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The nonlinear fuzzy intelligent theory for high-bypass-ratio two-spool unmixed-flow jet engines

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Abstract. In our research we have offered a solid solution for aeronautical analysis. which can guarantee the asymptotic stability of coupled nonlinear facilities. According to the theoretical solutions and methods presented, the engine of this aircraft is a small high-bypass turbofan engine. using the non-linear aero-motor control approach and this paper focuses on the power management function of the aero-motor control system. These include static controls and transient controls. A mathematical model of the high-bypass-ratio two-spool unmixed-flow aeroengine was developed through a set of nonlinear dynamic equations verified by experimental data. A single actuator using the displacement method is designed to maintain a certain level of thrust under steady-state conditions. and maintains repeatable performance during transient operation from the requested thrust phase to the next. A single controller can compensate for the effects of noise and harmonic noise at many performance points. And the dynamic performance of a single controller is satisfactory during the transient. for fairness Numerical and computer experiments are described in the perfection of the methods we offer in research.

Keywords: aviation vehicles; inequality controlling & nonlinear stability analysis; linear matrix; spacecraft

1. Introduction

There are two important functions in an aero engine control system: power management and limit protection and power management, including steady-state control and transient-state control. However, the actual control of an aircraft engine consists of static control. Transient controllers and limited controllability Integrated, analog, PI controllers are widely used in industrial applications (including aircraft engines) for steady-state control. The gain approach is based on multi-PI controllers currently implemented in air motor control drums. These sliders correspond to different situations. A corresponding transition strategy is required for the modes selected by the controller. This controller structure has several disadvantages. which is not suitable for the need for advanced control methods. Therefore, the use of nonlinear control technology in aeromotor control makes sense. Performance management of the aeromotor control method is the focus of this research. A single controller differs from a traditional controller, which consists of a static controller and a transient controller. Development of a governor capable of maintaining a given thrust level under steady state conditions. and maintains repeatable performance during transient

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operation from the requested thrust phase to the next. This paper reviews advanced nonlinear control methods. Recently, some of these methods have been proposed to study literature stability and stability of large systems (Yang and Chang 1996, Bedirhanoglu 2014, 2004, 2005, Chiang *et al.* 2007, Liu *et al.* 2009, Liu *et al.* 2010, Hung *et al.* 2019, Eswaran and Reddy 2016 and references included).

The alternative to this research is to develop a method to control the rolling function, which is known to be efficient compared to parametric uncertainty and is used in many industrial applications including wind turbines. The objective of this research is to propose a nonlinear control strategy for the high-bypass-ratio two-spool unmixed-flow aero engine, that is, to implement aero engine energy management. Its main achievements are the high-bypass-ratio two-spool unmixed-flow non-linear model of the aero engine and its advanced non-linear controller. Both can be used for steady state control and transient control. Introducing delay factors often introduces uncertainty and often complicates the analysis. Therefore, the analysis of system latency stability in research (Mori 1985, Trine Aldeen 1995, Tsai *et al.* 2012, 2015, Tim *et al.* 2019, Chen 2011, 2014, Tim *et al.* 2020) have been published and demonstrated.

In recent years there have been many interesting topics related to system control. There have been many successful applications, some successful. It is clear that many fundamental problems remain to be solved. And the main problem in control systems is designing systems to ensure stability. Several stability studies have been done recently (see Tanaka Sugeno 1992, Tim *et al.* 2021, Zhen *et al.* 2021, Chen *et al.* 2022, Hsiao *et al.* 2003, Wang *et al.* 1996, Tanaka *et al.* 1996, Feng *et al.* 1997 and references therein). For example, Chiang *et al.* (2001, 2002, 2004) provided a new criterion for the system, Cheng *et al.* (2002) provided LMI forms for the system, Hsiao *et al.* (2003, 2005) Application of AI theory to nonlinear systems, Hsieh *et al.* (2006) proposed stability analysis for AI, Lin *et al.*, (2010) *et al.* given control implementation in TLP system, Chen *et al.* (2006, 2007, 2009) also demonstrated the effectiveness of neural networks through LDI theory. Recently, Chen *et al.* However, published studies still do not solve the stability and instability problems of large systems with multiple delays.

