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Comparison of PID Coefficients Determination Methods for Aircraft Pitch Angle Control

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ABSTRACT

For aircraft to perform a stable flight, dynamic stability must be ensured during the design phase. Different linear and non-linear control methods are used to ensure that this stability is not disturbed and the necessary maneuvers can be performed. Aircraft is a dynamic system with 6 degrees of freedom and each control surface should be considered when designing control systems. In this study, the pitch angle of an aircraft is controlled using 4 different methods found in the literature. In this study, the linearized longitudinal equations of motion of the aircraft selected for control were extracted and transfer functions were obtained. The methods designated were used to calculate the coefficients of the PID controller and the calculations and modeling were done through MATLAB/Simulink. The methods used in the study are mainly as follows: Ziegler-Nichols, Modified Ziegler-Nichols, Tyreus-Luyben, Astrom and Hagglund. The study aims to determine the best-performing method among these 4 methods for controlling the pitch angle of the aircraft. Comparisons were made on the graphs and tables obtained for the study and the best-performing method was determined.

PID Katsayılarını Belirleme Metotlarının Uçak Yunuslama Açısı Kontrolü için Kıyaslaması

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Tyreus-Luyben,
Uzunlamasına Hareket,
Yunuslama Açısı,
Ziegler-Nichols.

ÖZET

Hava araçlarının kararlı bir uçuş sergileyebilmesi için tasarım aşamasında dinamik kararlılığın sağlanmış olması gerekmektedir. Seyir halinde bu kararlılığın bozulmaması ve gerekli manevraların yapılabilmesi için doğrusal ve doğrusal olmayan farklı kontrol yöntemleri kullanılmaktadır. Uçak dinamik olarak 6 serbestlik derecesine sahip bir sistem olup kontrol sistemleri tasarlanırken her bir kontrol yüzeyi göz önünde bulundurulmalıdır. Bu çalışmada, bir hava aracının yunuslama açısının kontrolü literatürde bulunan 4 farklı metot kullanılarak yapılmıştır. Çalışmada kontrolü yapılmak üzere seçilen hava aracının doğrusallaştırılmış uzunlamasına hareket denklemleri çıkarılmış ve transfer fonksiyonları elde edilmiştir. Belirtilen metotlar PID kontrolcüsünün katsayılarını hesaplamak için kullanılmış olup yapılan hesaplamalar ve modellemeler MATLAB/Simulink ortamında test edilmiştir. Çalışmada kullanılan metotlar şunlardır: Ziegler-Nichols, Modifiye Edilmiş Ziegler-Nichols, Tyreus-Luyben ve Astrom ve Hagglund. Çalışmanın amacı kullanılan bu 4 metot arasından hava aracının yunuslama açısının kontrolü için en iyi performans göstereni belirlemektir. Çalışma amacı doğrultusunda elde edilen grafikler ve tablolar üzerinden karşılaştırmalar yapılmış ve en iyi performans gösteren metot belirlenmiştir.

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INTRODUCTION

For aircraft to perform a stable flight, dynamic stability must be ensured during the design phase (Nelson, 1998). Different linear and nonlinear control methods are used to maintain this stability and to perform the necessary maneuvers. In the early years of aviation, the control operations carried out by the aircraft crews were started to be carried out by control methods such as PID, which were developed later (Keane, & Carr, 2013).

Aircraft is a dynamic system with 6 degrees of freedom and each control surface should be considered when designing control systems (Stevens et al., 2015). For this reason, there are many different control studies in the literature due to the complexity of the system. When the literature is examined, it is seen that the PID control method gives agreeable results for UAVs (Ahmed et al., 2019; Durmaz et al., 2013). Determining the control coefficients is of great importance in PID control design, thus determining the system's stability. It is seen from the literature that the Ziegler-Nichols method performs well in determining the PID control coefficients (Ahmed et al., 2019; Ulus & Ikbal, 2019).

Different control approaches have been used in the literature to improve the performance of aircraft systems (Dhadekar & Talole, 2018; Hušek & Narenathreyas, 2016). PID and fuzzy controllers have been investigated for longitudinal control of aircraft and different combinations of these two controllers (Mamdani tuned PID, PID, Takagi-Sugeno, Parallel Distributed Controller (PDC)) have been tested (Narenathreyas, 2013). The results show that nonlinear controllers such as fuzzy control give better results than linear controllers, but the computational load is higher and stability cannot be guaranteed (Narenathreyas, 2013; Öztürk & Özkol, 2021). In addition, since the fuzzy-PID control structure does not show the desired performance improvement, the fuzzy-PID control structure trained by the genetic algorithm has been tested and new methods with better control performances have been proposed (Tang et al., 2001). However, this has made the controllers more complex and computationally demanding.

