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Simulation of the Control System for Aircraft Nose Landing Gear Retraction and Extension

Abdallah Abuzrida*
Department of Aeronautical Engineering, College of Civil Aviation-Misurata, Misurata, Libya
*Email (for reference researcher): abdullahabuzarida@misrataca.edu.ly

محاكاة نظام التحكم في سحب وتمديد عجلات الهبوط الأمامية للطائرة

عبدالله أبوزريدة
قسم هندسة الطيران، كلية الطيران المدني- مصراتة، مصراتة، ليبيا

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Abstract:
This study models and simulates an aircraft's nose landing gear control system, focusing on its dynamic behavior under different operating conditions. The study investigates the system response during landing gear extension and retraction using MATLAB/Simulink, emphasizing the effects of feedback control, external disturbances, and time-constant variation on system stability and performance. The primary objective of the project is to assess the effectiveness of a closed-loop control strategy using a PID controller compared with an open-loop configuration. A suitable transfer function was chosen to simulate the dynamic system of the retraction and extension motion of the landing gear. A pole-zero technique was used to determine the system's stability or instability, and a PID controller was designed and tuned to enhance stability, reduce overshoot, and improve disturbance rejection. The system was analyzed in both disturbed and undisturbed environments. Simulation results demonstrate that the open-loop system becomes unstable in the presence of disturbances, whereas the closed-loop system achieves a settling time of approximately 3.15 s with a significantly reduced overshoot percentage of 12.51%, compared to 46.03% in the open-loop case. Furthermore, the impact of altering the landing gear actuator's time constant in the transfer function equation was investigated. At $\tau = 3$, the best performance was obtained, offering a fair trade-off between stability and response time.

Keywords: PID Controller; Transfer Function; Closed-Loop Control System; Disturbance; Settling Time; Retraction Time; Extension Time.

الملخص:
تُحاكي هذه الدراسة نظام التحكم في جهاز الهبوط الأمامي للطائرة، مع التركيز على سلوكه الديناميكي في ظل ظروف تشغيلية مختلفة. وتدرس استجابة النظام أثناء مدّ وسحب جهاز الهبوط باستخدام برنامج MATLAB/Simulink، مع التركيز على تأثيرات التحكم التغذية الراجعة، والاضطرابات الخارجية، وتغير الثابت الزمني على استقرار النظام وأدائه. والهدف الرئيسي للمشروع هو تقييم فعالية استراتيجية التحكم ذات الحلقة المغلقة باستخدام وحدة تحكم PID مقارنةً بتكوين الحلقة المفتوحة. وقد تم اختيار دالة نقل مناسبة لمحاكاة النظام الديناميكي لحركة سحب ومدّ جهاز الهبوط. واستُخدمت تقنية الأقطاب والأصفار لتحديد استقرار النظام أو عدم استقراره، وتم تصميم وحدة تحكم PID وضبطها لتعزيز الاستقرار، وتقليل التجاوز، وتحسين رفض الاضطرابات. وتم تحليل النظام في بيئات مضطربة وغير مضطربة. أظهرت نتائج المحاكاة أن النظام ذو الحلقة المفتوحة يصبح غير مستقر في وجود الاضطرابات، بينما يحقق النظام ذو الحلقة المغلقة زمن استقرار يبلغ حوالي 3.15 ثانية مع انخفاض ملحوظ في نسبة التجاوز إلى 12.51%، مقارنةً بنسبة 46.03% في حالة الحلقة المفتوحة. علاوة على ذلك، دُرست آثار تغيير ثابت الزمن لمشغل جهاز الهبوط في معادلة دالة النقل. عند $\tau = 3$ ، تم الحصول على أفضل أداء، مما يوفر توازنًا مناسبًا بين الاستقرار وزمن الاستجابة.

الكلمات المفتاحية: وحدة تحكم PID، دالة التحويل، نظام تحكم ذو حلقة مغلقة، اضطراب، زمن الاستقرار، زمن السحب، زمن التمدد.

1.Introduction

The landing gear is one of the aircraft subsystems that is most critical to the safety of the aircraft. It must provide structural support in a service environment and reliable extension, retraction, and locking under all phases of flight. Various factors like mechanical components, actuator characteristics, external loads, and the nonlinearity of the system will affect the dynamic behavior of landing gear. Hence, modeling of its motion will help to evaluate its performance and reliability of operation [1–3]. The retraction mechanism already encompasses joint clearance, and mechanical degradation and environmental conditions have been the subject of recent works [2].

The development of model-based engineering approaches now provides a good means of investigating aircraft landing-gear behavior before experimentation. Delprete et al. [1] formulated a unified design methodology, where simulations complemented optimizations, to assess the interactions of landing gear subsystems via their representative models. The results of their simulations indicate how effective digital models can be for predicting behavior and evaluating design alternatives in early aircraft development. Other recent studies show that effects of non-linearity due to mechanical clearances and wear can have a large impact on both dynamic properties and location accuracy of landing-gear retraction mechanisms [2].

In terms of control, the landing-gear actuation has to reach the commanded position accurately in an acceptable time without excessive oscillations and overshoot. Increased difficulties in complying with the requirements arise for the system subject to external disturbance, actuator dynamic impact, parameter variations, or mechanical non-linearity. Recent work on aircraft landing-gear automation has shown that command strategies are insufficient when there are simultaneous non-linearities, environmental variations, and multiple gear states [3]. Researchers conducted simulation studies in MATLAB with the run of six simulations on agile landing gear for soft landing. Their results illustrate the growing interest in more adaptive control laws for landing-gear systems.

Although various advanced control strategies have been developed, a proportional–integral–derivative (PID) controller is still a good baseline control strategy for aerospace control applications due to the relatively simple structure, ease of implementability, and ability to improve tracking accuracy and decrease steady-state error. Recent studies in airplane control use either PID controllers, which are conventional controllers, or components of hybrid architectures. Dong et al. [4] studied a coordinated model-predictive-control/PID architecture for automatic carrier landing and showed improved command tracking and disturbance rejection compared with stand-alone control approaches. This shows that PID control remains a useful control element, although more advanced control methods are being developed lately.

The actuator's dynamic behavior is another important aspect in landing gear actuation. Actuation systems exhibit non-instantaneous response to command signals due to hydraulic and electrohydraulic actuator dynamics and time delays. Consequently, these dynamics and delays can hamper the landing gear system's speed, stability, and tracking accuracy. As a result, a simplified dynamic actuator would be a useful intermediate representation between an ideal control model and a detailed nonlinear hydraulic model. Additionally, Jiang et al. [2] highlighted the impact of degradation and environmental effects on the dynamic behavior of landing-gear mechanisms, which reinforces the need to take account of non-ideal system behavior during control-system evaluations.

Monitoring and operational reliability analysis of landing gear is becoming easier, aided by the growing use of digital modeling. Sabag et al. [5] make a digital twin of an aircraft landing-gear system that combines operational flight data with load modeling and wear estimation to assist in failure analysis and predictive maintenance. The contribution of their work extends the application of physics-based simulation from traditional design appraisal to the assessment of condition and reliability management.

However, emerging studies indicate that much of the advanced work is focusing on nonlinear, fuzzy, digital twin, predictive maintenance, or optimization approaches. Despite these methods being a significant step forward, there is value in systematically evaluating a closed-loop PID architecture with low complexity and varying disturbances and actuator dynamics. A comparative study of open-loop and closed-loop behavior, together with the servo-valve time constant, can clearly characterize the effect of feedback and actuator dynamics on the landing-gear tracking performance. This is particularly applicable to model-based studies, where aircraft hydraulic-system data is not readily available.
Therefore, the present study proposes and assesses a representative model of the nose landing gear control for an aircraft using MATLAB/Simulink. The research deals with the motion of retracting and extending the landing gear. The research also looks at a closed-loop PID-based control strategy and its efficacy in normal and disturbance conditions. The validation of the developed model is done with the important dynamic-performance indicators: settling time, peak overshoot, overshoot percent, and steady-state error. A first-order servo-valve model is added to the system to determine the impact of the actuator time constant on the response. An integrated flight-operation scenario is finally simulated to evaluate the proposed controller's capability to maintain accurate landing-gear tracking in representative operating conditions.

