Original Research Article

Design and Simulation of Aircraft Pitch Control Using Matrix Transformation Techniques

ABSTRACT

Aircraft pitch control is very important in take-off and stabilization. This critical criterion exists because the pitch can cause the aircraft to be in turbulence if the aircraft's pitch control is not calibrated correctly. However, controlling this parameter is not an easy task and challenging to be solved. This research aims to design a controller used on aircraft pitches control using the matrix transformation technique. The proposed technique makes it possible to obtain linear state feedback control in an explicit form with the desired eigenvalue.Furthermore, the proposed technique can improve response time, stability, and handling various flight conditions compared to conventional PID. The proposed technique uses transformation matrix T to find the feedback gain matrix K.The controller is used to find out the response value by several experiments with fixed setpoints, changed setpoints, and by adding load to the system. Based on the results with a fixed setpoint, the system response has $0.47\ s$ time constant, and $0.39\ s$ delay time. The simulations show the system response can follow the setpoint well without any overshoot.

1. INTRODUCTION

For ensuring the safe operation of modern aviation, aircraft control systems are critical. One of the critical parameters that need accurate control is the aircraft's pitch[1][2]. The pitch control influences the aircraft's ability and keep a level flight. Conventional pitch control technique basically depends on classical control theories like Proportional-Integral-Derivative (PID) controller[3]. However, this technique may sometimes fall short when applied in complex aerodynamics, especially in modern aviation[4][5].

Along with the development of increasingly modern times, technology embedded in aircraft is also increasingly sophisticated [6][7]. Basically, an aircraft is regulated by elevator, rudder, and aileron. The elevator serves to regulate the pitch motion of the aircraft[8][9]. Basic control of the aircraft has 3 basic movements in determining the longitudinal stability of the plane including pitch and establishing lateral stability there roll, and yaw [10][11]. Pitch control is very important in take-off and stabilization when flying down. This critical criterion exists because the pitch can cause the aircraft in turbulence if the aircraft's pitch control is not calibrated correctly [12][13].

Overshooting issues are very important in some practical applications such as in the production process, which can result in damage to the product, another example is in aircraft [14]. The control system on the aircraft must have high precision control, which overshoot can risk the aircraft[15]. In the past few years, there have been many studies on the controller methods to reach an overshoot response to linear systems [16][17].

Digital control theory usually assumes the same sampling interval [18][19]. This research aims to design a controller that is used on aircraft pitches using the Ackerman formula. The Ackerman formula makes it possible to obtain linear state feedback control in an explicit form with the desired eigenvalue [20][21]. The Ackerman formula used determine of matrix

K using the matrix transformation method, it was chosen because the method used is quite simple and can produce the desired response[22][23].

This article consists of 5 parts. Part I contains the background of this research, the description of the problems to be studied, and the purpose of this research. Part II contains a mathematical model of the plant, which is a mathematical model of the aircraft pitch. Part III explains the control method proposed in the study. Part IV contains the implementation of the control method in the plant and its results. Part V contains conclusions from experiments that have been carried out.

2. MODELLING OF AIRCRAFT PITCH CONTROL

This section presents the mathematical model of the aircraft's pitch control system as a basis for simulations for the development of proposed control techniques. Aircraft are considered rigid objects, and their movements consist of small interference originating from external conditions [24][25]. The are two equations of an aircraft namely a lateral equation and a longitudinal equation. Figure 1 is the control system of the plane's pitch where X_b, Y_b, Z_b are the aerodynamic forces section and θ, Φ, δ_e are the pitch, roll and deflection angle of the elevator respectively [26][27].The aerodynamic moment component, angular velocity and velocity component are presented in Fig. 2. where L, M, N represent the roll, pitch and yaw. Analysis and modelling of the system are obtained by the General Aviation Airplane [28][29].
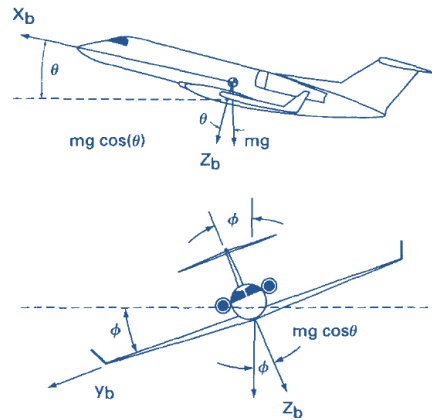