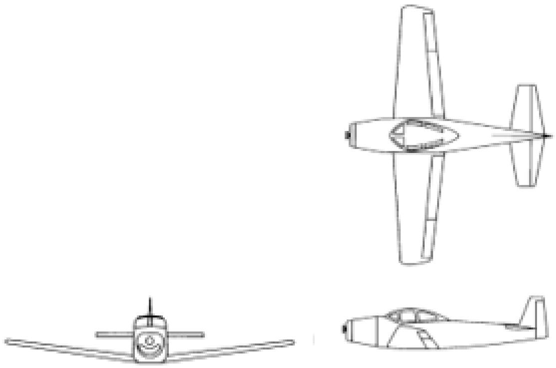
For the control of aircraft, the use of robust and PID control structures is preferred both to reduce the computational load and to ensure the stability of the aircraft. Ziegler-Nichols (ZN), Modified Ziegler-Nichols (MZN), Tyreus-Luyben (TL), and Astrom-Hagglund (AH) methods were compared to determine the PID coefficients used in longitudinal motion control of aircraft and was observed that the Modified Ziegler-Nichols (MZN) method performed the best (Deepa & Sudha, 2016).

Within the scope of this study, the control methods for the longitudinal motion of aircraft were reviewed in the literature (Rosario-Gabriel & Cortés, 2018) and the Ziegler-Nichols methods available in the literature were tested and compared for pitch angle control of the NAVION aircraft.

METHOD

The data used in the system analysis and modeling in this study are from General Aviation Airplane: NAVION at sea level and M=0.158. The calculated motion derivatives of the airplane under the given conditions are used to control the longitudinal motion. The state space representations of the linearized longitudinal equations of motion of the aircraft with 6 degrees of freedom are given below. In addition, the geometrical data of the airplane used in this study and the stability parameters of the longitudinal motion derivatives are shown in the table below.

Figure 1
General Aviation Airplane: NAVION (Nelson, 1998)



State-space representations:

$$\dot{x} = Ax + B\eta \quad (1)$$

State space representation for longitudinal motion;

$$\begin{bmatrix}\Delta\dot{u}\\ \Delta\dot{w}\\ \Delta\dot{q}\\ \Delta\dot{\theta}\end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & u_0 & 0 \\ M_u + M_{\dot{w}}Z_u & M_w + M_{\dot{w}}Z_w & M_q + M_{\dot{w}}u_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix}\Delta u\\ \Delta w\\ \Delta q\\ \Delta\theta\end{bmatrix} + \begin{bmatrix} X_\delta & X_{\delta_T} \\ Z_\delta & Z_{\delta_T} \\ M_\delta + M_{\dot{w}}Z_\delta & M_{\delta_T} + M_{\dot{w}}Z_{\delta_T} \\ 0 & 0 \end{bmatrix}\begin{bmatrix}\Delta\delta_e\\ \Delta\delta_T\end{bmatrix} \quad (2)$$

$$\begin{bmatrix}\Delta\dot{u}\\ \Delta\dot{w}\\ \Delta\dot{q}\\ \Delta\dot{\theta}\end{bmatrix} = \begin{bmatrix} -0.09148 & 0.04242 & 0 & -32.17 \\ 10.51 & -3.066 & 152 & 0 \\ 0.2054 & -0.05581 & -2.114 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix}\Delta u\\ \Delta w\\ \Delta q\\ \Delta\theta\end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -12.64 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix}\Delta\delta_e\\ \Delta\delta_T\end{bmatrix} \quad (3)$$

Table 1
General Aviation Airplane: NAVION (Nelson, 1998)