Therefore, this study provides a stability formula based directly on the Lyapunov method, which provides asymptotic stability for large systems with multiple delays. According to this explanation and the limited control system, fuzzy control groups are involved in the stabilization of large systems in multi-delay systems involving many interconnected systems. Furthermore, these subsystems are represented by a simple Takagi-Sugen delay model in the models Each of these laws is represented by a linear model of the system. Therefore, the linear response of the controller can be used as a fixed response. Therefore, the type of hedging design based on the fuzzy model is the parallel distributed hedging (PDC) model. Lines in all linear spaces use the same assumptions. and we focus on the results showing the best performance of the proposed damage propagation theory for structural analysis of composite materials in space.

Stability measurements are obtained and verified using the Lyapunov method to ensure the asymptotic stability of the system with multiple delays and we focus on the results showing the best performance of the proposed damage propagation theory for the analysis of complex space structures. Finally, descriptive results and conclusions for the numerical model are presented.

2. Coupled system description

This research aims to design a controller based on an aircraft engine model that can control the performance of an aircraft engine in steady and transient conditions. Therefore, aircraft engine models should capture the dynamic and static characteristics of an aircraft engine in a wide range of light. Differential equations are a useful way of establishing a mapping relationship between state variables and input variables. When the diff term is zero, steady state characteristics can be obtained The non-zero term describes a dynamic process, ie the simulated two-axis differential equation. Under high-pressure and low-pressure rotor rotation processes, single-volume dynamic equations are developed in engine modeling, combining variations in aerodynamic parameters and simultaneous equations.

This research ignores heat exchange between high-temperature gases and ingredient of waves, derived from Newton's second law. Eq. (2.1) is the wave dynamics proposed to describe the wave dynamics process at high and low pressure.

$$J\frac{d\omega}{dt} = \Delta M = (M_T - M_C) \tag{2.1}$$

where ΔM Oh The very much strength, M_T Oh The turbine torque, M_C Oh squeezer torque, J Oh The weather from inaction from high Print wave and wave andω sense square speed from the wave aero engine version. The high-bypass-ratio two-spool unmixed-flow engine is developed by low rotor and high print rotor and Dynamic volume Samakarn DGEN 380 engine non-linear system to the engine input vectors:

$$\dot{x} = f(x) + g(x) \cdot u,$$

with x is the state vector and u is the input vector, respectively, defined as follows:

$$x = [n_1 \;\; n_2 \;\; T_4]^T,$$
$$u = [W_f].$$

The vector $f(\mathbf{x})$ and the matrix $g(\mathbf{x})$ read as follows:

$$f(x) = \begin{bmatrix} C_1 \cdot \frac{1}{n_1} \cdot \left(W_{LPT} \cdot q_{m,LPT} \cdot \eta_{lm} - W_{Fan} \cdot q_{m,Fan}\right) \\ C_2 \cdot \frac{1}{n_2} \cdot \left(W_{HPT} \cdot q_{m,HPT} \cdot \eta_{hm} - W_{HPC} \cdot q_{m,HPC}\right) \\ \frac{R \cdot T_4 \cdot q_{m,in}}{C_V \cdot P_4 \cdot V} \cdot (C_P - C_V) \cdot (T_3 - T_4) \end{bmatrix},$$

$$g(x) = \begin{bmatrix} C_1 \cdot \frac{1}{n_1} \cdot W_{LPT} \cdot \eta_{lm} \\ C_2 \cdot \frac{1}{n_2} \cdot W_{HPT} \cdot \eta_{hm} \\ \frac{R \cdot T_4}{C_V \cdot P_4 \cdot V}(C_V - C_P) \cdot T_4 \end{bmatrix},$$

where $C_1 = (30/\pi)^2(1/J_1), C_2 = (30/\pi)^2(1/J_2)$, W_{Fan} means the work consumed by the fan, W_{HPC} means the work consumed by the high pressure compressor, W_{HPT} means the work produced by the high pressure turbine, and W_{LPT} means the work produced by the low pressure turbine.