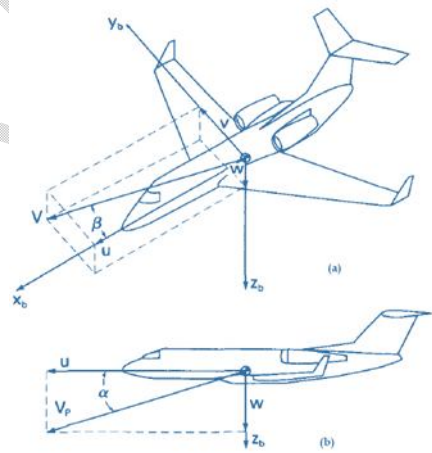**Fig. 1 Aircraft Pitch Control.**

Fig. 2 The components in body coordinate.

Several conditions must be considered for modelling. First, aircraft conditions must be stable at a constant speed and altitude, so that the thrust and resistance and weight balance cannot be considered. Second, there is no impact on the modification in pitch for aircraft speed. The dynamic equations of an aircraft are presented in (1), (2), and (3)[30].

$$X - mgS_\theta = m(\dot{u} + qv - rv) \tag{1}$$
$$Z + mgC_\theta C_\Phi = m(\dot{W} + pv - qu) \tag{2}$$

$$M = Iy\dot{q} + rq(Ix + Iz) + Ixz(p^2 - r^2) \tag{3}$$

The longitudinal parameters utilized in this paper are presented in Table 1[31].

TABLE 1. LONGITUDINAL PARAMETERS

Longitudinal Derivatives	Devices $Q = 36.8 lb/ft2; QS = 6771lb;$ $QS\bar{c} = 38596 ft.lb;, \bar{c}/2u0 = 0.016s$		
	X (S⁻¹)	Z (F⁻¹)	Pitching Moment (FT⁻¹)
Rolling Velocities	$X_u = -0.045$	$Z_u = -0.369$	$M_u = 0$
Yawing Velocities	$X_w = 0.03$	$Z_w = -2.02$ $Z_{\dot{w}} = 0$	$M_w = 0.05$ $M_{\dot{w}} = 0.051$
Angle of attack	$X_\alpha = 0$ $X_{\dot{\alpha}} = 0$	$Z_\alpha = -355.42$ $Z_{\dot{\alpha}} = 0$	$M_\alpha = -8.8$ $M_{\dot{\alpha}} = -0.8976$
Pitching rate	$X_q = 0$	$Z_q = 0$	$M_q = -2.05$
Elevator Deflection	$X\delta_e = 0$	$X\delta_e = -28.15$	$X\delta_e = -28.15$

Small disturbance can be applied to linearization in equations (1), (2), and (3). The formula is substituted by variables as follows.

$$u = u_0 + \Delta u; \; v = v_0 + \Delta v; \; w = w_0 + \Delta w$$
$$p = p_0 + \Delta p; \; q = q_0 + \Delta q; \; r = r_0 + \Delta r;$$
$$\delta = \delta_0 + \Delta\delta \tag{4}$$

This indicatesthat the expression $v_0 = p_0 = q_0 = r_0 = w_0 = 0$. Afterwards, using linearization the (5), (6) and (7) are as follows

$$\left(\frac{d}{dt} - Xu\right)\Delta u - X_w\Delta w + (g\cos\theta_0)\Delta\theta = X\delta_e\Delta\delta_e \tag{5}$$

$$-Z_u\Delta u + \left[(1 - Z_w)\frac{d}{dt} - Z_w\right]\Delta w - \left[(u0 + Z_q)\frac{d}{dt} - g\sin\theta_0\right]\Delta\theta = Z_{\delta e}\Delta\delta_e \tag{6}$$

$$-M_u\Delta u - \left(M_w\frac{d}{dt} + M_w\right)\Delta w + \left(\frac{d^2}{dt^2} - M_q\frac{d}{dt}\right)\Delta\theta = M_{\delta e}\Delta\delta_e \tag{7}$$

By manipulating and substituting longitudinal stability parameter values derived from table 1, the following transfer function for the transformation is presented in (8).

