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Fuzzy Stability Augmentation System For Aircraft Handling Qualities

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ABSTRACT: The handling qualities of an aircraft are those qualities or features that govern the ease and precision with which a human pilot is able to perform actions. Therefore, the requirements akin to them are subjective, hence they can only be described qualitatively.

Stability augmentation systems are means for suitably providing the aircraft with appropriate handling qualities. They are based on state feedback control concepts and improve the stability characteristics of aircraft which lack desirable handling qualities. However, most of the existing stability augmentation systems only cope with real-valued feedback gains. Since the flight characteristics vary smoothly in the flight envelope and that unknown disturbances may affect the aircraft dynamics, existing stability augmentation systems usually produce not so reliable control performance. The present paper proposes a method for stability augmentation in which the requirements for the handling qualities are modeled by using fuzzy sets to capture the subjective features tied to the concept of quality.

1 Introduction

The relevancy of an aircraft flight with respect to the human pilot control actions is called handling qualities. The handling qualities of an aircraft are those qualities or features that govern the ease and precision with which a human pilot is able to perform actions. Therefore, the requirements akin to them are subjective, hence they can only be described qualitatively. The aerodynamic stability derivatives of an aircraft affect the damping and the frequency of its longitudinal and lateral dynamics. Because the stability derivatives change all along the flight envelope, the handling qualities vary as well.

Stability augmentation systems are means for suitably providing the aircraft with appropriate handling qualities. They are based on state feedback control concepts and improve the stability characteristics of aircraft which lack desirable handling qualities. They consist first in determining the feedback gain matrix K according to the handling quality requirements and then in computing the control law: $U = f(K^T, X, U_p)$, where f is a function, K^T is the transpose of the feedback gain matrix, X is the state vector and U_p is the pilot input. However, most of the existing stability augmentation systems only cope with real-valued feedback gains. Since the flight characteristics vary smoothly in the flight envelope and that unknown disturbances may affect the aircraft dynamics, existing stability augmentation systems which are mostly based on linear and crisp models usually produce not so reliable control performance.

The present paper proposes a method for stability augmentation in which the requirements for the handling qualities are modeled by using fuzzy sets to capture the subjective features tied to the concept of qualities. This enables us to take into account the uncertainties in the aircraft model and those pertaining to the qualitativeness of the knowledge about handling qualities. As such, the components of the feedback gain matrix K are fuzzy numbers and the computation of u in the aforementioned equation gives a fuzzy control vector. To produce smooth control actions we propose an adaptive method for defuzzifying the control vector. This ensures to deal conveniently with the handling qualities in the entire flight envelope even when the state vector of the aircraft is only known approximately. Finally the proposed approach is illustrated by an application example on longitudinal handling qualities to demonstrate its relevancy.

2 Longitudinal Handling Qualities

In this section we should describe longitudinal handling qualities [5]. For that we examine the longitudinal motion of an aircraft without control input. The longitudinal motion of an aircraft, with controls fixed, is characterized by two oscillatory modes of motion when disturbed from its equilibrium state. One of these modes is slightly damped, has a long period and is called the long-period or the phugoid mode. The other mode is highly damped, has a very short period and is called the short-period mode.

The long-period can be seen as a gradual inter-

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change of potential and kinetic energy about the equilibrium altitude and airspeed. The long-period mode is characterized by changes in pitch, altitude and velocity. Generally these changes occur at a slightly constant angle of attack. Thus, an approximation to the long-period mode can be obtained neglecting the pitching moment equation and assuming that the angle of attack remains strictly constant.

Among the two characteristic modes, the most important from the standpoint of stability and control is the short-period mode. When this mode has a high frequency and is highly damped, then the aircraft will respond swiftly to an elevator input without any undesirable overshoot. When it is slightly damped or has a small frequency, the aircraft may be difficult to control, and this may even be dangerous to fly. Meanwhile, the phugoid mode occurs so slowly that the pilot can easily act against the disturbances by small controls. eventhough the pilot can easily control the phugoid mode, it would be extremely tiring and boring if the damping ratio were too low.

By using active control stability augmentation system, the requirement of static stability can be relaxed without degrading the aircraft flying qualities.