The following we review a nonlinear aviation stability, that is to simplify the construction of the equation Eq. (2.2), we consider a nonlinear model as follows (Kou *et al.* 2023)

$$\text{Rule } i: \text{ IF any } x_{1j}(t) \text{ is } M_{i1j} \text{ and } \cdots \text{ and } x_{g\,j}(t) \text{ is } M_{ig\,j} \tag{2.2}$$
$$\text{THEN } \dot{x}_j(t) = A_{ij}x_j(t) + \textstyle\sum_{k=1}^{N_j} A_{i\rightleftarrows k\rightleftarrows j}x(t - \tau_{k\rightleftarrows j}) + B_{ij}u_j(t)$$

with

$$w_{ij}(t) = \prod_{p=1}^{g} M_{ipj}(x_{pj}(t)),\ \ h_{ij}(t) = \frac{w_{ij}(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} \tag{2.3}$$

$$\dot{x}_j(t) = \sum_{i=1}^{r_j} h_{ij}(t)\left\{A_{ij}x_j(t) + \sum_{k=1}^{N_j} A_{i\rightleftarrows k\rightleftarrows j}x(t-\tau_{k\rightleftarrows j}) + B_{ij}u_j(t)\right\} + \sum_{\substack{n=1\\ n\neq j}}^{J} C_{nj}x_n\,(t) \tag{2.4}$$

in which $\sum_{i=1}^{r_j} h_{ij}(t) = 1$.

We assume the uncertain terms $\Delta\phi_1(x,t)$ and $\Delta\phi_2(x,t)$ are such that $\forall x \in X$ and t $t \geq 0$,

$$\left|\frac{\Delta\phi_i}{\phi_i}\right| << 1,$$

The following laws are considered

$$\bar{u} = (\phi_{2N})^{-1} \cdot (-\phi_{1N} + \theta),$$

where θ it is treated as a new control input, one is given

$$\dot{S} = (\Delta\phi_1 - \phi_{2N}^{-1}\phi_{1N}\Delta\phi_2) + (I_{2\times 2} + \phi_{2N}^{-1}\Delta\phi_2)\theta$$

where $S_A = \Delta\phi_1 - \phi_{2N}^{-1}\phi_{1N}\Delta\phi_2$ and $S_B = I_{2\times 2} + \phi_{2N}^{-1}\Delta\phi_2$

This S_A and S_B bounded, meaning that there is a positive constant S_{AM}, S_{Bm} and S_{BM} exactly like in $\forall x \in X$ and $t \geq 0$,

$$|S_A| \leq S_{AM},$$
$$0 < S_{Bm} \leq |S_B| \leq S_{BM}.$$

Is $S = 0$ in a short time; even with uncertain values from S_A and S_B, control is this is the base in scroll mode control approach [8] and to write exactly like

$$\theta = \begin{bmatrix} K_1 sign(S_1) \\ K_2 sign(S_2) \end{bmatrix},$$

where K_1 and K_2 coefficients from the underwear gunctionality test law and the K writing exactly like

$$K > \frac{S_{AM} + \lambda}{S_{Bm}},$$

where l is Mr positive as they allow to fulfill displacement condition $S\dot{S} \leq \lambda|S|$ (this is $S\dot{S} < 0$) which ensures the convergence of S up to 0.

3. Coupled system criterion of smart control

According to the decentralized fuzzy controllers using the parallel distributed compensation (PDC) method to stabilize the coupled system in the following form:

Rule *i*: IF $x_{1j}(t)$ is M_{i1j} and $\cdots$ and $x_{g\,j}(t)$ is $M_{ig\,j}$

$$\text{THEN } u_j(t) = -K_{ij}x_j(t)\,, \tag{3.1}$$

$$u_j(t) = -\frac{\sum_{i=1}^{r_j} w_{ij}(t) K_{ij} x_j(t)}{\sum_{i=1}^{r_j} w_{ij}(t)} = -\sum_{i=1}^{r_j} h_{ij}(t) K_{ij} x_j(t). \quad (3.2)$$

$$\dot{x}_j(t) = \sum_{i=1}^{r_j} \sum_{f=1}^{r_j} h_{ij}(t) h_{fj}(t) [A_{ij} - B_{ij} K_{fj}] x_j(t) + \phi_j(t). \quad (3.3)$$

$$\text{for } i = 1, 2, \cdots, r_j\,;\ i < f \le r_j\,;\ j = 1, 2, \cdots, J \quad (3.4)$$

$$\dot{V} = \sum_{j=1}^{J} \dot{v}_j(t) = \sum_{j=1}^{J} [\dot{x}_j^T(t) P_j x_j(t) + x_j^T(t) P_j \dot{x}_j(t)] \quad (3.5)$$