Dynamic Pressure, Weight, Reference Geometry and Mass Characteristics:		
$(Dynamic\ Pressure)\ Q = 1190\frac{lb}{ft^2}$	$(Weight)\ W = 2750\ lbs$	
$(Wing\ Area)\ S = 184\ ft^2$	$(Wing\ Span) b = 33.4\ ft$	
$(Mean\ Chord)\ \bar{c} = 5.7\ ft$	$I_{xx} = 1048\ slug.ft^2$	
$I_{yy} = 3000\ slug.ft^2$	$I_{zz} = 3530\ slug.ft^2$	
Longitudinal Motion Derivatives (for M=0.158 and sea level)		
$C_L = 0.41$	$C_D = 0.05$	$C_{L_\alpha} = 4.44$
$C_{D_\alpha} = 0.33$	$C_{m_\alpha} = -0.683$	$C_{L_{\dot{\alpha}}} = 0.0$
$C_{m_{\dot{\alpha}}} = -4.36$	$C_{L_q} = 3.8$	$C_{m_q} = -9.96$

$C_{L_M} = 0.0$	$C_{D_M} = 0.0$	$C_{m_M} = 0.0$
$C_{L_{\delta_e}} = 0.355$	$C_{m_{\delta_e}} = -0.923$	

Pole graphs of short and long period movements are given below.

Figure 2
Short Period Motion Poles

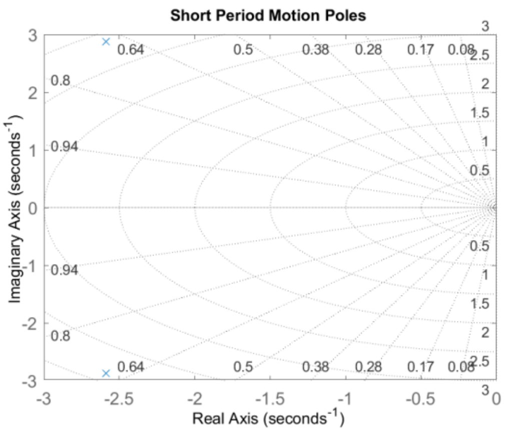


Figure 3
Long Period Motion Poles

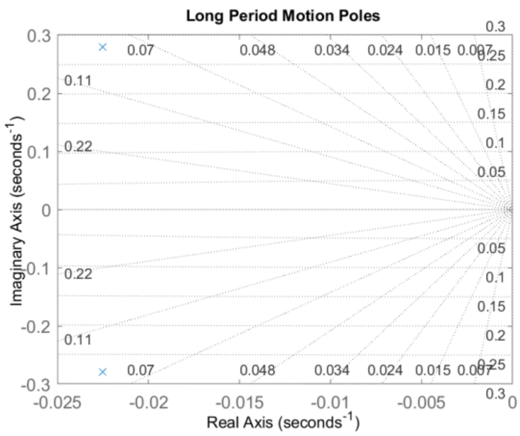


Table 2
Roots and Values for Short and Long Period Motions

Motion	Short Period	Long Period
Roots	$-2.59 \pm 2.87i$	$-0.0225 \pm 0.279i$
Damping ratio	0.67	0.0804
Frequency (rad/s)	3.87	0.28

Pitch Displacement Control

The transfer function of the rate of change of the pitch angle to the elevator deflection angle is given below by equation 4;

$$\frac{\Delta q(s)}{\Delta \delta_e(s)} = \frac{-12.64s - 38.75424}{s^2 + 5.18s + 14.96} \tag{4}$$

The transfer function used in the system design for the control of the pitch angle is given by the following equation;

$$\frac{\Delta \theta(s)}{\Delta \delta_e(s)} = \frac{1}{s}\frac{\Delta q(s)}{\Delta \delta_e(s)} = \frac{-12.64s - 38.75424}{s(s^2 + 5.18s + 14.96)} \tag{5}$$

Before adding the PID controller to the system, a motor transfer function was also added as $\left(-\frac{10}{s+10}\right)$ and the step input and root locus curve were generated. The results are given as graphics in Figure 3-4;