The flying qualities of a human-piloted aircraft are related to the stability and control characteristics and can be defined as those stability and control characteristics that are important in forming the pilot's impression of the aircraft. The pilot form subjective opinions about the ease or difficulty of controlling the aircraft in steady and maneuvering flight. These opinions are rated into three levels. Before describing these levels it is necessary to talk about the flight phase categories:

Category A: Nonterminal flight phases that require rapid maneuvering, precision tracking, or precise flight-path control. This category deals exclusively with military aircraft.

Category B: Nonterminal flight phase that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required.

Category C: Terminal flight phases are normally accomplished using gradual maneuvers and usually require accurate flight-path control. Included in this category are takeoff, approach, wave-off/go-around and landing.

The levels describing the pilot opinion about the flying qualities of an aircraft are:

Level 1: Flying qualities clearly adequate for the mission flight phase.

Level 2: Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.

Level 3: Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A flight phases can be terminated safely, and Category B and C phases can be completed.

Research work has shown the relationship between the levels of flying qualities and the damping ratio and undamped natural frequency of the short-period mode. Table 1 is a summary of the longitudinal specifications for short-period motions which is valid for any aircraft.

	Categories A & C	**Category B**
Level 1	$0.35 \leq \zeta \leq 1.30$	$0.3 \leq \zeta \leq 2.0$
Level 2	$0.25 \leq \zeta \leq 2.00$	$0.2 \leq \zeta \leq 2.0$
Level 3	$\zeta \geq 0.15$	

Table 1. Damping ratios ζ for the short-period mode.

3 The fuzzy stability augmentation system

From the previous section it is clear that the concept of flying qualities is qualitative, hence subjective. Consequently, we resort to fuzzy computing for achieving the desired flying qualities. The stabilizing control for meeting flying qualities can therefore be done by fuzzy control. Before presenting the methodology we use for solving the problem in the framework of fuzzy computing, we present a concrete stability augmentation problem that will be used in the remaining of the paper for illustrating our approach.

3.1 Problem statement

Let us consider an aircraft in a longitudinal flight described in the state space by the equation:

$$\dot{X} = AX + BU \qquad (1)$$

where $X = \begin{pmatrix} \alpha \\ q \end{pmatrix}$, α being the angle of angle of attack and q the pitch rate, $U = \begin{pmatrix} \eta \\ \eta \end{pmatrix}$, η being the elevator deflection.

In the case of bad flying qualities, the pilot input U_p should be augmented so that the airplane dynamics meets the flying quality requirements. Using a linear state feedback control law $U_{sf} = -K^T X$, where K^T is the state feedback gain vector, the augmented dynamics of the aircraft becomes:

$$\dot{X} = A_{au} X + BU_p \qquad (2)$$

where $A_{au} = A - BK^T$.

Let k_1 and k_2 be the components of vector K^T. The problem statement consists in determining these components such that the augmented dynamics of the aircraft is an oscillatory damping motion satisfying the short-period mode level 1 requirements for categories A and C. This means that the damping ratio of the new dynamics of the aircraft should be $\zeta \in [0.35, 1.30]$ and a natural frequency $\omega_n \geq 1$ for categories A and B, and $\omega_n \geq 0.7$ for category C .

For a given state evolution matrix A, the characteristic equation of $A_{au} = A - BK^T$ is of the form (determinant of $\lambda I - A_{au}$):

$$\lambda^2 + \lambda.f(k_1, k_2) + g(k_1, k_2) = 0 \qquad (3)$$

where f and g are functions. By identifying it to the equation of an oscillatory damping motion which is:

$$\lambda^2 + 2\omega_n\zeta\lambda. + \omega_n^2 = 0 \qquad (4)$$

we get the system of equations in k_1 and k_2 :

$$\{2\omega_n\zeta = f(k_1, k_2);\ \omega_n^2 = g(k_1, k_2)\} \qquad (5)$$

If $K^T = [k_1\ k_2]$ is a solution of that system of equation then the state feedback control law is:

$$\eta = -k_1\alpha - k_2 q \qquad (6)$$

The resolution of the above equation is sound in the case of crisp values for k_1 and k_2. This only occurs when the damping ratio ζ and the natural frequency ω_n are real numbers. Meanwhile, due to uncertainties and in the sake of sure stability augmentation, it is more secure to consider the damping ratio or the natural frequency or both as fuzzy numbers. In this case it is convenient to solve the problem in the framework of fuzzy control. We present the methodology usually used to solve fuzzy control problems, that is, rule-based fuzzy control, then we will show its limitations for solving the stability augmentation problem, and finally we we will present an alternative solution for that problem.