$$\frac{\Delta q(s)}{\Delta\delta_e(s)} = \frac{-\left(M_{\delta e} + \frac{M_{\dot{\alpha}}Z_{\delta e}}{U_0}\right)s - \left(\frac{M_\alpha Z_{\delta e}}{u_0} - \frac{M_{\delta e}Z_\alpha}{u_0}\right)}{s^2 - \left(M_q + M_{\dot{\alpha}} + \frac{Z_\alpha}{u_0}\right) + \left(\frac{Z_\alpha M_q}{u_0} - M_\alpha\right)} \tag{8}$$

The expression of pitch angle deviation to elevator angle deviation is obtained through the pitch rates change to elevator angle change.

$$\Delta q = \Delta\dot{\theta} \tag{9}$$
$$\Delta q(s) = s\Delta\theta(s) \tag{10}$$
$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s} * \frac{\Delta q(s)}{\Delta\theta(s)} \tag{11}$$

Therefore, the expression of the aircraft pitch control system is shown as follows.

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s} * \frac{-\left(M_{\delta e} + \frac{M_{\dot{\alpha}}Z_{\delta e}}{u_0}\right)s - \left(\frac{M_\alpha Z_{\delta e}}{u_0} - \frac{M_{\delta e}Z_\alpha}{u0}\right)}{s^2 - \left(M_q + M_{\dot{\alpha}} + \frac{Z_\alpha}{u_0}\right) + \left(\frac{Z_\alpha M_q}{u_0} - M\alpha\right)} \tag{12}$$

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{11.7304s + 22.578}{s^3 + 4.9676s2 + 12.941s} \tag{13}$$

The expression ischanged to the state space form as follows.

$$\begin{bmatrix} \Delta\dot{\alpha} \\ \Delta\dot{q} \\ \Delta\dot{\theta} \end{bmatrix} = \begin{bmatrix} -2.02 & 1 & 0 \\ -6.9868 & -2.9476 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta\alpha \\ \Delta q \\ \Delta\theta \end{bmatrix} + \begin{bmatrix} 0.16 \\ 11.7304 \\ 0 \end{bmatrix} [\Delta\delta_e] \tag{14}$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta\alpha \\ \Delta q \\ \Delta\theta \end{bmatrix} + [0] \tag{15}$$

3. TRANSFORMATION MATRIX T

In this paper, matrix K feedback method is used to regulate the pitch angle. Transformation matrix T is one of the methods used to find the feedback gain matrix K. This method is selected because it can provide good results on a system. In general, finding the feedback matrix K using transformation matrix T is done in foursteps. The first step is checking the system controllability. To check controllability, we mustfind the system rank. Matrix T is needed in the system to check whether the systemcan be completely controlled. The transformation of matrix T is expressed as follows.

$$T = \begin{bmatrix} B & \vdots & AB & \vdots & \cdots & \vdots & A^{n-1}B \end{bmatrix} \begin{bmatrix} a_{n-1} & a_{n-2} & \cdots & a_1 & 1 \\ a_{n-2} & a_{n-2} & \cdots & 1 & 0 \\ \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ a_1 & 1 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \end{bmatrix} \tag{16}$$

The second step is determining the values of $a_{1,} a_{2}, \cdots, a_n$ by using the characteristic polynomial.

$$|sI - A| = s^n + a_1 s^{n-1} + \cdots + a_{n-1}s + a_n \tag{17}$$

Then, the third step is utilizing the desired eigenvalue and obtaining the value of $\propto_1, \propto_2, \cdots, \propto_n$.
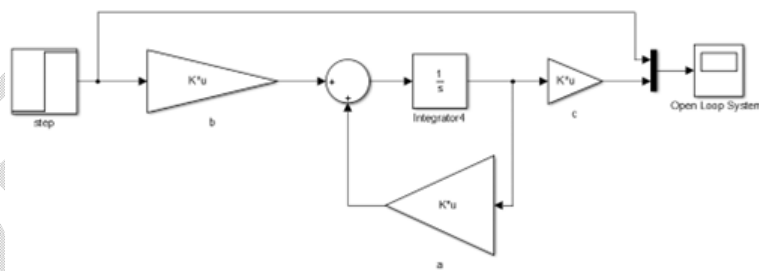
$$(s - \mu_1)(s - \mu_2)\ldots(s - \mu_n) = s^n + \propto_1 s^{n-1} + \cdots + \propto_{n-1} s + \propto_n \tag{18}$$