Figure 4
Short Period Motion Poles

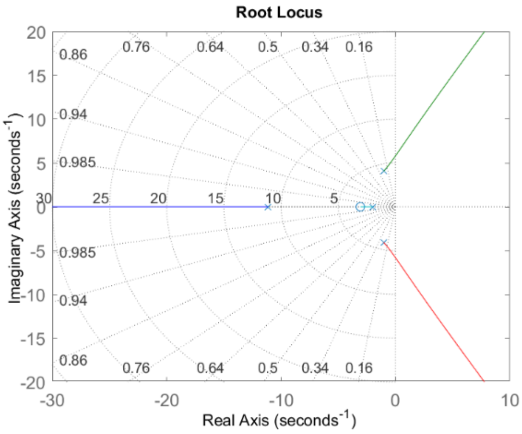
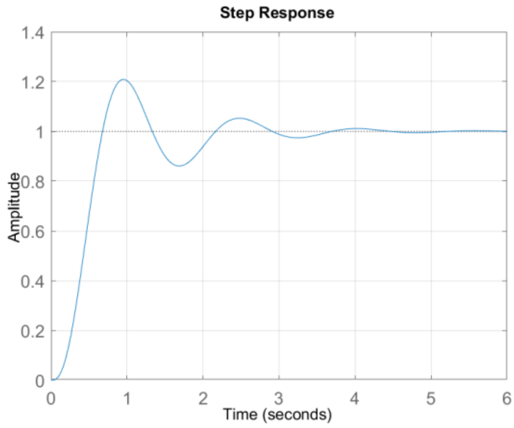


Figure 5
Long Period Motion Poles



In the next four subsections, the coefficients K_p, K_i, K_d of the PID controller added to the system are calculated separately by Ziegler Nichols, Modified Ziegler Nichols, Tyreus-Luyben, Astrom and Hagglund methods.

1. Ziegler-Nichols Method

K_p, K_i, K_d coefficients for the PID controller were calculated using the Ziegler-Nichols method in the following order (Deepa & Sudha, 2016):

1. Starting with a small value of K_p (in this study we started with a value of 1), coefficients K_i, K_d were taken as 0,
2. Increasing the K_p value little by little until neutral stability is achieved. At this stage, starting from a value of 1, K_p was increased until a neutrally stable graph was obtained, which was $K_p = 2.863$,
3. To record the critical $K_{p@neutral\ stability}$ value obtained in the previous stage as K_u and to record the oscillation period at this value as T_u. At this stage, the period was measured in several places on the graph obtained using Simulink, the average value of 1.079 was determined as T_u.
4. $$K_p = 0.6 \times K_u = 0.6 \times 2.863 = 1.718$$

$$T_i = \frac{T_u}{2} = 0.5395$$

$$T_d = \frac{T_u}{8} = 0.1349$$

the above values were calculated.

5.

$$K_i = \frac{K_p}{T_i} = 3.184$$

$$K_d = K_p \times T_d = 0.232$$

the above values were calculated.

By substituting the PID coefficients to be used for the pitch angle control designed in Simulink using the calculated coefficients, the following block diagram is obtained;

Figure 6
Block Diagram of the Control System Designed Using the Ziegler-Nichols Method

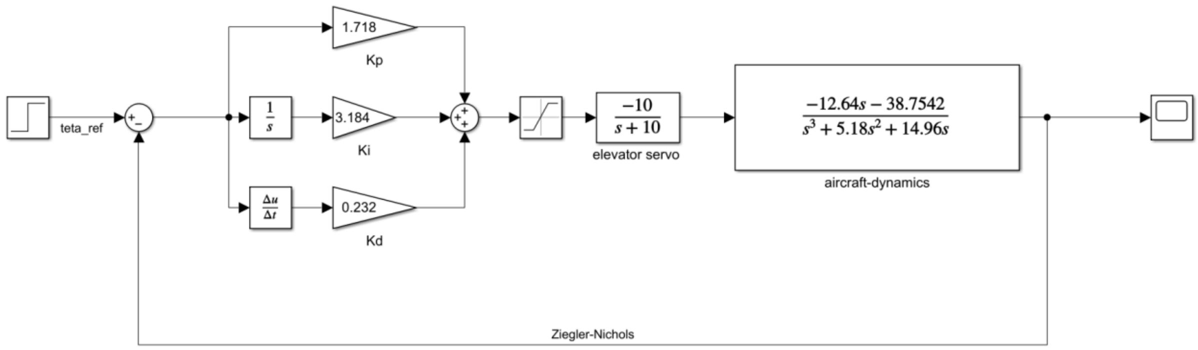
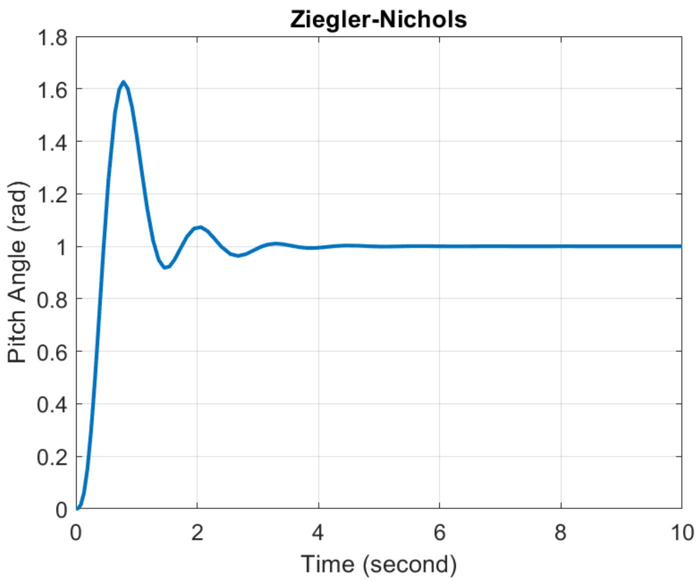