2.Methodology

2.1 Simulation Framework

A representative aircraft nose landing gear (NLG) retraction and extension system was adopted using a model-based simulation approach to understand its dynamic behavior and control performance. The full model of the landing gear was designed in MATLAB/Simulink to study the response of the landing gear in both nominal and disturbed conditions. The open-loop and closed-loop configurations were compared, the efficiency of the PID controller was examined, and the effect of actuator dynamics on the system response was investigated.
The simulation framework included a dynamic plant for landing gear, a control loop using feedback, a PID controller, a disturbance subsystem, and a first-order servo-valve model. The PID controller processed the tracking error produced from comparing the commanded landing-gear position with the measured output. The freedom with which the control system can mitigate such disturbances was tested. The final model included the dynamics of a servo-valve to model the actual response of the actuator.

2.2 Dynamic Model of the Nose Landing Gear

The NLG actuation system was modelled by a third-order linear transfer function that describes the dynamic response of the control input that commands the landing-gear angular position. The simulation used [6] as the transfer function.

$$G(s) = \frac{0.2s+2}{s^3+71.5s^2+113s+455.5} \quad \text{........................(1)}$$

In this expression, G(s) denotes the plant of the landing gear, while s is the Laplace-domain variable. The angular position of the landing gear is represented by the output of the Plant, while the input represents the control signal applied to the actuation.

2.3 Stability Analysis of the Landing Gear Model

A pole-zero evaluation of the landing gear plant was conducted before implementing the feedback controller to determine the system's stability or instability and response. The poles from the transfer function were located at p1 = −70, p2 = −0.761+ j2.44, p3 = −0.761- j2.44. As shown in Figure 1, since all poles lie in the left half of the complex s-plane, it indicates the asymptotic stability of the plant. The complex conjugate pair is said to be dominant poles as they are close to the imaginary axis. These poles are underdamped, with a damping ratio of around 0.298 and a natural frequency of approximately 2.55 rad/s. Its overshoot is roughly 37.5%. Hence, the uncontrolled plant is stable, but because it has relatively low damping and a large overshoot, it is indicated that feedback control is required to improve its transient response and tracking response.

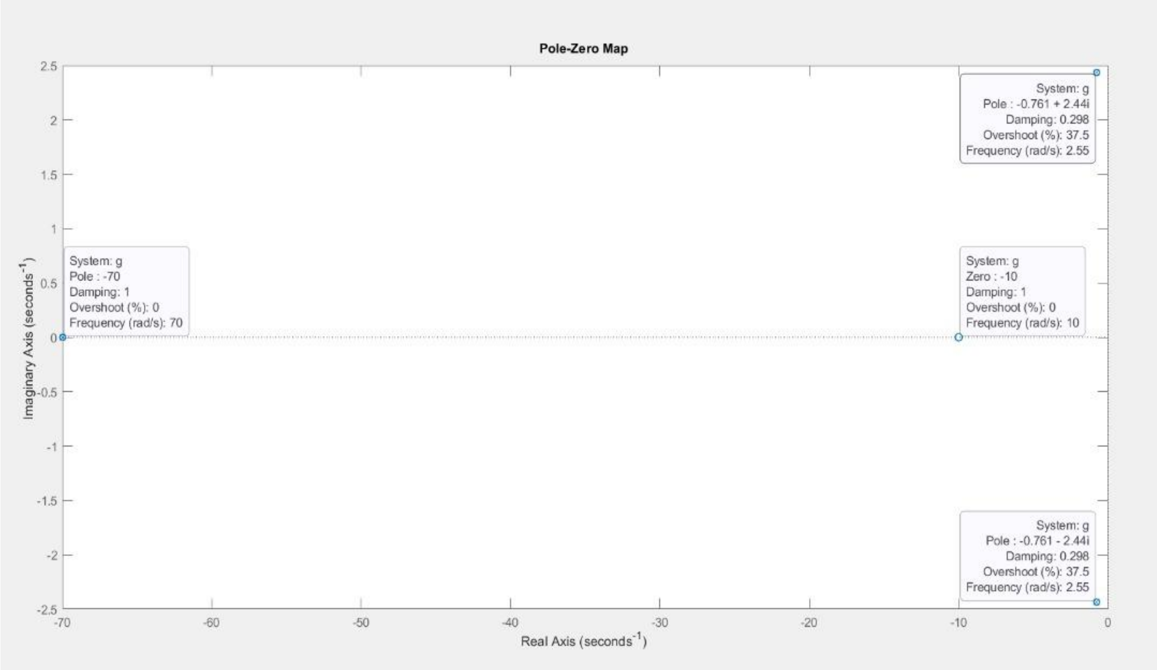

Figure 1. Pole-zero map of the landing gear dynamic model.

2.4 PID Controller Design

A PID controller has been built to control the landing-gear angular position by the difference between the commanded and actual positions. The control error is defined as

$$e(t) = r(t) - y(t) \quad \text{.............................. (2)}$$

Where r(t) is the landing gear's reference position and y(t) is the actual system output. The PID controller gives a control signal defined as follows. [7]

$$u(t) = K_P e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad \text{................................ (3)}$$

Where Kp, Ki, and Kd denote the proportional, integral, and derivative gains, respectively.

2.4.1 PID Gains Determination Process (tuning determination)

The second stage of the investigation was to determine the appropriate values of the gains K_p, K_i, and K_d, for the landing gear reference model. For this, a special MATLAB interactive tuning interface was developed. This interface utilizes three adjustable sliders for K_p, K_i, and K_d, correspondingly, which enable the researcher to observe in real time how each of the parameters affects the closed-loop response of the system.

This tuning relied on evaluating key performance indicators derived from the step response, including overshoot, settling time, and steady-state error. For every update in the slider values, the tool reconstructs the closed-loop transfer function using unity feedback; it simulates the time response and extracts performance metrics through MATLAB's stepinfo function. In this way, a systematic approach was followed to iteratively adjust the parameters of the controller until a satisfactory dynamic response was achieved.

In contrast to traditional manual tuning, the GUI-based tuning mechanism had the advantage of immediate visualization of the controller's effect on the transient and steady-state characteristics. The third-order reference dynamic model formulated earlier in the study was used as the plant for tuning, ensuring that the designed controller is consistent with the desired behavior of the system. Through iterative experimentation with the tuning interface, those gains that produced the most balanced performance-characterized by reduced overshoot, good tracking ability, faster settling time, and minimal steady-state error-were selected. The controller gains used in all subsequent simulations are:

$$K_p = 140, K_i = 400, K_d = 60.$$

These values provided a stable and responsive closed-loop behavior aligned with the performance objectives of the landing gear actuation model.

Figure 2 illustrates the PID controller's behavior. The proportional, integral, and derivative parts of the PID control interact with each other to control the response of the system. The proportional part helps in making it more responsive, while the integral and derivative parts improve damping.