4. Example

In this section, we will examine Fisher's equations and temperature control of high-speed aircraft cooling coils to demonstrate about this effectiveness of these proposed method in design. Fisher's equations have been used as the basis for various models of spatial gene spread of populations, chemical wave propagation, flame propagation, branched brown motion processes, and reactor theory. Consider a aviation stability from the coupled system composed of three linking in and out states which are described as follows.

Subsystem 1:

Rule 1: If $x_{11}(t)$ is M_{111}

Then $\dot{x}_1(t) = A_{11} x_1(t) + B_{11} u_1(t)$

Rule 2: If $x_{11}(t)$ is M_{211}

Then $\dot{x}_1(t) = A_{21} x_1(t) + B_{21} u_1(t)$

$$\text{with } A_{11} = \begin{bmatrix} -29 & 1 \\ 3 & -12 \end{bmatrix}, A_{21} = \begin{bmatrix} -25 & -4 \\ 5 & -14 \end{bmatrix}, B_{11} = \begin{bmatrix} 0.5 \\ -2 \end{bmatrix}, B_{21} = \begin{bmatrix} 0.3 \\ 1 \end{bmatrix} \quad (4.1)$$

and membership functions for Rule 1 and Rule 2 are

$$M_{111}(x_{11}(t)) = \frac{1}{1+\exp[-2x_{11}(t)]},\ M_{211}(x_{11}(t)) = 1 - M_{111}(x_{11}(t)).$$

Subsystem 2:

Rule 1: If $x_{12}(t)$ is M_{112}

Then $\dot{x}_2(t) = A_{12} x_2(t) + B_{12} u_2(t)$

Rule 2: If $x_{12}(t)$ is M_{212}

Then $\dot{x}_2(t) = A_{22} x_2(t) + B_{22} u_2(t)$

$$\text{with } A_{12}=\begin{bmatrix}-30 & 1\\ -5 & -16\end{bmatrix}, A_{22}=\begin{bmatrix}-25 & 1\\ -6 & -13\end{bmatrix}, B_{12}=\begin{bmatrix}0.2\\ 2\end{bmatrix}, B_{22}=\begin{bmatrix}0.6\\ -3\end{bmatrix} \quad (4.2)$$

and membership functions for Rule 1 and Rule 2 are

$$M_{112}(x_{12}(t)) = \exp[-x_{12}^2(t)],\ M_{212}(x_{12}(t)) = 1 - M_{112}(x_{12}(t)).$$

Subsystem 3:

$$\text{Rule 1: If } x_{13}(t) \text{ is } M_{113}$$
$$\text{Then } \dot{x}_3(t) = A_{13}x_3(t) + B_{13}u_3(t)$$
$$\text{Rule 2: If } x_{13}(t) \text{ is } M_{213}$$
$$\text{Then } \dot{x}_3(t) = A_{23}x_3(t) + B_{23}u_3(t)\,.$$

$$\text{with } A_{13}=\begin{bmatrix}-37 & 2\\ 2 & -13\end{bmatrix}, A_{23}=\begin{bmatrix}-34 & -3\\ 3 & -14\end{bmatrix}, B_{13}=\begin{bmatrix}0.8\\ -2\end{bmatrix}, B_{23}=\begin{bmatrix}0.9\\ 1\end{bmatrix} \quad (4.3)$$

and membership functions for Rule 1 and Rule 2 are

$$M_{113}(x_{13}(t)) = \frac{1}{1+\exp[-4x_{13}(t)]},\ M_{213}(x_{13}(t)) = 1 - M_{113}(x_{13}(t))\,.$$