Figure 7
Step Response Graph for Ziegler-Nichols Method



2. Modified Ziegler-Nichols Method

When calculating the coefficients of the PID Controller with the Modified Ziegler Nichols Method, only the 4th and 5th steps change as given below;

$$K_p = 0.33 \times K_u = 0.33 \times 2.863 = 0.9405$$

$$T_i = \frac{T_u}{2} = \frac{1.084}{2} = 0.5395$$

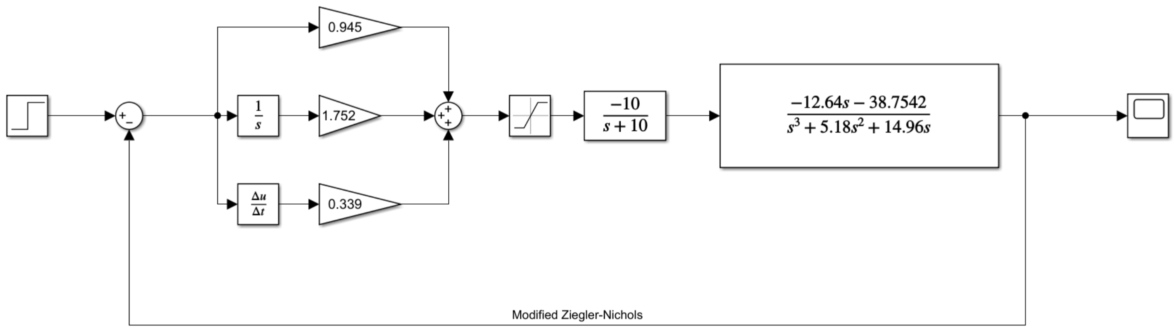
$$T_d = \frac{T_u}{3} = 0.359$$

$$K_i = \frac{K_p}{T_i} = 1.752$$

$$K_d = K_p \times T_d = 0.339$$

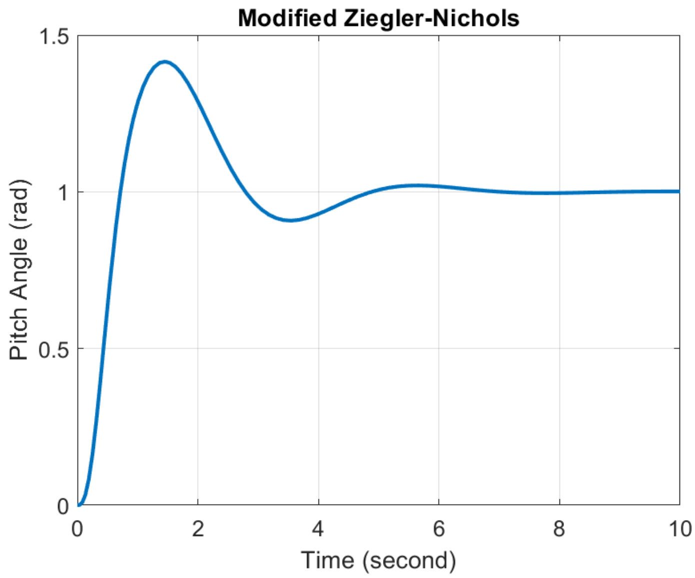
In this case, when the calculated coefficients are substituted for the PID coefficients to be used for the pitch angle control designed via Simulink, the block diagram obtained is as follows;

Figure 8
Block Diagram of the Control System Designed Using the Modified Ziegler-Nichols Method



The step response graph obtained in this case was obtained as follows.