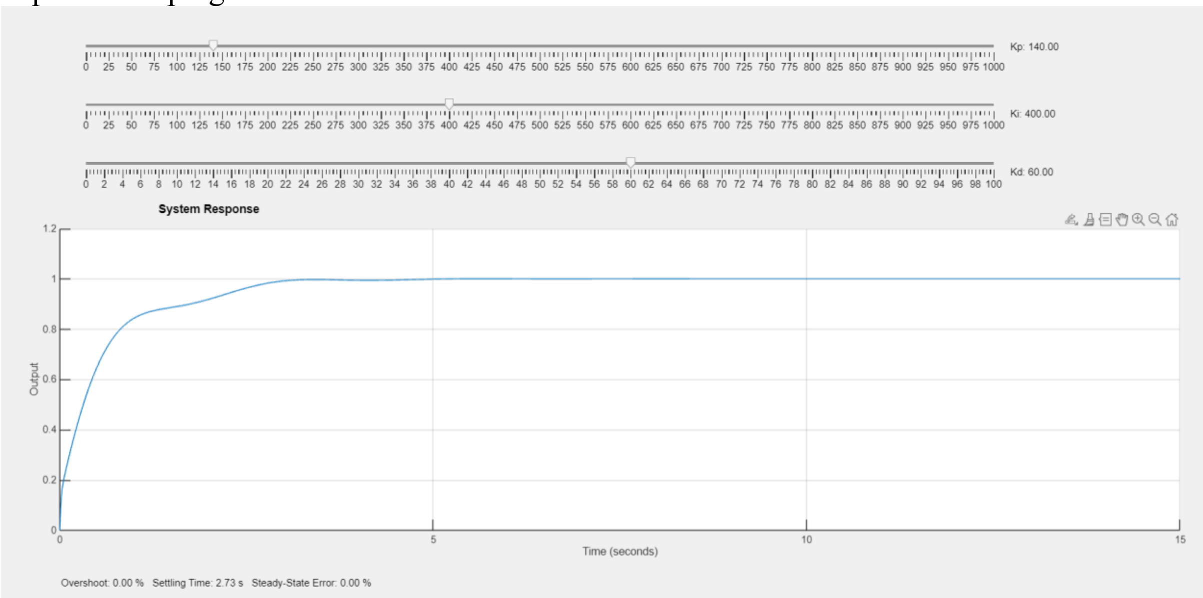

Figure 2. PID controller tuning

2.5 Open-Loop and Closed-Loop Configurations

Two types of control configurations were identified to quantify feedback control contribution.

2.5.1 Open-Loop System Description

The landing-gear plant was given control input in an open-loop configuration with no feedback correction. As a result, they were not automatically compensated for changes in the plant output due to disturbances or dynamics of the system.

Figure 3 represents the open-loop configuration of the landing-gear model under the effect of disturbances. This configuration receives a reference input command used for testing the transient behavior of the plant. It can be seen that the input signal is branched to monitor it directly before entering the system.

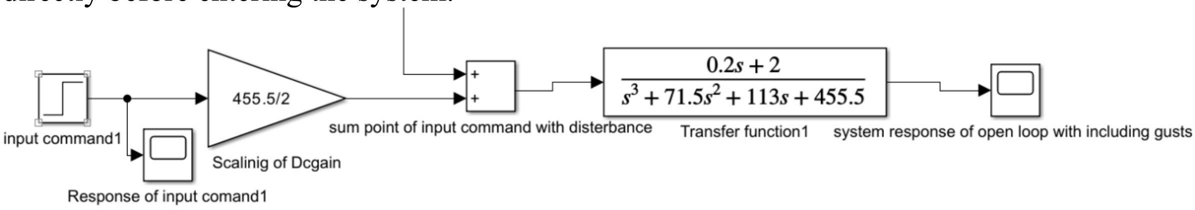

Figure 3. Open-loop configuration

The input to the shown model is a step-type signal representing a sudden change in the desired position or reference angle of the landing gear model. A step input is used to test the system's transient characteristics, such as rise time, settling time, and steady-state behavior, in response to an abrupt change in command.

Figure 4 illustrates the command response signal used as reference input to the landing-gear control system. The command stays steady at 90°, and this corresponds to the normal extended position for the landing gear. A steady reference is intentionally utilized in order to test the controller's ability to hold the output at a given set point when the desired angle has not changed. In using a fixed command instead of a step or ramp, the figure isolates the stability characteristics of the system and helps assess how internal disturbances or noise may affect the response. The flat horizontal line simply confirms that the command is steady and does not introduce variation, which can affect the system dynamics.

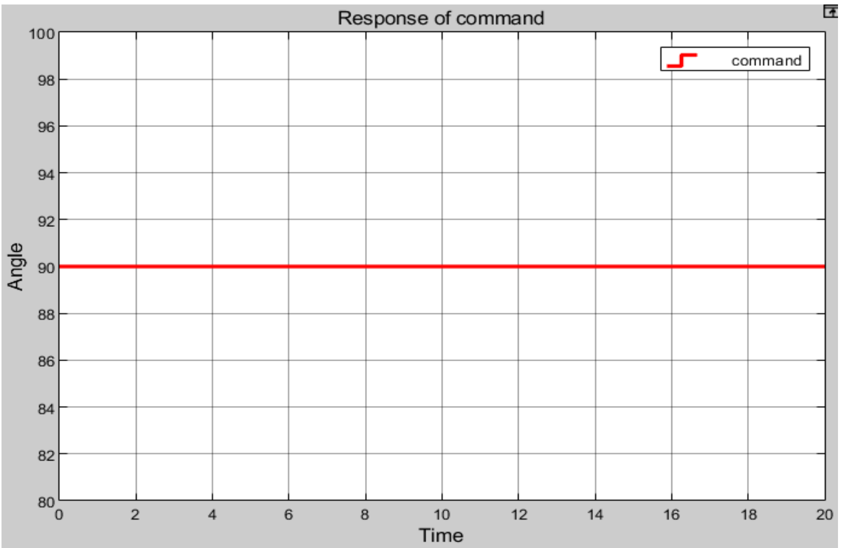

Figure 4. Response of command

Immediately following the input command, the signal is divided into two paths as shown in Figure 3:
-Path one feeds the input to a monitoring scope.
-Path two continues to the dynamic model of the system via the scaling block.
This branching enables the observation of both the input and the system output resulting from it, simultaneously, for comparison.
As shown in Figure 3, the gain block multiplies the input command by a constant equal to 455.5/2. This factor has been applied to match the DC-level characteristics of the input with the reference model's denominator constant term, which is 455.5. Scaling in this manner allows the model to ensure that the steady-state output maintains consistency with the behavior to be expected from the designed reference transfer function. It is a proper normalization that allows the system to stay within its linear range and avoid numerical instability.

2.5.2 Closed-Loop System with PID Controller

Figure 5 depicts the entire closed-loop system with a PID controller designed for landing gear motion control in the presence of disturbances. The reference input is subtracted from the output of the plant at the summation point to produce the tracking error. This error signal is then fed to a PID controller consisting of three parallel branches:
Proportional path: As mentioned, Kp = 140 is responsible for reacting to instantaneous error and therefore increases the responsiveness of the system.
- Integral path Ki = 400: Eliminates steady-state error by integrating past error.
- Derivative path, Kd = 60, which predicts future error and hence provides damping against overshoot.

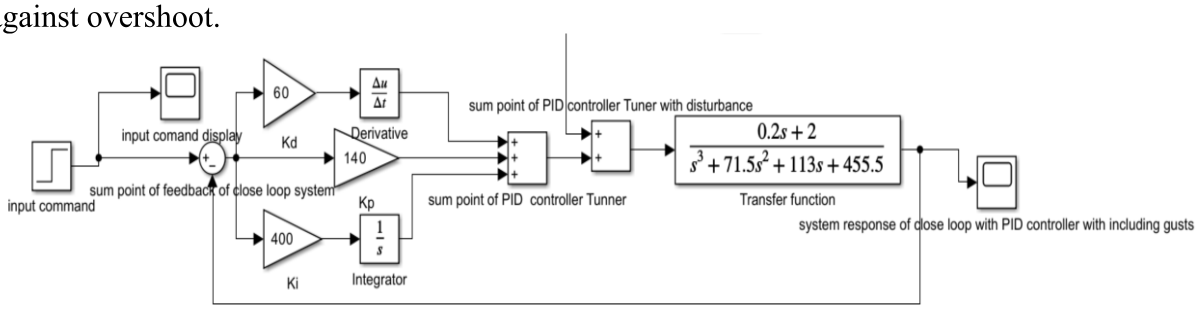

Figure 5. Closed-Loop System with PID Controller

The outputs from these three pathways are summed to give the control signal, which in turn drives the plant transfer function. The same disturbance shown in Figure 5 is injected into the plant input to enable a direct comparison with the open-loop case.
The system output is tapped via a scope block to facilitate disturbance rejection, improved tracking, and increased stability. This closed-loop method shows how feedback, along with PID action, really optimizes system performance over the open-loop case.

