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TECHNICAL NOTE

Optimized Fuzzy Logic for Nonlinear Vibration Control of Aircraft Semi-active Shock Absorber with Input Constraint

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ABSTRACT

Landing impact and runway unevenness have proximate consequence on performance of landing gear system and conduce to discomfort of passengers and reduction of the pilot's capability to control aircraft. Finally, vibrations caused by them result in structure fatigue. Fuzzy logic controller is used frequently in different applications because of simplicity in design and implementation. In the present paper, this control approach is performed by minimum error criteria procedure and bees algorithm as the optimization technique for the model of semi-active suspension system that chooses damping performance of shock absorber at touchdown to be the purpose of control on landing gear and its efficiency is evaluated with the competence of passive control. Results of numerical simulation by matlab/simulink software indicate that the force induced to body and the vertical vibration of fuselage have important improvement (60% and 50%) for fuzzy intelligent method optimized by bees algorithm compared to passive approach which lead to increase in quality of landing, easiness of passengers and structure's fatigue life in various operation conditions.

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1. INTRODUCTION

Fuzzy controllers are nonlinear controllers which have successful applications in practical problems. Fuzzy systems can be utilized in mechanical control systems like air conditioning, cars, ships, robotic arms, in industrial control processes and many other types of application. Fuzzy logic is applicable in many different areas for wide variety of problems. Engineering, medicine, and biology are just a few fields where fuzzy logic is successfully applied.

Fuzzy controllers, unlike the classical controllers (PID and LQR Controller) can control system without mathematical model of the system using the experience of experts in the law "if-then" which is expressed in fuzzy. That is one major advantage of fuzzy logic, because the designer does not need to know everything about the system before starting the work, and simplicity provides solutions to what were once unsolvable problems. One of the main disadvantages of fuzzy controllers is that they are not able to learn, have knowledge and experience of experts in the knowledge basis used in the controllers [1]. In order to overcome this problem and automate the designing of fuzzy controllers, an optimization algorithm can be used. For this purpose, there are several ways in which fuzzy logic is combined with other algorithms such as Genetic Algorithm [2], Ant Colony [3], Particle Swarm Optimization [4] and Neural Network [5]. Another effective method is to design fuzzy controllers using the Bees Algorithm. The Bees Algorithm is used to optimize various problems [6-8]. The benefit of this new algorithm is then used by researchers in a variety of functions such as single objective, multi objective, with and without constraints [6, 7, 9-12].

Parallel high-speed solenoid valves as actuator for the semi-active controlled landing gear has been selected. The simulation results indicate that the semi-active control based on fuzzy PD control rule can effectively improve the control performance and reduce

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impact load during landing. Two explorers [14] have presented a semi- active landing gear system for full aircraft model controlled with fuzzy logic. It is shown that the impact and vibration isolation properties as well as the dynamic response of motions can be significantly improved. [15] demonstrated performance improvement of semi-active vibration absorber system on the basis of PID-BA approach that selects orifice area of subsystem as control parameter without input constraint.

The aim of this paper is to present a novel method to automatically adjust membership functions of fuzzy logic controllers optimally. This method is useful for widespread systems. The membership functions include numerous variables. In the first step, the structure of fuzzy logic controller is described. In the second step, structure of Bees Algorithm is described. In the third step, the two masses mathematical model of landing gear with semi-active performance is developed. In the fourth step, fuzzy logic controller membership functions such as triangular, bell shape, Gaussian and trapezoidal obtained for model which is optimized by the Bees Algorithm. In the next step a comparison is made between the simulation obtained by the present method and simulation by the passive approach. Finally concluding remarks are given.

2. DESCRIPTION OF FUZZY LOGIC CONTROLLER

Fuzzy logic systems have a direct relationship with fuzzy concepts, such as fuzzy sets, linguistic variables, and fuzzy logic. From the mathematical point of view, a fuzzy logic system is a nonlinear mapping of an input feature (data) vector into a scalar output. In this section, a fuzzy logic controller is considered in closed loop system according to Mamdani model [16]. Shock absorber stroke measured by transducer as y (t) and reference value as r (t) and error rate are fuzzy logic controller inputs and oil orifice area is output as u (t). The block diagram of fuzzy control system consists of following four main parts as shown in Figure 1.