3.2 Rule-Based Fuzzy control

Hereafter is summarized the general scheme of rule-based fuzzy control systems [2,4]. First the value ranges of the process variables are quantized into fuzzy sets with predefined membership functions. Then the relationships between the control variables and the controlled variables of the process to be controlled are expressed as fuzzy production rules provided by process operators, or people knowing the process behaviors. This constitutes the rule-base which contains the control rules. For example, we may have simple fuzzy control rules of the kind: *if error (e) is A and sum of errors (ie) is B and change of error (de) is C then the control action is D*. The quantities A, B, C and D in the example are linguistic-valued, for example, they may be *low*, *medium*, *high* or *very high*. While evaluating a rule, the degrees of membership of the antecedent values are combined to form the output strength of that rule. The last step concerns the defuzzification process which aims at computing the controller output based on strengths and membership functions. Defuzzification is required for either decipher the quantified meaning of the linguistic values such as *low* or *high*, or to resolve conflicts between competing actions such as "the control action is *low* and *medium*".

The two most often used defuzzification methods in fuzzy control are the center of area (COA) and the mean of maxima (MOM) methods [5,7].

The MOM method provides a control action which is the mean value of all the control actions whose membership functions reach the maximum. Formally, if u_i is the support value at which the membership function reaches its maximum, and n is the number of such support values, then the defuzzified control action by the MOM strategy is expressed as:

$$u^* = \sum_{i=1}^{n} u_i/n \qquad (7)$$

The COA method gives a control action which is the center of gravity of the centroid points of the membership functions with the areas of the respective membership functions taken as weights. In fact each area is computed after a level-cut of the membership function, the level of the cut being the corresponding output strength determined during rules evaluation. Sometimes, to simplify, the output strengths serve as weights instead of the areas. Formally, when for instance the areas, say A_i, are chosen as weights, and that the centroid points are v_i, then the defuzzified control action by the MOM strategy is expressed as:

$$u^* = \sum_{i=n}^{n} A_i.v_i / \sum_{i=1}^{n} A_i \qquad (8)$$

As exposed in the following section, the proposed approach uses both the MOM and COA methods for defuzzification.

3.3 The Proposed Approach

Solving the Stability Augmentation System (SAS) problem as stated in the problem statement section with rule-based fuzzy control may be awkward because it is difficult to derive reliable fuzzy rules for the problem. The method that we propose is to defuzzify the control η obtained by (Eq. 6). Another aspect of the problem is that we would like the SAS to cope with the entire flight envelope, this requires to resort to an adaptive defuzzification strategy for computing the actual control value over time.

Defuzzification is known as choosing the best value representing a fuzzy set according to some aggregation rule. Being such, it is an expected value of a some distribution. Therefore, we need some set of entity values and their corresponding weights. In fuzzy control based on rules, entity values are given by, for example, the centroid points of membership functions, and the weights by the areas or the strengths of rules as described in section 3.2.

Braae and Rutherford [(1)], and Larkin [(3)] analyzed the COA and MOM strategies and concluded that the COA strategy provides better results than the MOM strategy. Scharf and Mandic [(6)] pointed out that the MOM strategy gave a better transient performance while the COA strategy gave a better steady-state performance. These results suggest us to devise an adaptive fuzzification strategy which matches the MOM strategy during the transient phase and the COA strategy when the process is closed its steady-state. That means that from the transient phase to the steady-state phase the defuzzification strategy should move progressive and smoothly from the MOM strategy to the COA strategy.

Assume that the quantization of the control variable with membership functions is as depicted in (fig. 1), and that the evaluation from the (Eq. 6) gives u_k shown in (fig. 1). Fuzzy interval u_k intersects the fuzzy subsets having membership functions $u^{(1)}, u^{(2)}$ and $u^{(3)}$. Let A_1, A_2 and A_3 be the respective areas of $u^{(1)}, u^{(2)}$ and $u^{(3)}$ in u_k, and v_1, v_2 and v_3 be respectively the support values in u_k at which the membership functions of $u^{(1)}, u^{(2)}$ and $u^{(3)}$ reach their maximum values. Then the MOM strategy is used to defuzzify u_k based on the distribution $\{(v_1, 1), (v_2, 1), (v_3, 1)\}$ where the 1 represents weights, and the COA strategy is also used to defuzzify u_k based on the distribution $\{(v_1, A_1), (v_2, A_2), (v_3, A_3)\}$ where the areas A_i, $(i = 1, 2, 3)$, act as weights.