2.5.3 Disturbance Subsystem

Figure 6: The disturbance-generation module injects external perturbations into the landing-gear dynamic model. There exist two main disturbance sources in this subsystem: a gust signal block and a disturbance-rate block, each for a different kind of environmental or mechanical fluctuation. The gust generator produces low-frequency oscillatory disturbances capable of representing pressure variations, while the disturbance rate block applies higher-frequency variations modeling fast fluctuations or structural vibrations.

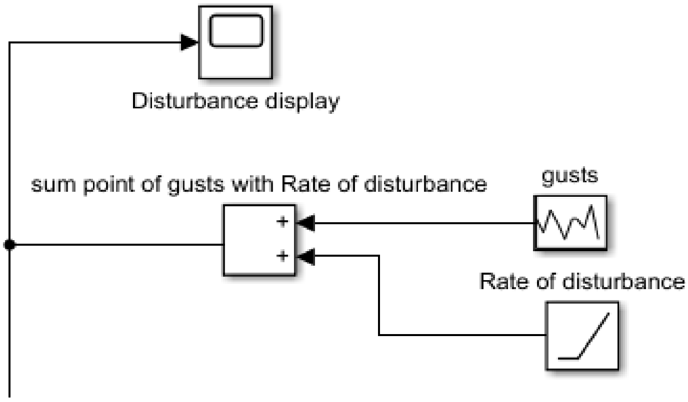

Figure 6. Disturbance Subsystem

These disturbance signals are combined at a summation node so that the system will be able to model representative mixed disturbances. This node output is then fed into the main system, whose effect on the dynamics can thus be observed. This subsystem has been created to test the robustness of the controller by analyzing the behavior of the plant under real-world uncertainties.
Figure 7 illustrates a combined disturbance injected into the landing gear control system (gust component and disturbance-rate component).

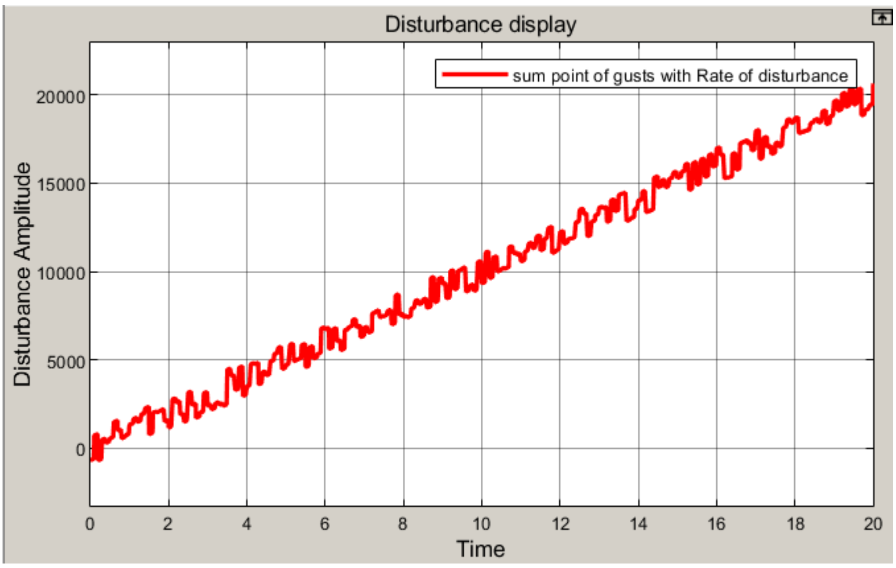

Figure 7. Injected Disturbance into landing gear system

This signal continuously varies around an overall increasing trend, which can represent the time-varying and unpredictable nature of aerodynamic disturbances or hydraulic pressure irregularities that may affect the landing gear during flight. The high-frequency oscillations simulate rapid gust loads, while the general upward drift reflects accumulated or gradually increasing disturbances. The controller is severely challenged because the disturbance input is neither constant nor periodic, providing a good test for the disturbance-rejection performance both in open-loop and closed-loop configurations. The main goal of including disturbance into the control system is to test the robustness of the PID control system to disturbance stresses.

2.5.4 A combination of open and closed systems, including disturbance

Figure 8 illustrates the comprehensive MATLAB/Simulink architecture developed to simulate the landing gear's operational performance through a comparative analysis of open-loop and closed-loop control strategies. The model is structured into two primary parallel paths to evaluate the system's robustness against external perturbations. The closed-loop configuration incorporates a PID controller—comprising proportional ($K_p = 140$), integral ($K_i = 400$), and derivative ($K_d = 60$) blocks—designed to minimize the steady-state error and optimize the response time. This control signal is fed into a third-order transfer function that represents the physical plant's dynamics. To simulate real-world conditions, a disturbance sub-system, labeled as 'gusts' and 'rate of disturbance,' is integrated into the model to test the controller's ability to maintain stability under environmental loads. Conversely, the open-loop path includes a DC gain scaling block but lacks a feedback mechanism, serving as a baseline for comparison. Finally, the simulation utilizes various 'Scope' blocks and a comparison unit to provide a visual and numerical assessment of the system's operation time, overshoot, and settling behavior in both controlled and uncontrolled states.

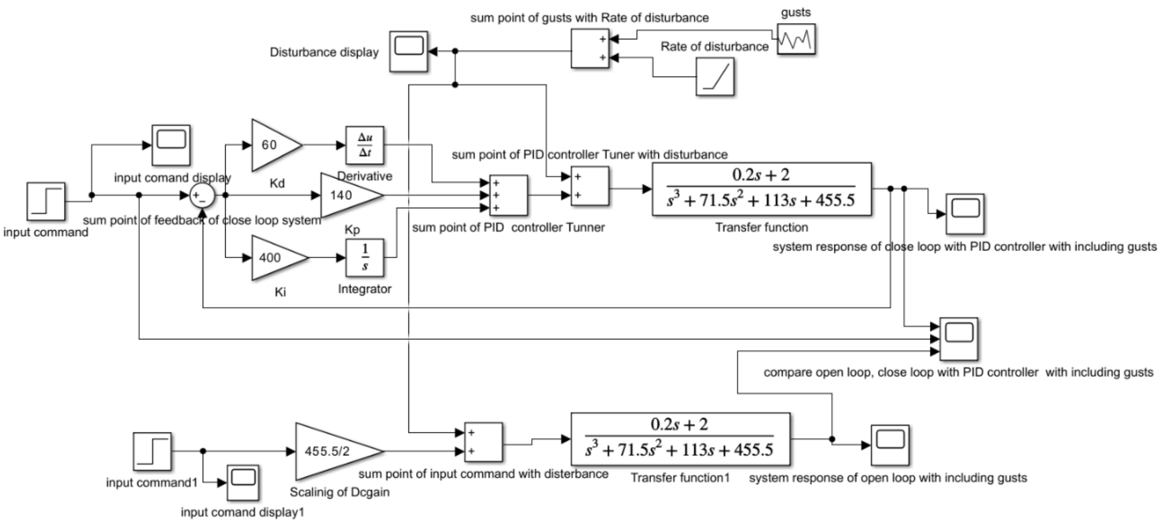

Figure 8. Open-Loop and Closed-Loop System with PID Controller

2.6. Servo-Valve Dynamic Model

The response time of the actuation system was taken into account by modeling the servo valve using a first-order dynamic model. This model is often employed as a simplified representation of servo-valve behaviour [8]. The given information is a transfer function.

$$G_{sv}(s) = \frac{K_v}{\tau_v s+1} \quad \text{.. (4)}$$

In this equation, Kv describes the valve gain, and τv indicates the equivalent time constant. In the current investigation, unity was the normalisation of the gain, and so the model was given [9].

$$G_{sv}(s) = \frac{1}{\tau s+1} \quad \text{.. (5)}$$

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Different simulation cases were carried out to study the effect of the time constant on the landing-gear response. For the final configuration, τ = 3 s was chosen. This value is a good compromise between response time and control signal smoothing. The actuator model that resulted was.

$$G_{sv}(s) = \frac{1}{3s+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

According to Modern Control Engineering by Katsuhiko Ogata, the transient response of first-order systems follows well-established rules regarding settling time and steady-state behavior. Ogata explains that a first-order system reaches approximately 63.2% of its final value at t = 3, and about 99.3% of its final value at τ = 5 [10].