Moreover, the coupled in and out states matrices among three aviation stability are

$$C_{21}=\begin{bmatrix}1.5 & -2.1\\ -1 & 3\end{bmatrix},\quad C_{31}=\begin{bmatrix}5 & 4.5\\ 3 & 2.5\end{bmatrix},\quad C_{12}=\begin{bmatrix}2 & -3\\ -1.4 & 1.5\end{bmatrix},$$
$$C_{32}=\begin{bmatrix}1 & -2.4\\ -1.4 & 1.2\end{bmatrix},\quad C_{13}=\begin{bmatrix}2 & -0.5\\ -0.6 & 0.5\end{bmatrix},\quad C_{23}=\begin{bmatrix}1 & -1.4\\ 1.2 & -0.3\end{bmatrix}. \quad (4.4)$$

Therefore, aviation stability from coupled systems have the states matrices A_{ij} and B_{ij} shown in Eqs. (4.1-4.3).

Since the pairs (A_{ij}, B_{ij}), $i = 1,2$; $j = 1,2,3$ are all given, we analyze controlled coupled structures as

$$\text{Rule 1: If } x_{11}(t) \text{ is } M_{111} \quad \text{Then } u_1(t) = -K_{11}x_1(t)\,,$$
$$\text{Rule 2: If } x_{11}(t) \text{ is } M_{211} \quad \text{Then } u_1(t) = -K_{21}x_1(t)\,.$$
$$\text{Rule 1: If } x_{12}(t) \text{ is } M_{112} \quad \text{Then } u_2(t) = -K_{12}x_2(t),$$
$$\text{Rule 2: If } x_{12}(t) \text{ is } M_{212} \quad \text{Then } u_2(t) = -K_{22}x_2(t)\,,$$
$$K_{12} = \begin{bmatrix}-14.2857 & -0.5714\end{bmatrix} \text{and } K_{22} = \begin{bmatrix}0.5495 & -1.5568\end{bmatrix}.$$
$$\text{Rule 1: If } x_{13}(t) \text{ is } M_{113} \quad \text{Then } u_3(t) = -K_{13}x_3(t)\,,$$
$$\text{Rule 2: If } x_{13}(t) \text{ is } M_{213} \text{ Then } u_3(t) = -K_{23}x_3(t)\,.$$

In order to satisfy the aviation stability conditions from coupled system of Theorem 1, Eq. (3.6) must be positive we can obtain Q_{ij}, $i = 1,2$; $j = 1,2,3$ from Table 1.

Table 1 The case analysis of the algorithms presented for the instances

input	output	comparison		
		NA	PI	fuzzy
1	12,12,8	4.91	3.18	1.86
2	12,12,12	11.43	12.13	8.32
3	12,12,18	36.62	12.22	6.12
4	12,18,8	12.42	8.22	2.62
5	12,18,12	11.22	13.82	4.82
6	12,18,18	18.62	17.82	8.92
7	12,22,8	6.86	8.71	3.88
8	12,22,12	8.66	7.18	2.33
9	12,22,18	22.18	13.42	12.11
10	18,12,8	7.82	6.67	3.63
11	18,12,12	7.32	7.62	3.11
12	18,12,18	13.82	6.62	4.22
13	18,18,8	13.22	14.22	4.62
14	18,18,12	14.22	13.72	7.18
15	18,18,18	44.14	34.82	12.12
16	18,22,8	13.22	8.27	1.92
17	18,22,12	24.22	17.81	8.32
18	18,22,18	39.22	19.82	6.62
19	22,12,8	11.81	9.87	8.82
20	22,12,12	23.22	13.62	8.27
21	22,12,18	22.32	9.32	6.11
22	22,18,8	19.22	7.92	3.22
23	22,18,12	13.22	11.42	4.29
24	22,18,18	28.22	19.89	6.32
25	22,22,8	38.22	26.22	8.72
26	22,22,12	33.32	8.72	7.63
27	22,22,18	41.26	39.92	13.32
28	28,12,8	21.22	7.32	3.82
29	28,12,12	37.82	12.82	4.13
30	28,12,18	28.22	6.42	4.72
31	28,18,8	38.72	24.62	8.72
32	28,18,12	43.22	24.42	9.32
33	28,18,18	48.22	28.42	11.32
34	28,22,8	88.82	44.72	14.92
35	25,22,12	62.15	44.22	9.22
36	25,22,15	46.22	15.42	7.72