The last step is determining feedback gain matrix K using equation that expressed.

$$K = \begin{bmatrix} \propto_n - a_n & \vdots & \propto_{n-1} - a_{n-1} & \vdots & \cdots & \vdots & \propto_2 - a_2 & \vdots & \propto_1 - a_1 \end{bmatrix} \tag{19}$$

4.RESULT AND DISCUSSION

To get the performance of the proposed method, the MATLAB Simulink is employed. The open loop system of the aircraft pitch is presented in Fig 3.

Fig. 3 open-loop block diagram in MATLAB

The response system of diagram block in Fig 3 is presented in Fig. 4. The open loop response cannot follow the setpoint. the value of the response will continue to rise with time. From theresults, the controller is needed to make the response of the system follows the setpoint because the aircraft pitch requires high precision.
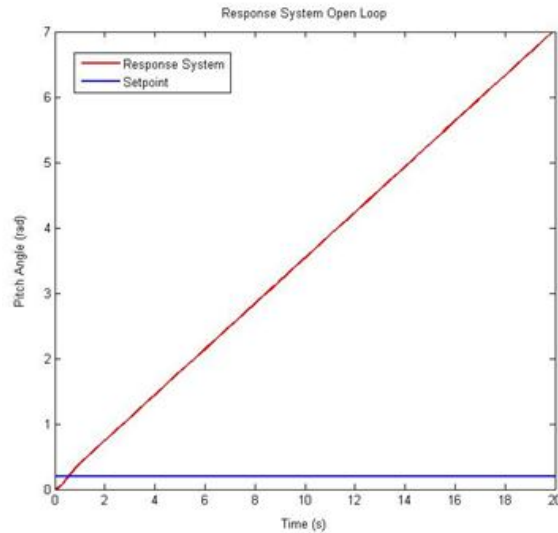
Fig. 4 response system without controller

Controller matrix K is obtained by means of transformation T matrix using equations (16)-(19). The parameters needed to use the matrix T transformation method must have the input, output and pole of the aircraft pitch system. The input and output of the aircraft are shown in equations (14) and (15), while the missing parameter is the pole. In this article the determination of the pole value of the system is obtained from the formula in MATLAB by entering the input and the output of the plant. After all the parameters exist, the next step is to determine the K matrix using equations (16) – (19) with the required parameters. From the calculation results, the K matrix value is shown in equation (20).

$$K = [0 \quad 0 \quad 0.87] \tag{20}$$

After obtaining the controller formula, the proposed controller is applied to control aircraft pitch. The proposed controller is examined using three conditions namely fixed reference, the variation of the reference and a load change. the reference employed in this paper is 0.2 rad. The result of fixed reference is depicted in Fig 5.
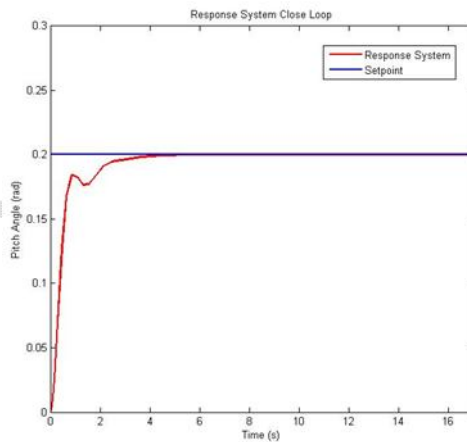
Fig. 5 System waveform of the pitch angle using Fixed reference

The proposed method is applied, and the performance of the system follows the reference. From the figure, the response of the system after using the proposed method, the time constant is 0.47 s. the detail performance of the system is presented in Table 2.

Table 2. Response System with fixed Setpoint

Technique	Reference (rad)	t_d (s)	Rise Time		Settling time	
			t_r (s)(5%-95%)	t_r (s)(10%-90%)	t_s (s)5%	t_s(s) 2%
Matrix transformation	0.2	0.39	2.003	1.54	2.09	2.93

Conventional PID	0.2	0.41	2.103	1.65	2.41	3..12

The next examination is the variation of reference namely 0.2 rad, 0 rad and 0.2 rad. The performance of the proposed controller is depicted in Fig. 6. It can be seen that at t=8 s, the reference is decreased to 0 rad and the pitch of the system can follow the reference. Then, at t=16 s the pitch reference is back to 0.2 rad and again the pitch response can follow the reference.