2.7 Final scenario

In this section, the explanation covers the simulation of the flight scenario under nose landing gear operating conditions. The closed-loop system will be utilized, including disturbances. The final scenario system describes the flight scenario for nose landing gear at takeoff, cruise, and landing. The scenario will be injected into the closed-loop control system to simulate the real flight conditions. The flight scenario will give commands to the closed-loop system, such as open (extension) or close (retraction) commands under controlled conditions.

2.7.1 Full Closed-Loop System

Figure 9 represents a full closed-loop system. The feedback control loop, the core of the system, is completed by comparing the reference command with the landing gear angle to create an error signal. The error feeds into proportional, integral, and derivative paths, respectively scaled by the tuned gains: Kp = 140, Ki = 400, and Kd = 60. The proportional term reacts to the instantaneous error, and the integral term eliminates long-term steady-state deviations, while the derivative term anticipates rapid error changes to enhance damping. To simulate real-flight conditions, the system features two disturbance inputs: a gust generator and a disturbance-rate signal. Similarly, the closed-loop output is routed through several scopes and displays that track performance metrics, including system response, command-tracking accuracy, and steady-state error. The SSE indicator shows residual error after the system settles. The integral action should ideally minimize this. Any lingering value, such as the one displayed in Figure 9, hints at slight tracking bias due to either actuator limits, system saturation, or disturbance persistence.

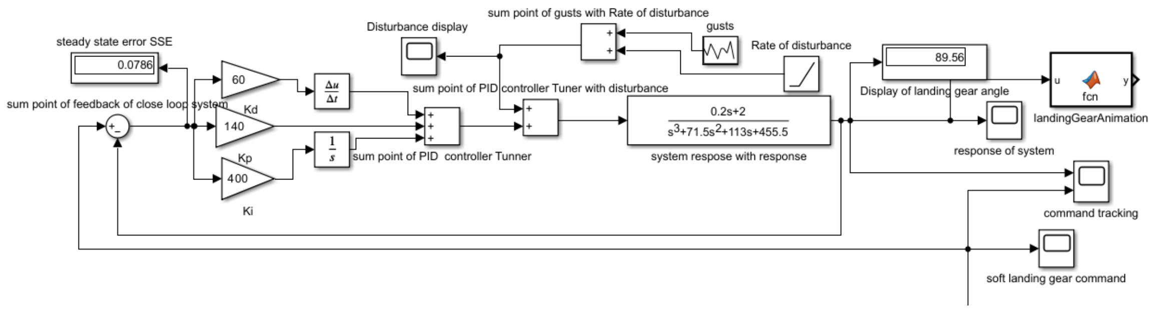

Figure 9. Full Closed-Loop System

A custom MATLAB animation function was integrated into the simulation environment in order to visualize the motion of the landing gear in deployment and retraction. This function uses the real-time landing-gear angle generated by the closed-loop control system and translates that into a smooth graphical motion.

2.7.2 Real Flight Scenario

The overall simulation architecture designed in MATLAB/Simulink is shown in Figure 10. The landing gear command generation subsystem, PID feedback controller, first-order servo valve model, external disturbance subsystem, and landing gear dynamic plant make up the model. The actual output of the landing gear is compared with the commanded landing gear position to generate a tracking error; this, in turn, is PID controlled using Kp = 140, Ki = 400, and Kd =

60. To test the robustness of the controller, gust and disturbance-rate signals are added. The servo valve is represented by the first-order transfer function 1/(3s+1) to account for actuator response. The position feedback for the landing gear is given to the controller through command tracking and system response outputs.

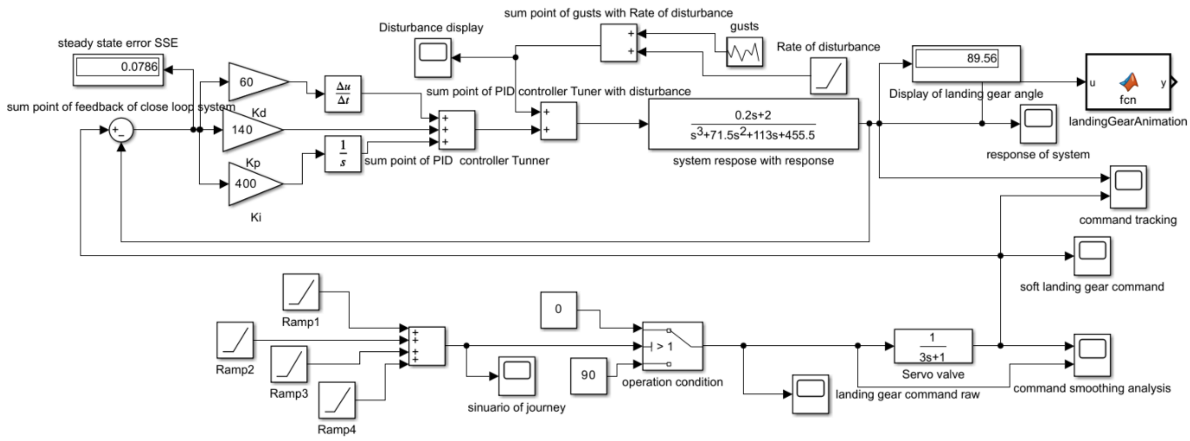

Figure 10. Final scenario of flight Journey

The lower part of Figure 10 describes the generation of landing gear command. Four ramp blocks are there. The summation block that has been labeled combines these. The ramps have been chosen so as to provide a representative sequence of landing gear operating commands as opposed to simply applying a single instantaneous step. The simulated flight scenario generates a signal representative of the desired landing gear behavior.

In this model, several ramp signals have been applied to see how the landing-gear control system would respond to gradually varying inputs at different times. Unlike a step input, which varies instantaneously, a ramp signal increases linearly with time, and as such, is ideal for testing the system's behavior under smoothly changing commands or slowly developing disturbances. Each of the ramp blocks was configured for a specific slope, start time, and initial output, as shown in Figure 10.

The signal parameters of the ramp blocks will be explained as follows:

- **Ramp Signal 1 (Ramp 1)**

This ramp starts to rise linearly at 10 seconds, with a slope of 0.555, which means the signal increases at a rate of 0.555 units per second. It represents the first gradual input disturbance or command change applied to the system and allows the model to evaluate the early transient response.

- **Ramp Signal 2 (Ramp 2)**

When the aircraft altitude reaches 10,000 ft at (t = 28) s, a ramp with a negative slope is applied. This command is introduced to counteract the previous increasing trend and maintain the aircraft at the 10,000 ft level. As a result, the net slope becomes zero, and the altitude remains constant, representing a cruising phase at a fixed flight level.

- **Ramp Signal 3 (Ramp 3)**

This ramp starts at (t = 70) s with a negative slope of (-0.667). It is applied to gradually reduce the previous trend until the slope reaches zero. This behavior models a smooth and controlled transition, simulating a gradual change in the flight condition rather than an abrupt maneuver.

- **Ramp Signal 4 (Ramp 4)**

To stop the negative trend introduced by Ramp Signal 3 and stabilize the slope at zero, another ramp with a positive slope of (+0.667) is applied at (t = 85) s. This action cancels the previous negative slope, ensuring that the system maintains a constant condition thereafter. This sequence allows the evaluation of the system's response to delayed corrective actions and its ability to achieve long-term steady operation.

Figure 11 illustrates a simulated flight-journey scenario that was used to identify the point at which landing gear would be extended or retracted in the course of the mission.

