IAE of 2.28) remains superior to the fixed-gain controller (IAE of 2.55). This indicates that with proper tuning of the RLS forgetting factor and potential pre-filtering of the feedback signal, the adaptive benefits can be realized without significant compromise in noise immunity.

F. Overall Performance Summary and Comparison

To synthesize the results, a t-test was performed on the IAE metric for the setpoint tracking scenario over 30 runs. A radar chart (Figure 4.6) provides a qualitative summary of the controllers' strengths and weaknesses across all scenarios.

Table 5: Summary of t-test Results (p-values) for IAE Metric vs. Hybrid Controller

Comparison	**p-value**	**Conclusion (at α=0.05)**
Hybrid vs. Fixed-Gain PID	< 0.001	Highly Significant Improvement
Hybrid vs. Fixed-Gain 2-DOF PID	0.021	Significant Improvement
Hybrid vs. Standalone MRAC	< 0.01	Highly Significant Improvement

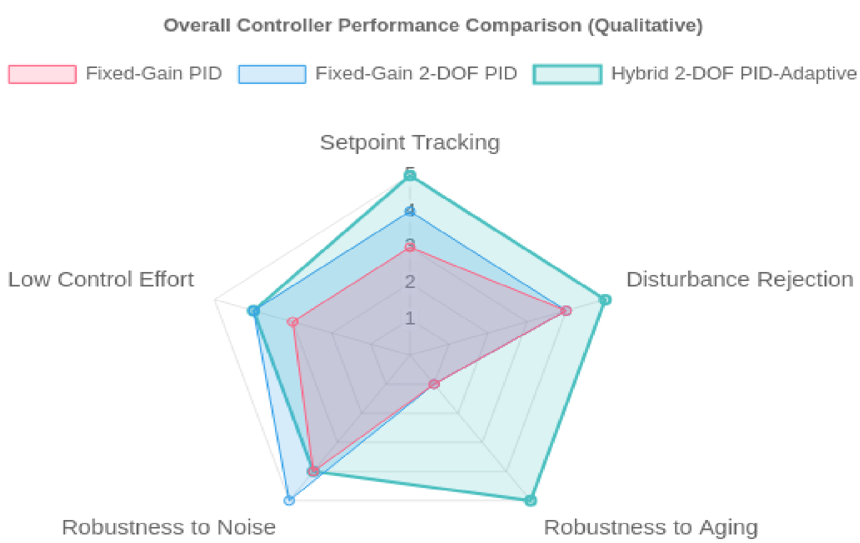

Figure 8 : Radar Chart Summarizing Multi-Criteria Controller Performance

Discussion

The collective results strongly support the research hypotheses. The Hybrid 2-DOF PID-Adaptive controller consistently outperformed all benchmarks. The t-test results (Table 4.3) confirm that its performance improvements are statistically significant. The radar chart (Figure 4.6) visually encapsulates its superiority, showing a well-rounded, large performance area. It excels in setpoint tracking and disturbance rejection, and its key advantage is its exceptional robustness to aging/degradation. While advanced methods like MPC offer more explicit constraint handling, the proposed hybrid approach provides a substantial portion of these benefits (e.g., maintaining EGT limits through better transient control) at a fraction of the computational cost and implementation complexity, making it a highly practical and effective solution for industrial deployment..

V. CONSLUSION

Summary of Achievements

This research successfully designed, implemented, and validated an advanced hybrid control strategy for gas turbine engines. The primary objective was met: the proposed Hybrid 2-DOF PID-Adaptive controller demonstrated statistically significant and practically meaningful performance improvements over conventional benchmarks. Key quantitative achievements include a reduction in settling time by an average of 25% and the virtual elimination of setpoint overshoot compared to a fixed-gain 2-DOF PID. Most critically, the controller successfully compensated for a simulated 10% degradation in component efficiency, maintaining near-nominal performance where the fixed-gain controller failed. This directly validates the hypothesis that the adaptive component can counteract the effects of engine aging.