The last test is the additional load with the aim to determine the durability of the system. Adding load is done by adding a load block to the main block diagram with the aim of disrupting the system response. The response of the pitch after adding the load are presented in Figure 7. The load is added to the system at t=13 s and t=18 s. As presented in the Figure, the proposed method can maintain the pitch although there are the changes in the load. The detail performance of the proposed method is presented in Table 3.

TABLE 3. THE PERFORMANCE OF THE SYSTEM AFTER ADDING THE LOAD

Reference (rad)	the pitch angle deviation (rad)	
	$t = 13\ s$	$t = 18\ s$
0.2	0.042	0.039
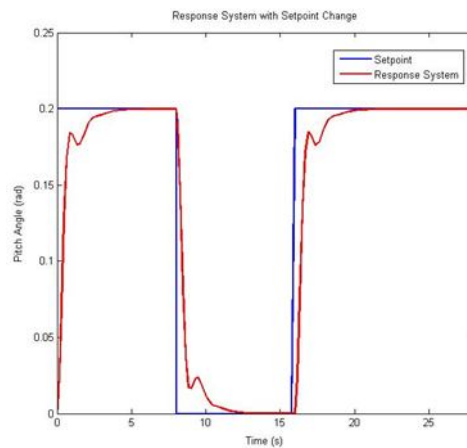
Fig. 6 System waveform of the pitch angle after changing the reference
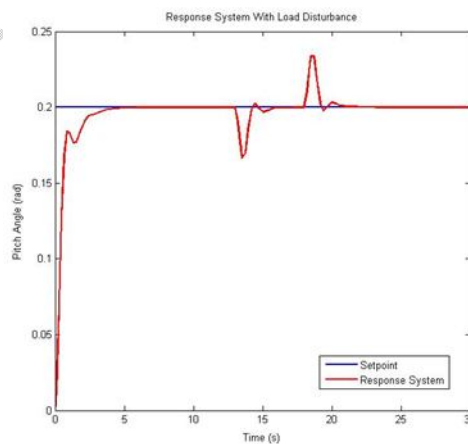
Fig. 7 System waveform of the pitch angle after adding the load disturbance

5. CONCLUSION

In this paper, design and simulation of aircraft pitch control using matrix transformation techniques has been proposed. The research reveals the effectiveness of the proposed technique in addressing the dynamic control challenges inherent

to aircraft pitch system. The matrix transformation technique offers a promising alternative to traditional control methods like PID controllers for aircraft pitch systems. The proposed controller is used to find out the response value by several experiments namelyfixed setpoints, changed setpoints, and by adding load to the system. Based on the results, the system response has a 0.47 s time constant, and 0.39 s delay time. From thesimulation the system response can follow the setpoint well without any overshoot.Future researchcan explore extending this approach to multi-axis control systems and connecting it with machine learning or AI-based optimization techniques for further advancements.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.

2.

3.

REFERENCES

[1]   M. Angelin Ponrani and A. Kirthini Godweena, "Aircraft Pitch Control using PID Controller," in *2021 International Conference on System, Computation, Automation and Networking, ICSCAN 2021*, 2021. doi: 10.1109/ICSCAN53069.2021.9526373.
[2]   C. Radhakrishnan and A. Swarup, "Improved aircraft performance using simple pitch control," in *2020 1st International Conference on Power, Control and Computing Technologies, ICPC2T 2020*, 2020. doi: 10.1109/ICPC2T48082.2020.9071452.
[3]   P. P. S. Saputra, R. Firmansyah, and D. Irawan, "Various and multilevel of coiflet discrete wavelet transform and quadratic discriminant analysis for classification misalignment on three phase induction motor," in *Journal of Physics: Conference Series*, 2019. doi: 10.1088/1742-6596/1367/1/012049.
[4]   A. O. Adetifa, P. P. Okonkwo, B. B. Muhammed, and D. A. Udekwe, "DEEP REINFORCEMENT LEARNING FOR AIRCRAFT LONGITUDINAL CONTROL AUGMENTATION SYSTEM," *Nigerian Journal of Technology*, vol. 42, no. 1, 2023, doi: 10.4314/njt.v42i1.18.
[5]   A. Johari *et al.*, "Improvement of pitch motion control of an aircraft systems," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 16, no. 5, 2018, doi: 10.12928/TELKOMNIKA.v16i5.7434.
[6]   S. A. Jalo, M. Ahmed, A. B. Abdulqadiri, M. U. Ilyasu, I. M. Inuwa, and G. Elhassan, "A Study on Aircraft Pitch Control in Rejecting Disturbances," in *Lecture Notes in Mechanical Engineering*, 2024. doi: 10.1007/978-981-99-6874-9_15.
[7]   R. Firmansyah and R. Irmawanto, "Comparison Study of PI Controller Tuning Method to Regulate the DC Motor Speed," in *ICRACOS 2021 - 2021 3rd International Conference on Research and Academic Community Services:*