Figure 9
Step Response Graph for the Modified Ziegler-Nichols Method



3. Tyreus-Luyben Method

When calculating the coefficients of the PID Controller with the Tyreus-Luyben Method, the 4th and 5th steps change as follows;

$$K_p = 0.45 \times K_u = 0.45 \times 2.863 = 1.288$$

$$T_i = 2.2 \times T_u = 2.374$$

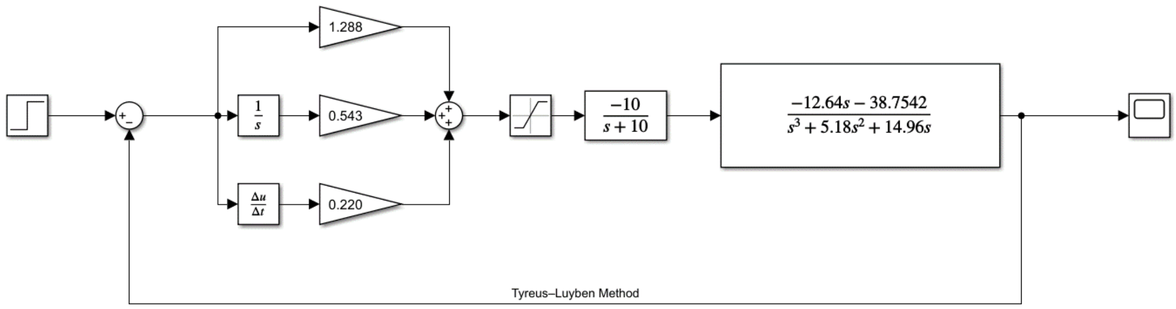
$$T_d = \frac{T_u}{6.3} = 0.171$$

$$K_i = \frac{K_p}{T_i} = 0.543$$

$$K_d = K_p \times T_d = 0.220$$

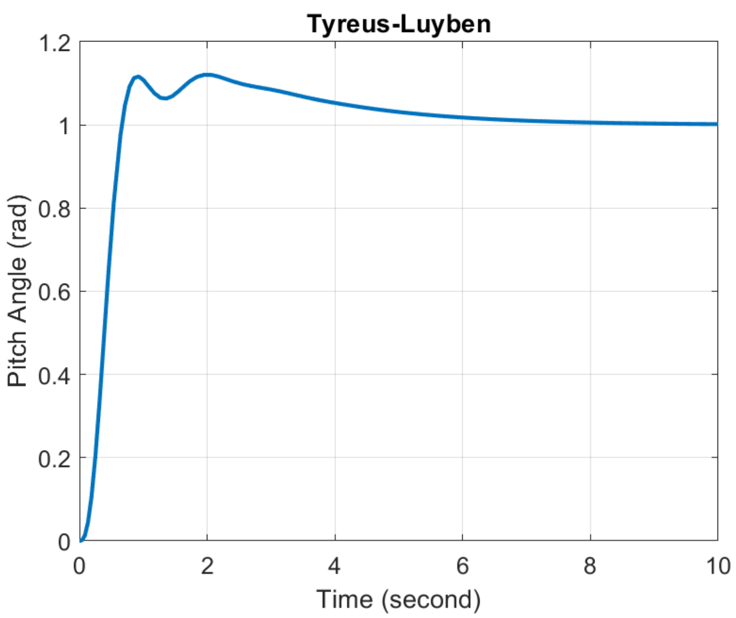
In this case, when the calculated coefficients are substituted for the PID coefficients to be used for the pitch angle control designed via Simulink, the block diagram obtained is as follows;

Figure 10
Control System Block Diagram Designed Using Tyreus-Luyben Method



The step response graph obtained in this case was obtained as follows;

Figure 11
Step Response Graph for Tyreus-Luyben Method



4. Astrom and Hagglund Method

When the coefficients of the controller are calculated by the Astrom and Hagglund Method, the 4th and 5th steps change as follows;

$$K_p = 0.32 \times K_u = 0.32 \times 2.863 = 0.916$$

$$K_i = 0.94$$

In this case, when the calculated coefficients are substituted for the PI coefficients to be used for the pitch angle control designed via Simulink, the block diagram obtained is as follows