Figure 11. Scenario of journey signals

The altitude profile starts at the ground and rises rapidly to about 10 units, representing the climb phase immediately following lift-off. The aircraft then cruises at the same altitude for a period of time, which is representative of stable flight conditions, before starting to descend back down to the runway. Finally, the altitude drops steadily as the aircraft dives down to the runway. When the altitude returns to zero, the aircraft is considered to have touched down and landed. This altitude-based scenario provides the basis for triggering the landing-gear command logic, especially the 1000-foot condition that requires the gear to be extended during descent.

Figure 12 depicts the raw landing-gear command output from the flight-scenario logic before using the servo valve, which gives smooth retraction and extension. At the start of the mission, the command stays at about 90°; this is a fully extended landing gear position. Then, when the simulated aircraft altitude crosses the threshold set before at 1000 ft, the command directly switches to 0°; this corresponds to a request to retract the gear. The sudden switch here represents the non-physical nature of the logical command signal itself; without passing through the smoothing block, it is described as the response of a servo valve. Later in the simulation, after the aircraft has departed again or transitioned through another flight phase, the command moves back to 90° and extends the gear. This raw command is deliberately sharp and non-physical and subsequently passes through the first-order filter to make the motion of the landing gear smooth and physical.

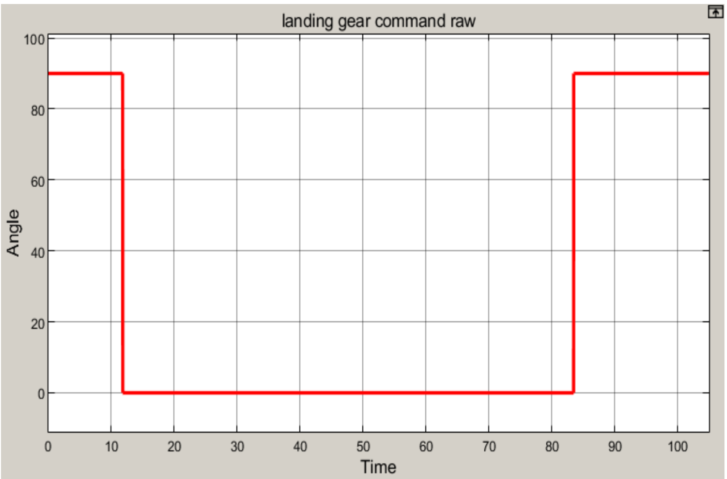

Figure 12. Landing gear commands without using servo valve

Figure 13 shows the impact of the command smoothing signals on the system input in comparison with the original command operating system. The horizontal axis illustrates the time, while the vertical axis shows the command angle.
The red graph indicates the original operating status, which has abrupt cuts in the command signal. At around t = 11.8 s, the signal suddenly changes from 90° to 0°, and at around t = 83.5 s, it suddenly goes back to 90°. Such abrupt changes in the signal indicate the ideal command but may be unrealistic in their effect on a real system if the system undergoes the same level of stress or oscillations.
In this case, the green line represents the smooth command that results when the smoothing transfer function (servo valve transfer function) is applied. In this process, instead of a sudden change, the smooth signal changes gradually, as indicated by the exponential response to the change. In the decay part, the command falls smoothly to zero, while in the rise part, the command grows smoothly to the target value without any overshoot.
This is evidence of the smoothing filter's efficiency in constraining abrupt transitions, thereby damping higher frequencies and increasing the system's stability. The resulting filtered output closely tracks the reference command while also providing a more representative system input.

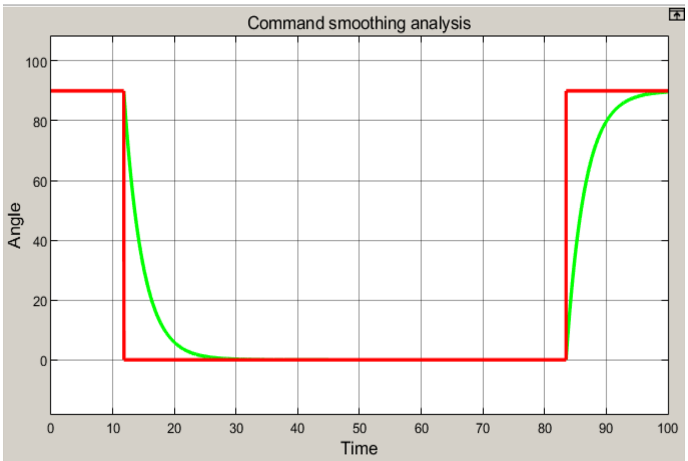

Figure 13. Comparison of landing gear commands with and without using the servo valve

3. Results and discussion

This section will discuss and interpret results gained by simulating the nose landing gear system in various operating modes. The purpose of this chapter will thus be to test the dynamics of the system in both open-loop and closed-loop modes, assess how effective the PID controller design will be, and examine how various disturbances will affect system performance. These results will progressively include basic open-loop and closed-loop results, comparisons, results incorporating disturbances, and eventually results simulating an entire flight scenario. This will thus serve to examine the stability, robustness, and accuracy of the tracking results, as well as the realism and efficacy of the proposed solution.

3.1 Comparative Analysis of System Response: Open-Loop System vs Close-Loop System using PID Controller without disturbances

Figure 14 is a graphical illustration of the comparison between the open-loop response and the closed-loop response. The figure illustrates the system response during an open-loop process with no feedback control. This system is dependent on the dynamics of the system for output values solely on the basis of the control inputs applied to it. Notice that during this system response, there is no corrective measure applied to overcome system variations or steady-state errors to make the system more robust.

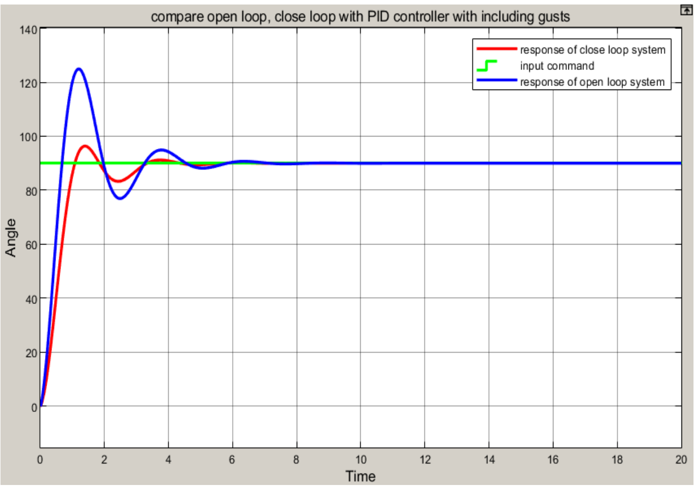

Figure 14. System response compare open-loop with closed-loop with PID controller, without disturbance

It can also be observed that the closed-loop response of the system, with the addition of the PID controller, results in a more stable system that converges faster to the desired command. With the feedback process, the controller is now able to diminish the difference between the desired and actual landing gears. As seen from the obtained responses, in the closed-loop response, the system needs approximately 3 seconds to reach a stable situation. The closed-loop response is better than the open-loop response regarding steady-state error, transient response, and robustness. Hence, the need for feedback control in landing gear actuation is emphasized.

3.2 System response of closed-loop with PID controller, including disturbance

Figure 15 compares the open-loop and closed-loop systems under disturbance. In the open-loop system, there exists instability. Since an open-loop system lacks feedback, it exhibits large variations between the desired and actual outputs because disturbances directly affect the system's output. This verifies that an open-loop system is highly sensitive to disturbances.

Key observations are the following: large deviation of the signal, no disturbance rejection ability, and increased oscillations.