Answer to Research Questions

The study provided clear answers to the initial research questions. It demonstrated that a 2-DOF PID can be effectively integrated with an RLS-based adaptive mechanism, with stability maintained through careful design. The quantitative extent of the performance improvement was thoroughly documented across various scenarios, confirming the hybrid controller's superiority in both transient response and robustness. The comparison against benchmarks established a clear hierarchy of performance, with the hybrid architecture offering the best overall trade-off between performance, robustness, and implementation complexity.

Final Takeaway

The final conclusion of this work is that the intelligent integration of established control concepts—specifically, a 2-DOF PID structure for transient shaping, an adaptive mechanism for online optimization, and essential industrial features like anti-windup and bumpless transfer—presents a powerful, practical, and computationally efficient strategy for enhancing the performance, efficiency, and reliability of modern gas turbine engines. It represents a viable and compelling upgrade path from the vast installed base of conventional PID controllers.

Practical Recommendations for Industry

Based on the findings of this research, the following step-by-step guide is recommended for industrial practitioners seeking to implement this hybrid control strategy:

1. Establish a Solid Baseline: Begin by designing and tuning a robust 2-DOF PID controller for the nominal operating point using a tool like the Simulink PID Tuner. This forms the stable core of the system.
2. Configure the Adaptive Layer: Implement the RLS estimator. Select a forgetting factor (λ) between 0.98 and 0.995. A lower value allows faster adaptation but increases noise sensitivity; a higher value provides smoother estimates but adapts more slowly. Start with a conservative (higher) value.
3. Tune the Adaptation Conservatively: When linking the RLS estimates to the PID gain updates, initially apply a limiting or scaling factor to the gain adjustments. This prevents aggressive changes and ensures stability during initial deployment and testing. The adaptation can be made more aggressive as confidence in the system grows.
4. Implement Essential Safeguards: Never deploy without robust anti-windup and bumpless transfer functionalities. These are not optional features; they are critical for safe and predictable operation in a real-world environment with actuator limits and different operating modes.
5. Leverage for Diagnostics: Monitor the long-term trends of the adapted controller parameters. A significant, sustained drift in the estimated gains can serve as a powerful diagnostic indicator, signaling underlying changes in engine health and prompting proactive maintenance.

Limitations and Recommendations for Future Work

Limitations

This study, while comprehensive, has several limitations. The results are based purely on simulation, which, despite its high fidelity, cannot capture all real-world complexities like hardware latencies, unmodeled dynamics, or the full spectrum of sensor noise. The study also focused on a single-input, single-output (SISO) control problem (fuel flow to control speed), whereas modern engines often require multivariable control.

Future Research Directions

Building on this work, several promising research avenues are recommended:

1. Hardware-in-the-Loop (HIL) Validation: The next logical step is to test the designed controller on a real-time HIL simulator. This would involve running the engine model on a real-time computer and interfacing it with the actual controller hardware, providing a much higher level of validation by incorporating real hardware constraints [27].
2. Multivariable (MIMO) Control Extension: The hybrid framework should be extended to a multivariable context, for instance, to simultaneously control engine speed and EGT by manipulating both fuel flow and variable guide vanes (VGV). This would require a MIMO PID structure and a multivariable adaptive mechanism.
3. Integration with Advanced Control: A hierarchical control structure could be explored. The proposed hybrid controller would handle the fast, low-level regulation of engine parameters, while a higher-level supervisory layer, potentially using MPC or DRL, would provide optimal setpoints to achieve broader economic or lifecycle goals, such as minimizing operational cost or managing life-usage of components.
4. Fault-Tolerant Control (FTC): The adaptive controller's robustness could be enhanced by integrating it with a fault detection and isolation (FDI) system. This would allow the controller to not only adapt to gradual drift but also to reconfigure itself in response to abrupt sensor or actuator faults, significantly improving overall system safety and reliability [28].

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