Figure 12
Block Diagram of Control System Designed Using Astrom and Hagglund Method

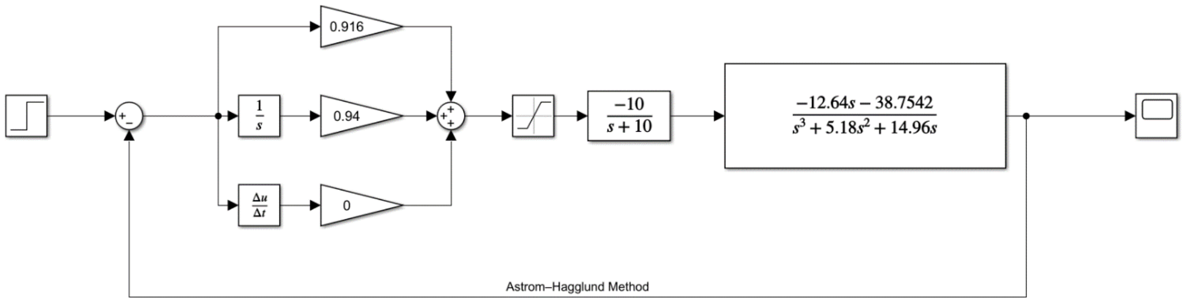
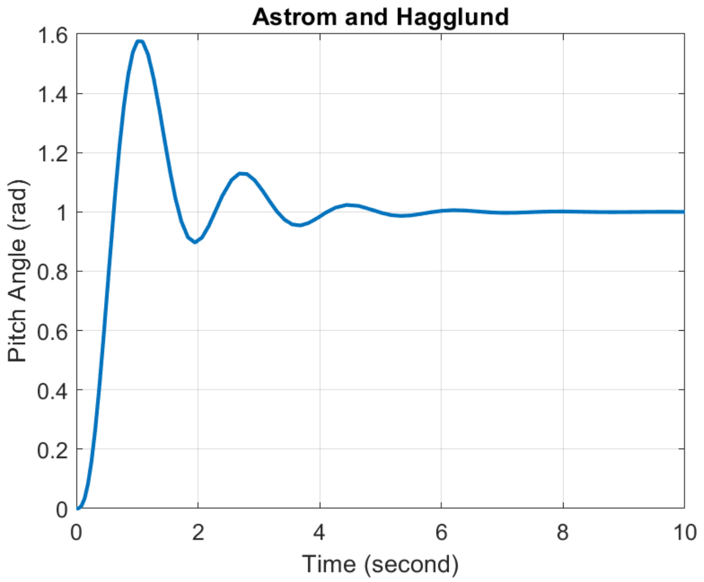


Figure 13
Step Response Graph for Astrom and Hagglund Method



RESULTS

In this study; 4 different methods proposed in the literature for determining PID control coefficients are analyzed. These methods were tested for the pitch angle control of the NAVION aircraft and the results are shown in Figure 13 and the control signals are shown in Figure 14.

When the results of the methods are analyzed, it is seen in Figure 13 that the traditional Ziegler-Nichols (ZN) method gives the fastest response but has the highest overshoot. The modified Ziegler-Nichols (MZN) method reacts slower than ZN, Astrom, and Hagglund (AH) and Tyreus-Luyben (TL) methods, but has less overshoot than ZN and AH methods.

Figure 14 shows that the control signals of the AH, MZN, and TL methods put less load on the motors compared to the conventional ZN method. Therefore, AH, MZN, and TL are the preferred methods for safer and smoother flights.