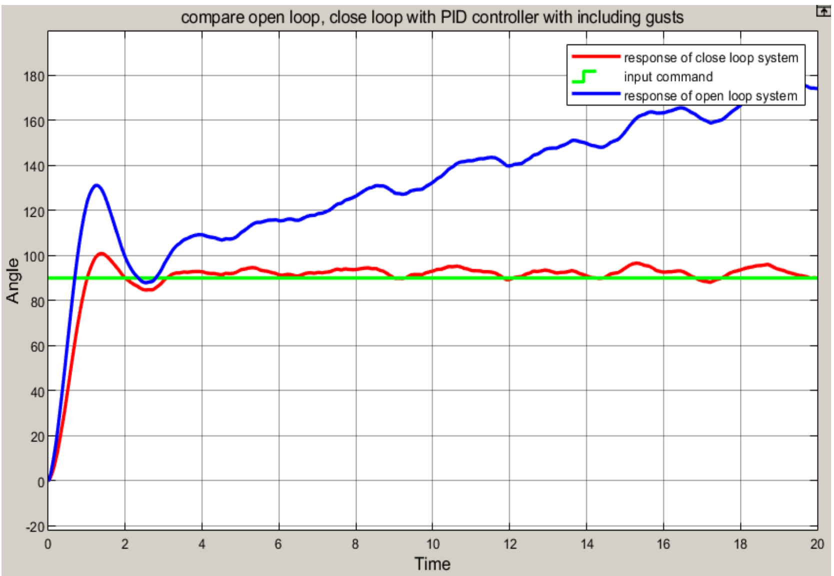

Figure 15. Responses comparing open-loop and closed-loop with a PID controller, including disturbance

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As can be seen, unlike in the open-loop case, the PID-controlled system is capable of rejecting disturbances. Even though small oscillations are observed, the system quickly recovers to track the reference command.
Notable characteristics: Strong interference rejection, Fast recovery time, and Steady-State
This comparison evidently shows the following:
-Advantages of closed-loop control systems
-Feedback and Its Importance for Disturbance Reduction
-The increased accuracy found in the PID-controlled system
This verifies that the PID controller is indeed robust under practical working conditions.
According to the obtained results, as shown in Figures 14 and 15, the following **table 1** will explain the performance analysis based on settling time, peak overshoot, and overshoot percentage.

Table 1. Performance analysis of open-loop and closed-loop systems

Performance Metric	Open-Loop with Disturbance	Closed-Loop with Disturbance	Open-Loop without Disturbance	Closed-Loop without Disturbance
Settling Time (s)	Unstable System	3.151	5.643	3.298
Peak Overshoot	131.430	101.262	125.030	96.320
Overshoot Percentage (%)	46.033%	12.513%	38.92%	7.02%

3.3 Full Scenario Simulation

The full scenario simulation will be conducted in several cases to compare the effects of disturbances and the servo valve on the control system responses.

3.3.1 Full scenario control system without servo valve

Figure 16 presents the time-domain tracking performance of the landing gear system under idealized conditions, specifically excluding external disturbances and the servo valve. The green trajectory represents the step-wise reference command, transitioning the landing gear angle between 90° and 0°. The red trajectory, representing the system's output response, illustrates that the PID controller successfully steers the system toward the target values; however, the transition phases exhibit a distinct transient period. This period is characterized by a noticeable overshoot and a series of damped oscillations before reaching a steady state. Such oscillatory behavior is indicative of the system's dynamic response under the current PID tuning parameters in a disturbance-free environment.

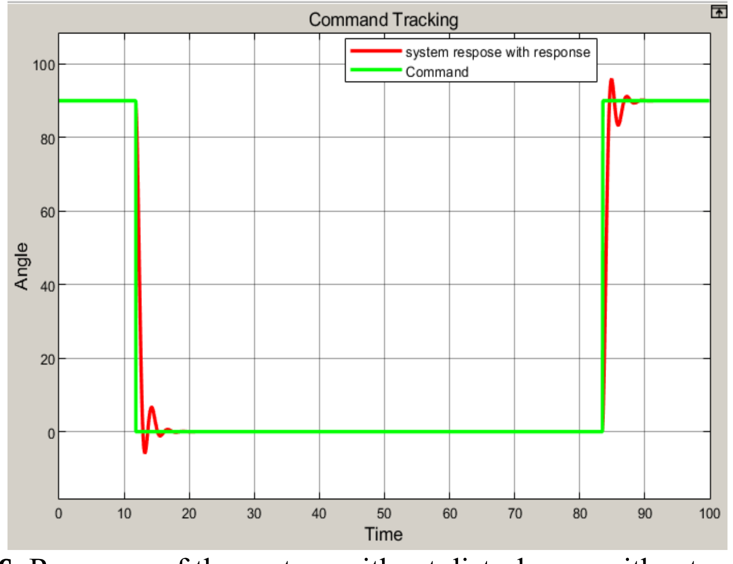

Figure 16. Response of the system without disturbance without servo valve

Figure 17 depicts the time-domain response of the system under the influence of external disturbances. The green trajectory represents the reference command, while the red trajectory shows the actual system response. It is evident that the introduction of 'Gusts' causes continuous high-frequency oscillations (jitter) throughout the entire operational cycle. Although the PID controller manages to track the primary transition from 0° to 90°, the precision is compromised by these perturbations.

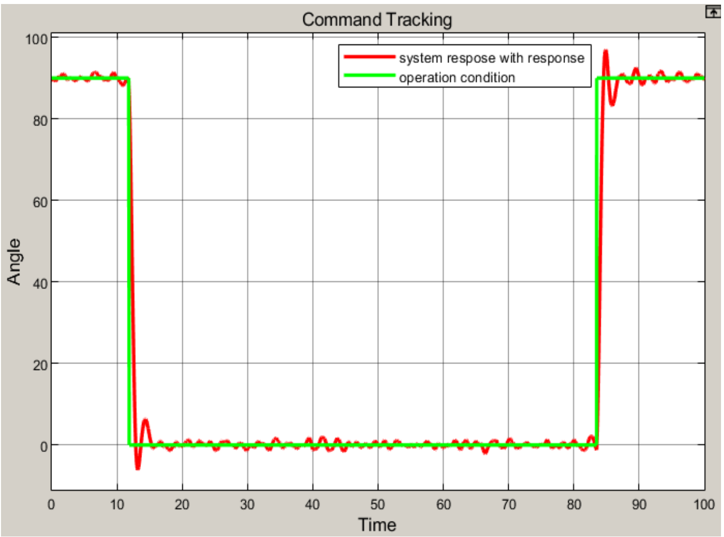

Figure 17. Response of the system with disturbance without servo valve

3.3.2 Full scenario control system with servo valve

Figure 18 shows the responses of command tracking of the landing-gear control system for three servo-valve time constants, τ =1, 3 and 5 s. In all three cases, the system properly tracks the commanded landing-gear motion for retraction and extension, with the response converging to approximately 0∘ for the retracted position and to approximately 90∘ for the extended position. The results observed that in all cases there are no overshoot responses, especially at the moment of extending or retracting the landing gear, and there is high convergence between the system response and ideal command response. When the servo-valve time constant is made greater, the system response slows down progressively, as does the delay between the commanded landing-gear position and the actual landing-gear position. The response for τ =1 s shows that tracking is fastest and apparent time lag is also least. The response with τ = 3 s is slower but still good, with command and system output nearly matching. With a time constant τ = 5 s, the actuator's response is slow, notably during landing-gear extension; however, the system does reach the commanded position with a very small steady-state error. The investigation showed that the increase in the servo-valve time constant dropped the response speed and increased the tracking delay. The tracking was found to be stably maintained with the closed-loop PID controller while the landing gear was effectively maneuvered to the required position for all time constant studies.
All cases excluded external disturbances.