From Figs. 1-2, we see the feasibility of proposed control results. Fig. 3 shows the variation of harmonics in a single controller and a PI controller when the high-bypass-ratio two-spool unmixed-flow aeromotor is operating at the idle power point. Harmonic noise has a terrible effect on air engines. Therefore, it is necessary to study the variation of harmonic noise It can be used to test the robustness of the controller. harmonic Additional damage to the 3rd system. Second, it breaks the static state of the aero engine. bagpipes the controller cannot withstand its influence. A single effactiv of the control adjusts the effect of the harmonics disturbance, which reflects the

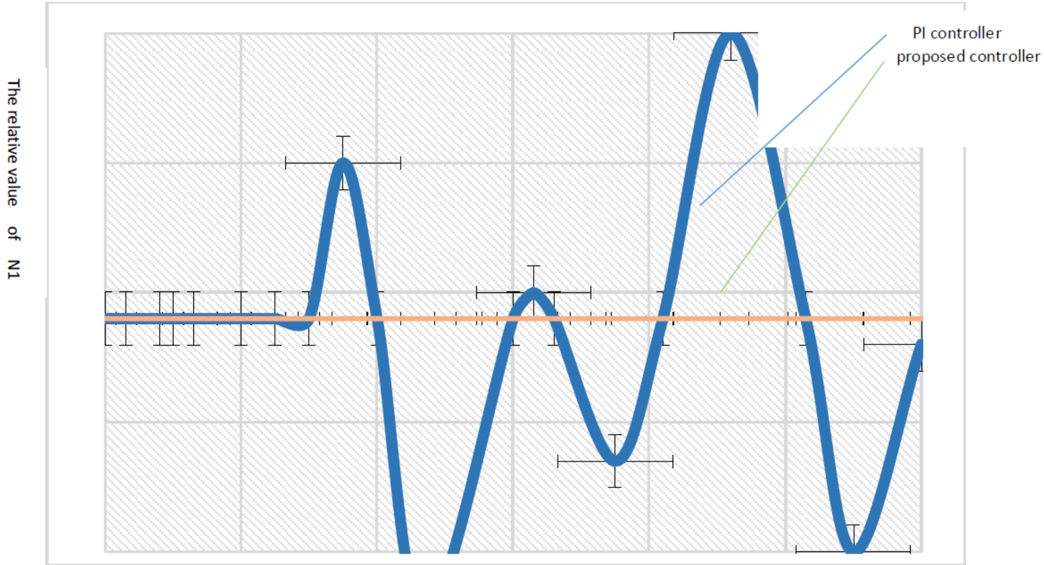

Fig. 1 The simulation results of harmonic disturbance of steady state power management particularly depicted low pressure rotor speed N_1 versus time (s). Turbine outlet temperature versus time (s)

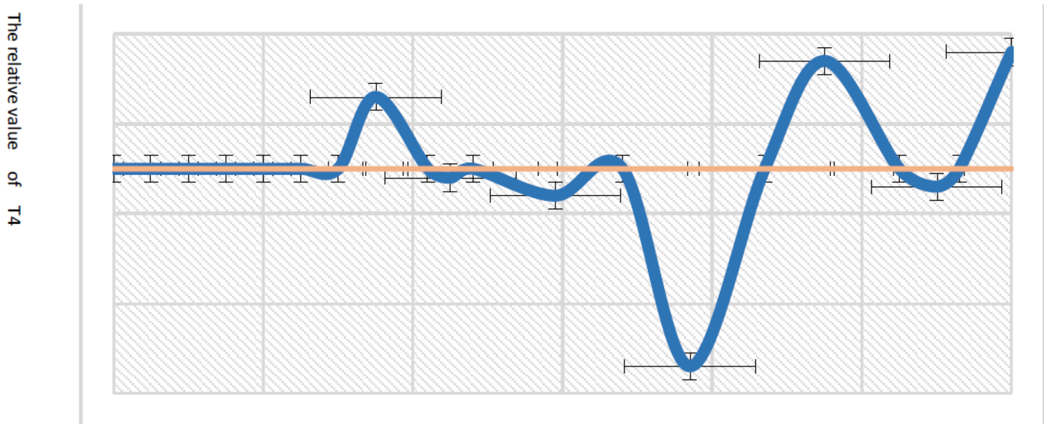

Fig. 2 The simulation results of harmonic disturbance of steady state power management particularly depicted turbine outlet temperature versus time (s)