Figure 14
Step Response Graphs of Controlled Systems

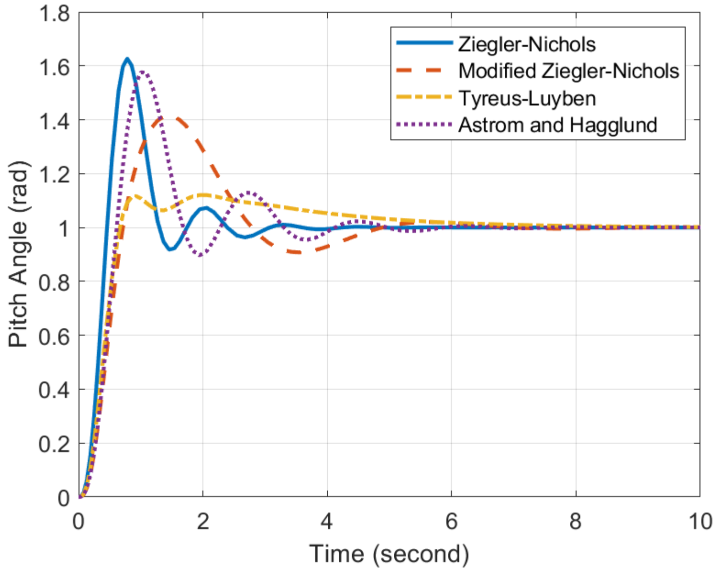
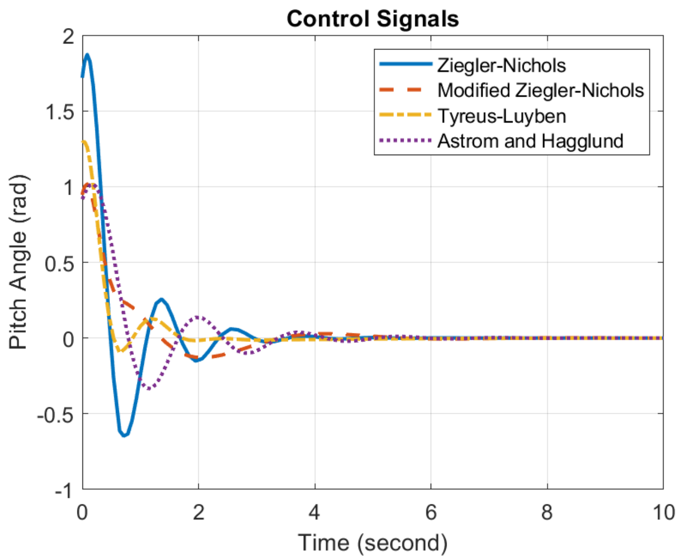


Figure 15
Controller Performance Graphs



Root Mean Square Error (RMSE) shows that all 4 methods give similar results. As can be seen in Table 3, the MZN method has a slightly lower RMSE value than AH and has fewer overshoots. The Tyreus-Luyben method has a lower RMSE and significantly fewer overshoots than the other methods.

Table 3
Parameters Before and After Control

Method	Rising Time (s)	Settling Time (s)	Overshoot (%)	RMSE
Ziegler-Nichols	0.2721	2.8918	62.6723	0.3940
Modified Ziegler-Nichols	0.4448	4.6044	41.3944	0.4111
Tyreus-Luyben	0.4107	5.6356	11.8418	0.3787
Astrom and Hagglund	0.3696	4.6417	57.5490	0.4136

CONCLUSION

When the step responses of the systems are analyzed, it can be said that the control system in which the PID coefficients are determined by the Tyreus-Luyben Method is more efficient since the overshoot is less, the error values are less than the other methods, and the steady state error is eliminated. In addition, when the control signals are analyzed, it is seen that the system is less loaded and the control signal oscillation is less. Since both the control signal and the results are better, Tyreus-Luyben performs better than the other methods.

Ethical Committee Approval

No human or animal subjects requiring ethical committee approval were used in this study. The research was conducted using publicly available data sets, literature reviews, or theoretical analyses. In accordance with ethical rules, full compliance with academic honesty and scientific ethical principles was maintained at every stage of the research process. Therefore, ethical committee approval was not required.

Author Contributions

Research Design (CRediT 1) Muhammet ÖZTÜRK (50%) – Saliha KÖPRÜCÜ (50%)

Veri Toplama (CRediT 2) Saliha KÖPRÜCÜ (60%) – Muhammet ÖZTÜRK (40%)

Research - Data Analysis - Validation (CRediT 3-4-6-11) Saliha KÖPRÜCÜ (80%) – Muhammet ÖZTÜRK (20%)

Writing of the Article (CRediT 12-13) Saliha KÖPRÜCÜ (80%) – Muhammet ÖZTÜRK (20%)

Text Revision and Improvement (CRediT 14) Saliha KÖPRÜCÜ (50%) – Muhammet ÖZTÜRK (50%)

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Conflict of Interest

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Sustainable Development Goals (SDG)

Sustainable Development Goals: 9 Industry, innovation and infrastructure

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