The mapping of the inputs to the outputs for a fuzzy system is in part characterized by a set of conditions, or in modus ponens (if-then) form. Fuzzy sets are used to quantify the information in the rule base and the inference mechanism operates on fuzzy sets to produce fuzzy sets. Hence, we must specify how the fuzzy system will convert its numeric inputs into fuzzy sets (a process called fuzzification) so that they can be used by the fuzzy system.

The inference mechanism has two basic tasks, determining the extent to which each rule is relevant to the current situation as characterized by the inputs and drawing conclusion using the current inputs and the information in the rule base. A number of Defuzzification strategies exist, and it is not hard to invent more. Each provides a means to choose a single output based on either the implied fuzzy sets or the overall implied fuzzy set [17].

3. TWO MASSES MODEL OF AIRCRAFT WITH SEMI-ACTIVE LANDING GEARS

Using Newton's second law of motion and the system model, the dynamic equilibrium equations for fuselage and semi-active shock absorber system is represented in Equation (1).

3. 1. Mathematical Model of Fuselage and Semi-active Vibration Absorber [17]

$$\begin{aligned} m_1\ddot{y}_1 &= m_1 g - L - F_a - F_o - f \\ m_2\ddot{y}_2 &= m_2 g - F_t + F_a + F_o + f \end{aligned} \qquad (1)$$

4. FUZZY CONTROLLER FOR SEMI-ACTIVE PERFORMANCE

In this section a fuzzy logic controllers is considered the dynamic model in closed loop with zero input according to Mamdani model [17, 18]. Error value (Level) and derived output (Rate) are fuzzy logic controllers inputs. Variation range is defined error between -1 to 1 and the output derived between -5 to 5. Also, the fuzzy logic controller output variation range is between -9 to 9. The number of membership functions for each of the two fuzzy controller inputs and output is equal to 7 and its type is triangular. The location of each membership functions is selected by user and is optimized in next section. Divisions and symbols the intervals are shown in Table 1.

Also, the rules required for fuzzy controllers that are 49 rules are given in Table 2 and the surface is shown in Figure 3.

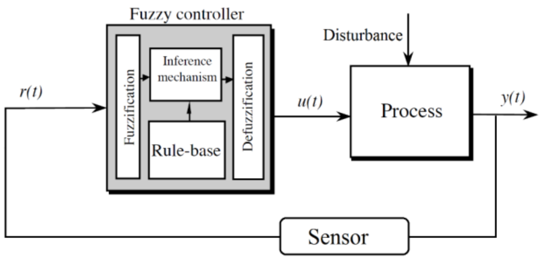

Figure 1. Block diagram of a fuzzy logic system

TABLE 1. Fuzzy variables symbols

Fuzzy variable	Symbol
Negative Big	NB
Negative Small	NS
Negative Zero	NZ
Zero	Z
Positive Zero	PZ
Positive Small	PS
Positive Big	PB

TABLE 2. Fuzzy associative memory table

Error rate / Error	NB	NS	NZ	Z	PZ	PS	PB
NB	Z	PZ	PS	PB	PB	PB	PB
NS	NZ	Z	PZ	PS	PB	PB	PB
NZ	NS	NZ	Z	PZ	PS	PB	PB
Z	NB	NS	NZ	Z	PZ	PS	PB
PZ	NB	NB	NS	NZ	Z	PZ	PS
PS	NB	NB	NB	NS	NZ	Z	PZ
PB	NB	NB	NB	NB	NS	NZ	Z

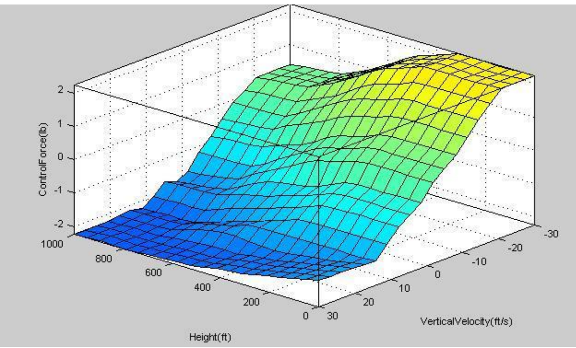

Figure 3. Surface view of rules

Finally fuzzy logic controller to control aircraft semi-active landing gear, by using the Simulink of MATLAB is shown in Figure 4.

