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From Theory to Flight: Design and Application of Pitch Rate Control Augmentation Systems

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Abstract: ***Control Augmentation Systems (CAS) are indispensable components of high-performance military aircraft that provide pilots with the means to optimize control, maneuverability, and agility during manual flight operations. This paper focuses on the design and implementation of Pitch Rate Control Augmentation Systems as an essential subset of CAS. Using the example of an F-16 aircraft, this paper explores the design process, control parameters, and feedback gains involved in developing an effective pitch-rate CAS. The results highlight the impact of various design choices on system behavior, demonstrating the importance of fine-tuning CAS for specific mission requirements and flying conditions.***

Keywords: pitch rate control, CAS, flight, control, autopilot

1. Introduction

The significance of Control Augmentation Systems cannot be overstated, particularly in the high-performance military aircraft domain. CAS [1-5] assumes a critical role when aircraft are tasked with pushing the envelope of their performance capabilities or embarking on missions that demand exacting precision, such as tracking targets with unwavering accuracy and engaging in dogfights. The relentless advancement of flight control technology has endowed CAS with the remarkable ability to furnish pilots with tailor-made control laws, thereby significantly enhancing an aircraft's maneuverability and agility. These enhancements are essential to ensure that military aircraft can fulfill their diverse roles with exceptional proficiency and adaptability, and CAS stands as a testament to the fusion of technology and pilot expertise in achieving these objectives.

In the ever-evolving landscape of modern high-performance military aviation, precision and maneuverability are not merely desirable attributes but essential prerequisites. In this context, Control Augmentation Systems (CAS) dramatically elevate an aircraft's agility and control response. This paper delves into the intricate world of Pitch Rate Control Augmentation Systems, a specialized category of CAS designed to empower pilots with unparalleled control over the aircraft's pitch axis, offering a closer look at their development, significance, and implementation. Section 2 describes the pitch rate control augmentation system. Longitudinal dynamics of F-16 are explained in section 3, and section 4 delves into the design procedure of the control system.

2. Pitch Rate Control Augmentation System

Figure 1 presents a schematic representation of a pitch-rate Control Augmentation System (CAS) [6-9]. In practice, Type-0 control within such systems often proves unsatisfactory due to the substantial control inputs required to modulate the aircraft's pitch, which can involve significant adjustments like multiple degrees of elevator deflection. This becomes problematic when the gains within the error channel remain relatively modest. Consequently, to address this issue and enhance control precision, CAS implementations typically resort to proportional-plus-integral (PI) compensation. Furthermore, in instances where the inherent pitch stiffness is insufficient to achieve desired control outcomes, an additional layer of refinement is introduced through inner-loop alpha feedback.

Moreover, the traditional proportional path of the PI compensator can be substituted with an inner-loop pitch-rate feedback mechanism, depicted as a dashed line in the diagram. This adjustment preserves the integrity of the closed-loop pole configuration while effectively eliminating the PI zero from the closed-loop transfer function. This strategic alteration serves to minimize the degree of overshoot observed in step-response, a pivotal aspect of control system performance. Notably, retaining the PI zero is advantageous when engaging in root-locus design. The ensuing discourse will illuminate the process of designing a pitch-rate CAS, particularly emphasizing its applicability within the context of short-period dynamics, although prudence must be exercised throughout this endeavor.

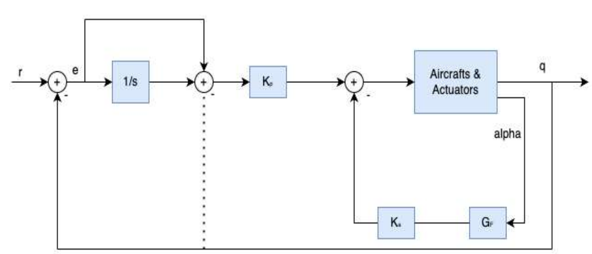

Figure 1: Pitch-rate control augmentation

3. Longitudinal Dynamics of F-16

A nonlinear model of the F-16 aircraft [10-13] , which encompasses six degrees of freedom (6 DOF), was meticulously linearized and trimmed to perfection during straight and level flight conditions, maintaining a velocity of 502.0 feet per second and a center of gravity (cg) position at 0.3c. This meticulous process led to the derivation of the longitudinal dynamics, a crucial foundation for the subsequent application of dynamic inversion control. The resulting model encapsulates the aircraft's behavior during

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these specific conditions, serving as the cornerstone for implementing and assessing the dynamic inversion control approach within the context of F-16 longitudinal dynamics.

$$A = \begin{bmatrix} -0.1270 & -235 & -32.2 & -9.51 & -0.244 \\ 0 & -0.9690 & 0 & 0.9080 & -0.0021 \\ 0 & 0 & 0 & 1.0 & -0.0020 \\ 0 & -4.56 & 0 & -1.58 & -0.2 \\ 0 & 0 & 0 & 0 & -20.2 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 20.2 \end{bmatrix}, C = [0.004 \quad 16.2520 \quad 0 \quad 13.3780 \quad -0.0485]x$$

$$D = 0$$

State variable x is given by x = [α   q]^T
Where α is the angle of attack and q is pitch rate. The input is elevator deflection δ_E

The actuator dynamics can be written as

$$TF = \frac{20.2}{s + 20.2}$$

An alpha filter is corporate having the following dynamics:

$$A = -10 \quad B = [10 \quad 0] \quad C = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad D = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

The filter has been defined with two inputs and two outputs and one input-output pair is a direct connection so that q is available as output 2.

4. Design Procedure

The control design process involves several key steps in optimizing the performance of the Pitch Rate Control Augmentation System. To achieve the desired outcome, various parameters need to be considered and adjusted. In the context of this study, the choice of feedback gain, particularly the value of k□, plays a crucial role.