Sustainable Innovation in Research and Community Services for Better Quality of Life towards Society 5, 2021. doi: 10.1109/ICRACOS53680.2021.9702007.

[8] Vishal and J. Ohri, "GA tuned LQR and PID controller for aircraft pitch control," in *India International Conference on Power Electronics, IICPE*, 2015. doi: 10.1109/IICPE.2014.7115839.

[9] R. Firmansyah and M. A. M. Ramli, "A new adaptive droop control strategy for improved power sharing accuracy and voltage restoration in a DC microgrid," *Ain Shams Engineering Journal*, vol. 15, no. 9, p. 102899, Sep. 2024, doi: 10.1016/J.ASEJ.2024.102899.

[10] J. Xu, H. Ma, J. Zhou, Y. Tian, and W. Han, "Hovering Attitude Control of Tilt Rri-rotor VTOL Aircraft," *NongyeJixieXuebao/Transactions of the Chinese Society for Agricultural Machinery*, vol. 49, no. 10, 2018, doi: 10.6041/j.issn.1000-1298.2018.10.002.

[11] R. Firmansyah, M. A. M. Ramli, and Endryansyah, "Voltage Regulation of Buck Converter in DC microgrid using Energy Valley Optimizer," in *2023 6th International Conference on Vocational Education and Electrical Engineering: Integrating Scalable Digital Connectivity, Intelligence Systems, and Green Technology for Education and Sustainable Community Development, ICVEE 2023 - Proceeding*, 2023. doi: 10.1109/ICVEE59738.2023.10348334.

[12] S. N. Deepa and G. Sudha, "Longitudinal control of aircraft dynamics based on optimization of PID parameters," *Thermophysics and Aeromechanics*, vol. 23, no. 2, 2016, doi: 10.1134/S0869864316020049.

[13] R. F. Muktiadji, M. A. M. Ramli, and A. H. Milyani, "Twin-Delayed Deep Deterministic Policy Gradient Algorithm to Control a Boost Converter in a DC Microgrid," *Electronics (Basel)*, vol. 13, no. 2, 2024, doi: 10.3390/electronics13020433.

[14] M. Tayyeb, U. Riaz, A. A. Amin, O. Saleem, M. Arslan, and M. H. Shahbaz, "Design of highly redundant fault tolerant control for aircraft elevator system," *Journal of Applied Engineering Science*, vol. 19, no. 1, 2021, doi: 10.5937/jaes0-27611.

[15] R. F. Muktiadji and J. Omotayo Oladigbolu, "Design of Dynamic Voltage Restorer Utilizing Adaptive Control to Mitigate Voltage Sag," in *2021 Fourth International Conference on Vocational Education and Electrical Engineering (ICVEE)*, IEEE, Oct. 2021, pp. 1–5. doi: 10.1109/ICVEE54186.2021.9649714.

[16] Y. Kanokmedhakul, N. Pholdee, S. Bureerat, and N. Panagant, "LQR AIRCRAFT PITCH CONTROLLER DESIGN FOR HANDLING DISTURBANCE USING DIFFERENTIAL EVOLUTION," *Journal of Research and Applications in Mechanical Engineering*, vol. 7, no. 2, 2019, doi: 10.14456/jrame.2019.14.