Let call u_k^{MOM} the defuzzified value of u_k using the MOM strategy, and u_k^{COA} the defuzzified value of u_k using the COA strategy. Then we compute the defuzzified value for u_k as:

$$u_k^* = (1 - \lambda_k) u_k^{COA} + \lambda_k u_k^{MOM}, \tag{9}$$

where $\lambda_k \in [0, 1]$.

The parameter λ_k is updated for each instant k. Since the quantity u_k^* has to go from u_k^{MOM} to u_k^{COA} as the behavior of the process moves from the transient states to the equilibrium state, the value of λ_k has to move too from unity to zero accordingly. Therefore λ_k should be an increasing function of the error. Although many possibilities may exist for incrementally determining λ_k from the error in such a way that the aforementioned constraints are fulfilled, we can simply do as follows: let e_{max} be the maximum value of the error in absolute value, and e_k be the error at instant k, then λ_k is computed as:

$$\lambda_k = \left(\frac{|e_k|}{e_{\max}} \right)^r, \tag{10}$$

where $r > 0$.

Although any positive value of r may be used, experimental tests have revealed that best results, in the sense of the steady-state error and the overshoot, are obtained for $r \geq 1$ but not too high. This can be explained by the fact that for this value range of r, when the control variable approaches the setpoint, λ_k moves more quickly to zero, thus the strategy becomes that of COA sooner. Meanwhile, when r is too high (for example $r \geq 10$), the defuzzification strategy is no more adaptive because it reduces to the COA strategy since λ_k is practically equal to zero (except when $|e_k|$ is close to e_{max}).

A modified semilinear adaptive defuzzification method, called M-SLIDE, based on the Kalman filtering of a parametric weight β is proposed in [(8)]. That method assumes the actual value of β to be known at each instant and it progressively adjusts the prediction of β with its actual value across-time. However, the problem is that the actual value of the parametric weight β cannot be known objectively.

4 Application Example: Landing Control

In this section we solve the problem presented in section 3.1. We consider [(5)]:

$$A = \begin{pmatrix} \text{-0.334} & 1.0 \\ \text{-2.52} & \text{-0.387} \end{pmatrix} \text{ and } B = \begin{pmatrix} \text{-0.027} \\ \text{-2.6} \end{pmatrix} \tag{11}$$

Here the aircraft's short-period characteristics are $\lambda_{1,2} = -0.3605 \pm 1.5872i$, which implies, as illustrated in figure 2, that the stability level is not so high. It is known that the roots of (Eq. 4), when the discriminant is negative, are of the form:

$$\lambda_{1,2} = -\zeta\omega_n \pm i\omega_n\sqrt{1 - \zeta^2} \tag{12}$$

This means that for the example we are dealing with, since $\lambda_{1,2} = -0.3605 \pm 1.5872i$, we have $\zeta = 0.2215$, (and $\omega_n = 1.6274$), which does not meet the flying quality level 1 requirements.