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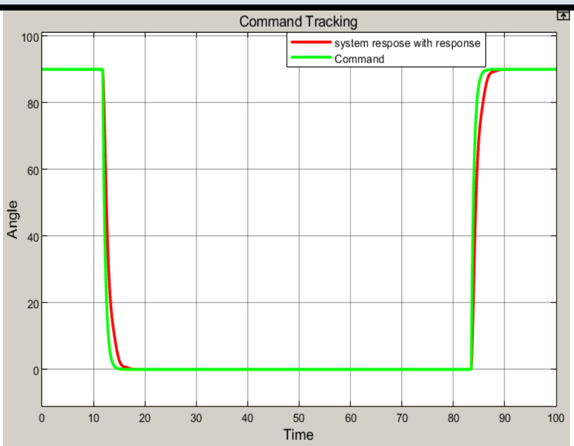
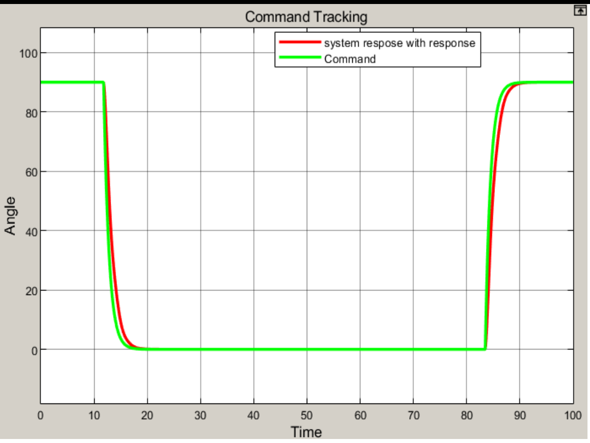
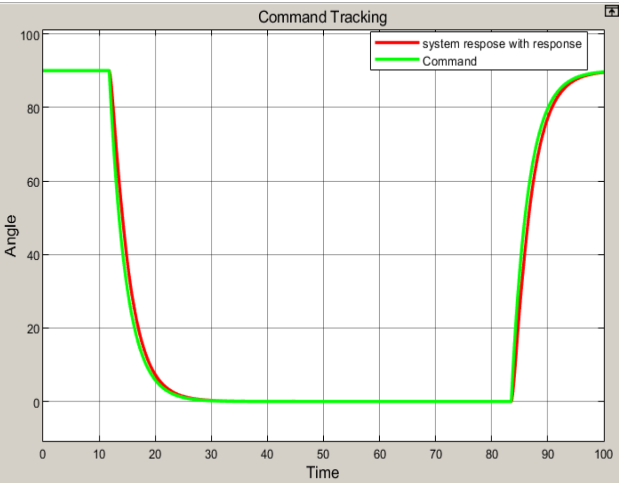


Time constant τ = 1



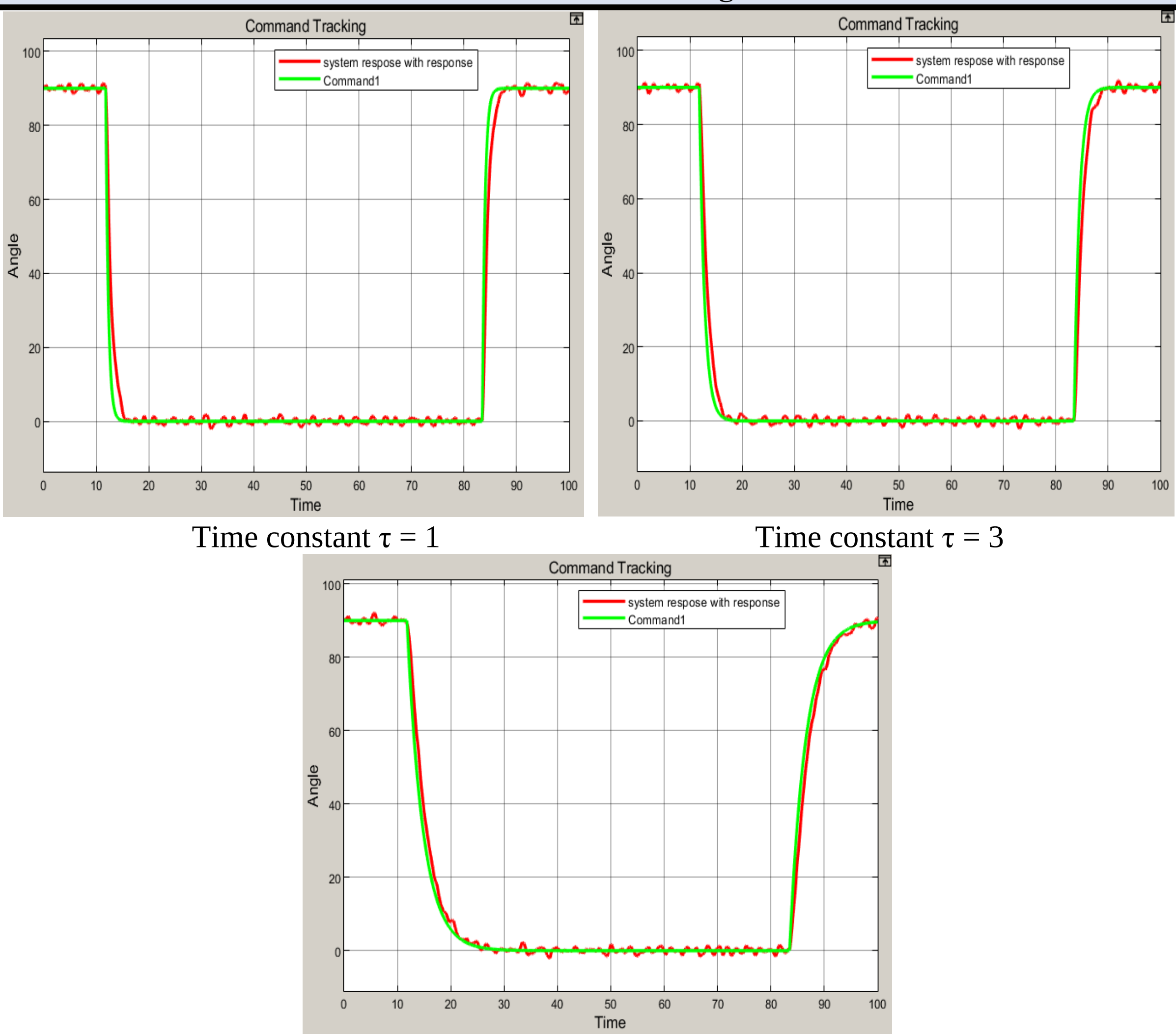
Time constant τ = 3



Time constant τ = 5

Figure 18. Response of the system without disturbance with servo valve at different time constants.

The results are shown in Figure 19; the command-tracking responses of the entire landing gear control system for three values of servo-valve time constant, τ =1, 3, and 5 s, with disturbances. The system successfully controls the commanded motion of the landing gear, both in retraction and extension, in all three cases with a small disturbance that yields only minor fluctuations around the reference trajectory. For τ =1 s, the response follows the commanded trajectory in measure, but significant high-frequency oscillations can be seen throughout the simulation. Adjusting the time constant to τ =3 s produces a response that does not quite track that of the set point but allows the actuator to move more smoothly. At τ=5 s, the response slows down, particularly during the extension phase. Furthermore, a greater transient delay is observed between the commanded and actual positions. Nevertheless, the system is stable and eventually approaches the commanded 90° extended position and 0° retracted position. In general, increasing the servo-valve time constant makes the actuator slower to respond and increases the tracking delay. While the output of the PID feedback controller is stable, it limits the effect of the disturbance applied in all three cases.



Time constant τ = 1 Time constant τ = 3

Time constant τ = 5

Figure 19. Response of the system with disturbance with servo valve

Conclusion

The modeling and simulation of the nose landing gear control system using MATLAB/Simulink have been accomplished with a great focus on dynamic performance, stability, and disturbance rejection. The results clearly depicted that the open-loop system is very sensitive to disturbances and might turn unstable, which is not feasible for safety-critical aircraft applications. On the other hand, the closed-loop system, which involves a well-tuned PID controller, produced the best responses in terms of stability, settling time, and overshoot reduction. Indeed, the response settles in approximately 3.15 s with an overshoot of 12.51% compared to the severe instability and an overshoot of more than 46% observed in the open-loop case. Moreover, the investigation for different time constants (delay time) increases the response time of the system. Hence, for the value of τ = 3, the suitable solution is obtained that brings a good compromise between fast response and smooth and stable landing gear motion. Variations of time constants lead to a change in the extension and retraction of the landing gear operation time. As the time constant increases, the system will operate more slowly. Finally, the findings confirmed that closed-loop PID control represents an essential way to ensure reliable, stable, and representative landing gear operation in terms of both nominal and disturbed conditions.

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