[17] E. Sayar and H. M. Ertunç, "Fuzzy logic controller and PID controller design for aircraft pitch control," in *Mechanisms and Machine Science*, 2019. doi: 10.1007/978-3-319-98020-1_7.

[18] J. E. Nanevicz and R. L. Tanner, "Some techniques for the elimination of corona discharge noise in aircraft antennas," in *Proceedings of the IEEE*, 1964, pp. 53–64.

[19] R. F. Muktiadji, M. A. M. Ramli, M. M. A. Seedahmed, R. Uswarman, and Endryansyah, "Power Sharing Control and Voltage Restoration in DC Microgrid Using PI Fuzzy," in *2022 Fifth International Conference on Vocational Education and Electrical Engineering (ICVEE)*, 2022, pp. 130–135. doi: 10.1109/ICVEE57061.2022.9930441.

[20] D. Izci, S. Ekinci, A. Demiroren, and J. Hedley, "HHO Algorithm based PID Controller Design for Aircraft Pitch Angle Control System," in *HORA 2020 - 2nd International Congress on Human-Computer Interaction, Optimization and Robotic Applications, Proceedings*, 2020. doi: 10.1109/HORA49412.2020.9152897.

[21] R. Firmansyah, M. Yusuf, P. P. S. Saputra, M. E. Prasetyo, F. M. Mochtar, and F. A. Kurniawan, "IoT Based Temperature Control System Using Node MCU ESP 8266," 2020. doi: 10.2991/aer.k.201124.072.

[22] M. Zahmatkesh, S. A. Emami, A. Banazadeh, and P. Castaldi, "Robust Attitude Control of an Agile Aircraft Using Improved Q-Learning," *Actuators*, vol. 11, no. 12, 2022, doi: 10.3390/act11120374.

[23] R. F. Muktiadji *et al.*, "Control of Boost Converter Using Observer-Based Backstepping Sliding Mode Control for DC Microgrid," *Front Energy Res*, vol. 10, 2022, doi: 10.3389/fenrg.2022.828978.

[24] A. Khalid, K. Zeb, and A. Haider, "Conventional PID, adaptive PID, and sliding mode controllers design for aircraft pitch control," in *2019 International Conference on Engineering and Emerging Technologies, ICEET 2019*, 2019. doi: 10.1109/CEET1.2019.8711871.

[25] R. Firmansyah *et al.*, "DC Motor Speed Control using Particle Swarm Optimization based on Labview," *JEEE-U (Journal of Electrical and Electronic Engineering-UMSIDA)*, vol. 8, no. 2, pp. 111–121, Oct. 2024, doi: 10.21070/jeeeu.v8i2.1701.

[26] A. Ur Rehman, M. U. Khan, M. S. Shah, Q. Maqsood, M. F. Ullah, and S. Uba, "Aircraft Pitch Control based on Genetic Algorithm Tuning with PID and LQR Controller," in *IMTIC 2021 - 6th International Multi-Topic ICT Conference: AI Meets IoT: Towards Next Generation Digital Transformation*, 2021. doi: 10.1109/IMTIC53841.2021.9719736.

[27] R. Firmansyah, "Design and Simulation Fast NMPC for tracking Two Stage Inverted Pendulum," InstitutTeknologiSepuluhNopember, 2013.

[28] T. Rogalski, D. Nowak, Ł. Wałek, D. Rzońca, and S. Samolej, "Control System for Aircraft Take-off and Landing Based on Modified PID controllers," *MATEC Web of Conferences*, vol. 252, 2019, doi: 10.1051/matecconf/201925206008.

[29] P. P. S. Saputra and R. Firmansyah, "Short Circuit Failure Detection in Induction Motor Using Wavelet Transform and Fuzzy C-Means," *SinkrOn*, vol. 8, no. 2, 2023, doi: 10.33395/sinkron.v8i2.12207.

[30] G. Sudha and S. N. Deepa, "Optimization for PID control parameters on pitch control of aircraft dynamics based on tuning methods," *Applied Mathematics and Information Sciences*, vol. 10, no. 1, 2016, doi: 10.18576/amis/100136.

[31] A. Idir, Y. Bensafia, K. Khettab, and L. Canale, "Performance improvement of aircraft pitch angle control using a new reduced order fractionalized PID controller," *Asian J Control*, vol. 25, no. 4, 2023, doi: 10.1002/asjc.3009.