strength of a single controller. From the steady-state simulation results, a single controller developed by this research has the expected steady-state control characteristics, that is, a single controller of the high-bypass-ratio two-spool unmixed-flow aircraft engine is capable of maintaining the grid thrust at a stable point when the system reaches the surface of the sliding function. The switching mode S is equal to 0 and the system stops in the switching mode state. This means that noise and harmonic noise do not change the state of the system. To ensure that the single controller used on the actual aircraft engine meets the control system requirements, the PLA controls at the 0.4 second point from 21% PLA power (idle power) to 22% PLA power efficiency (output climb). All values shown are typical values, i.e., zero represents the floating state (23%

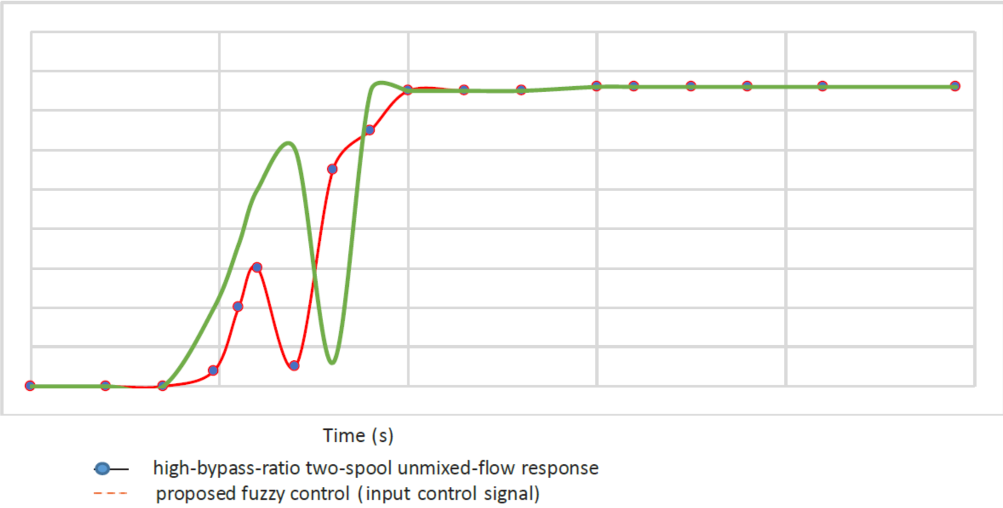

Fig. 3 The test of single controller

PLA energy) and one represents 27% PLA energy. Here the motor control response can meet the demands within the motor control

5. Conclusions

New configuration of small aircraft engines the high-bypass-ratio two-spool unmixed-flow aircraft engine is presented in this research. A nonlinear dynamic model of the high-bypass-ratio two-spool unmixed-flow aircraft engine was developed from the rotor dynamics equation. and the dynamic volume equation meanwhile a method is developed to control the rolling function. This is an advanced nonlinear control technique. A single controller using a slip control method is designed with the objective of maintaining stage thrust during steady state and maintaining reproducible performance during transient operation from one desired thrust level to another. And the dynamic performance of a single controller is satisfactory during the transient. Meanwhile, a controller calculates a smaller amount of fuel. These performances are explained through computer simulations. The individual controller is validated on the engine test bench. The results show excellent performance. We focus on damage propagation for structural analysis of in-plane composites. Modified fuzzy control commands The following is implemented as a feedback theory based on the energy function and the optimal stability criterion of LMI, which allows researchers to solve this problem and ensure that the whole integrated system is asymptotically stable. We focus on results that demonstrate the high performance of the proposed theory applied to damage propagation for in-plane structural analysis of composites.

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