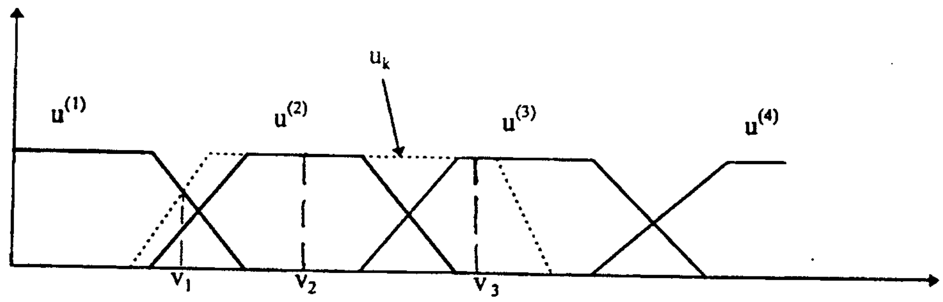
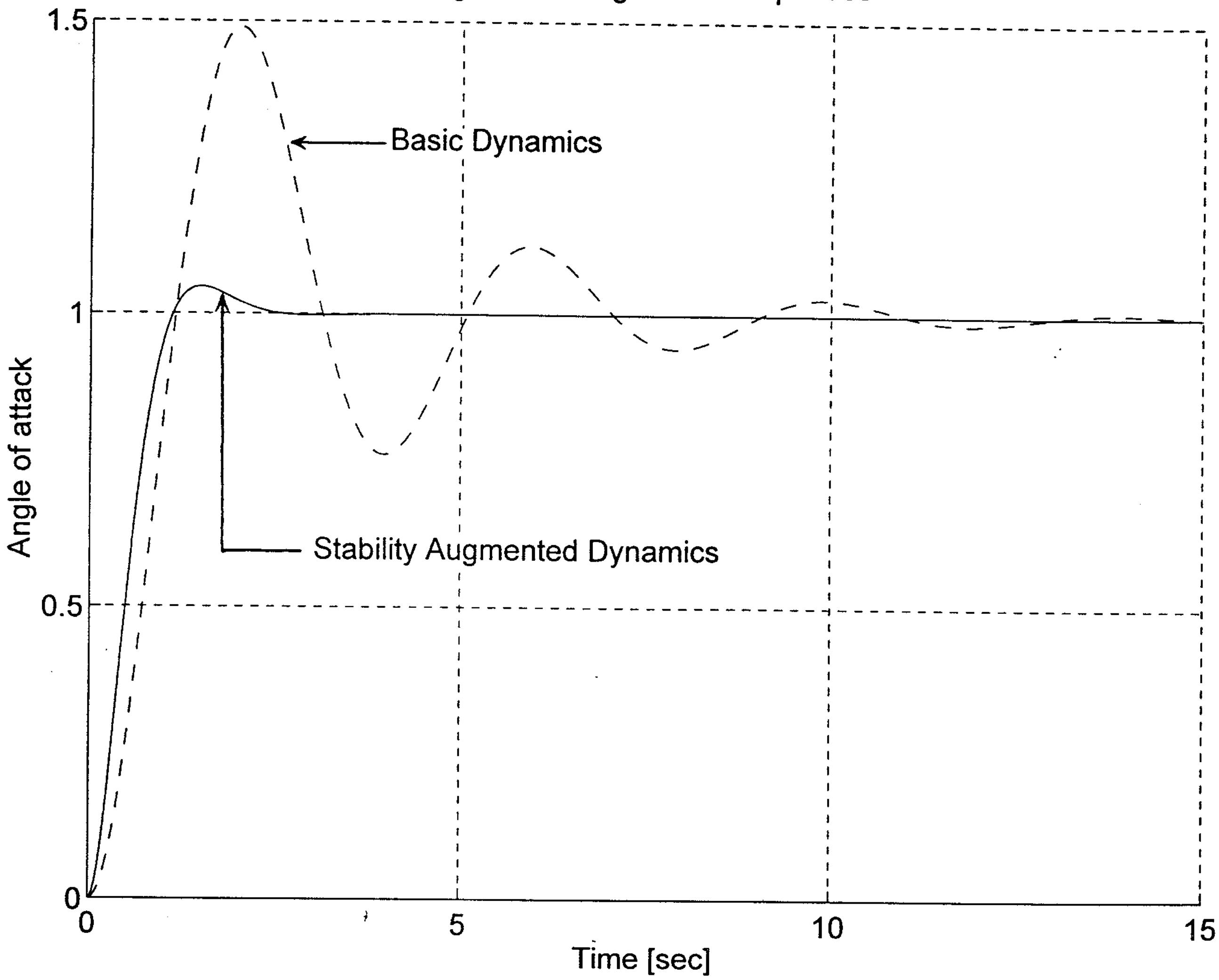


Figure 1: Defuzzification

Figure 2.: Longitudinal responses



Assume we would like to augment the stability of the aircraft to ensure $\zeta \in [0.6, 0.8]$ and $\omega_n \in [2.7, 3.3]$, this corresponds to central short-period characteristics $\lambda_{1,2} = -2.1 \pm 2.14i$.

Applying the method presented in section 3.3, we achieve a comfortable behavior of the aircraft as illustrated in figure 2. Figure 2 illustrates both the basic dynamics and the stability augmented dynamics of the considered aircraft model.

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