Firstly, the choice of k□ is pivotal, as it significantly impacts the system's performance. By considering different values of k□, we can gauge the system's response and behavior. In the initial scenario with k□ set at 0.20, the q/u1 transfer function is defined. This transfer function provides insights into the relationship between pitch rate and elevator deflection. It is essential to scrutinize this relationship to ensure the system's stability and responsiveness.

The subsequent step involves observing the behavior of the root locus of the outer loop as the proportional gain, k_p, varies. The root locus is a graphical representation of the system's pole locations concerning changes in k_p. Notably, the integrator pole's movement is a key point of interest. In particular, its positioning relative to the zero at –1.029 is crucial. Additionally, the location of the compensator zero should be strategically chosen to the left of this zero to ensure stability and desirable system dynamics. This process allows us to identify a suitable configuration where the short-period poles are maintained within an acceptable range.

To refine the system's performance further, the amount of alpha feedback, represented by k□, is modified. By reducing k□ to 0.08, the integrator pole's behavior is adjusted to achieve better performance characteristics. In this context, the compensator zero is retained at a specific location, intending to influence the short-period poles to meet the desired criteria. The resulting root-locus plot illustrates how these adjustments lead to the integrator pole reaching a favorable position while maintaining the short-period poles within the required range. This strategic control design, with k_p = 0.5, yields promising results and is considered a valuable approach for enhancing the system's performance. Ultimately, this design is evaluated through a closed-loop step response to ensure its effectiveness in practice.

5. Results

The results of the control system design and its evaluation are presented in Figure 2. This step response analysis offers critical insights into the system's behavior. The curve depicts the pitch-rate response with the compensator zero in place, showing a fast rise time but a notable drawback, a large overshoot of nearly 20%. This overshoot exceeds the acceptable range and falls short of satisfying the "deadbeat" requirement for optimal system response.

In contrast, the other curve illustrates the pitch-rate step response when the compensator zero is removed. Although this modification leads to a longer rise time, it exhibits a significant advantage – a reduced overshoot of approximately 2%. The settling time, a key measure of system stability, remains relatively consistent. This outcome suggests that removing the compensator zero might be a promising design adjustment, offering a more controlled and stable system response.

To further evaluate this promising design, the same feedback gains, with k□ set at 0.08 and k_p at 0.5, are applied to the complete longitudinal dynamics outlined in section 3. The closed-loop transfer function obtained reveals the system's dynamics, featuring specific pole and zero locations. Notably, the impact of these adjustments is seen in the short-period approximation, where the phugoid mode has degenerated into two real poles. Furthermore, the phugoid poles are canceled by zeros, ensuring they do not influence the pitch-rate response.

This behavior highlights the intricate and dynamic nature of a pitch-rate Control Augmentation System (CAS). While this particular design shows promise, it's essential to emphasize that a comprehensive optimization process requires rigorous comparisons with flying quality standards, piloted simulations, and real-world flight tests. Furthermore, the selection of feedback gains depends on various parameters, such as dynamic pressure, indicating the need for meticulous design adjustments throughout the speed-altitude envelope to achieve optimal system performance.

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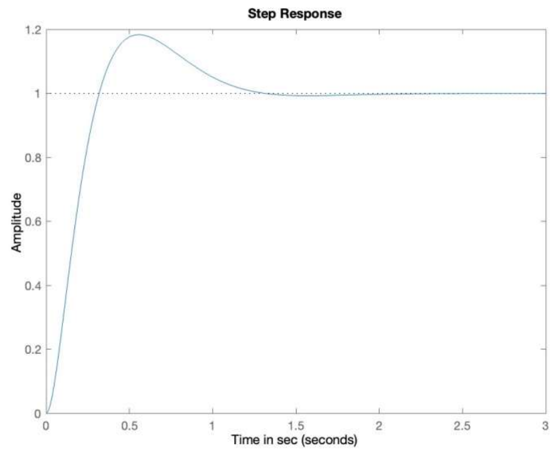

Figure 2: Closed-loop response

6. Conclusion

In conclusion, this paper has delved into the intricate world of Pitch Rate Control Augmentation Systems (CAS), which constitute a pivotal element in the development of advanced control systems for high-performance military aircraft. These systems have shown their mettle in enhancing precise control over pitch rates, a crucial factor in optimizing aircraft maneuverability. Their significance becomes most pronounced in demanding scenarios like dogfights and precision target tracking, where their role in providing the necessary agility and response capabilities cannot be overstated.

Throughout this exploration, we have underscored the value of CAS in high-performance military aircraft, particularly in situations where pilots must operate close to the aircraft's performance limits or undertake specialized tasks. The evolution of flight control technology has allowed CAS to provide task-specific control laws, which in turn enhance the aircraft's maneuverability and responsiveness. The ability to fine-tune the control system, optimizing the interaction between pilot and aircraft, is paramount in ensuring mission success and pilot safety in modern air combat environments.

Furthermore, the paper has illuminated the intricate process of CAS design and the importance of striking the right balance between feedback gains, pole-zero placement, and system response characteristics. It has shown that meticulous tuning is required to achieve the desired performance while adhering to strict flying quality standards and conducting comprehensive piloted simulations and flight tests.

In essence, the development and implementation of Pitch Rate Control Augmentation Systems stand as a testament to the relentless pursuit of precision, control, and maneuverability in high-performance military aviation. These systems not only bolster the capabilities of the aircraft but also serve as a testament to the synergy between humans and machines, where technology empowers pilots to execute complex maneuvers with confidence and precision. As we look to the future of military aviation, CAS will continue to play a central role in ensuring that aircraft remain at the cutting edge of agility and responsiveness, enabling them to meet the demands of modern air combat scenarios.

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