5. OPTIMIZATION of FUZZY CONTROLLER MEMBERSHIP FUNCTIONS USING BEES ALGORITHM

Several parts are analyzed to optimize the fuzzy controllers. In this paper the location of membership functions of two inputs and the single output of the controller is optimized. This fuzzy controller has been used for optimizing the ITAE function.

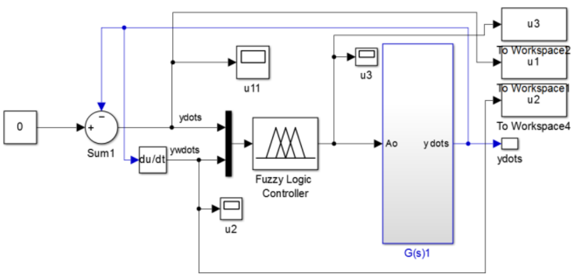

Figure 4. simulink model of Fuzzy controller for semi-active landing gear

Types of membership functions that are optimized in this section are triangular, bell shape, Gaussian and trapezoidal. The triangular membership function has three variables that indicate locations of first, center and ends of triangle.

Bell shaped membership function has three variables which represent function gradient at first (and end), the distance from center to first point (and end) and bell shaped center.

The Gaussian membership function has two variables which represent function gradient at first (and end) and the center of Gaussian functions. The trapezoidal membership functions are four variables that represent locations of four vertices of trapezoid.

The number of variables of each membership function, the number of membership functions (in this paper equal to 7) and the two inputs and output controller should be optimized for triangular (63 variables), bell shaped (63 variables), Gaussian (42 variables) and trapezoidal (84 variables). Parameters of Bees Algorithm are given in Table 3.

After finding the optimal location for the variables of interest, optimized fuzzy controller is obtained. Triangle membership functions optimized for both input and output controller are also shown in Figures 5-7 and the surface in Figure 8.

Bell shape, Gaussian and Trapezoidal membership functions are optimized as well.

TABLE 3. The bees algorithm optimization parameters

Parameter	Type of fuzzy membership functions			
	Trimf	**Gbellmf**	**Gaussmf**	**Trapmf**
N	70	70	50	100
M	25	25	20	30
E	10	10	10	10
nep	8	8	6	8
nsp	4	4	3	4
ngh	0.01	0.01	0.01	0.01

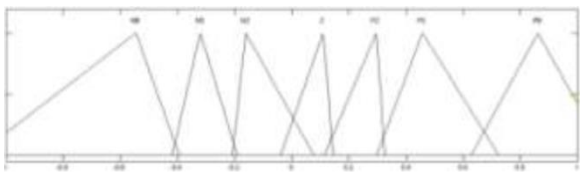

Figure 5. Fuzzy membership functions (optimal trimf) for error

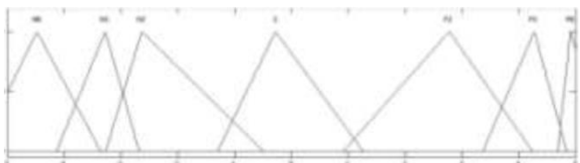

Figure 6. Fuzzy membership functions (optimal trimf) for ydot

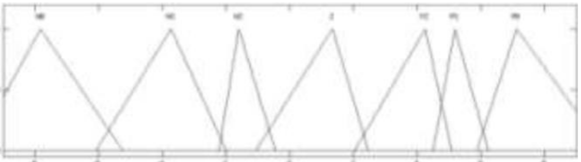

Figure 7. Fuzzy membership functions (optimal trimf) for output

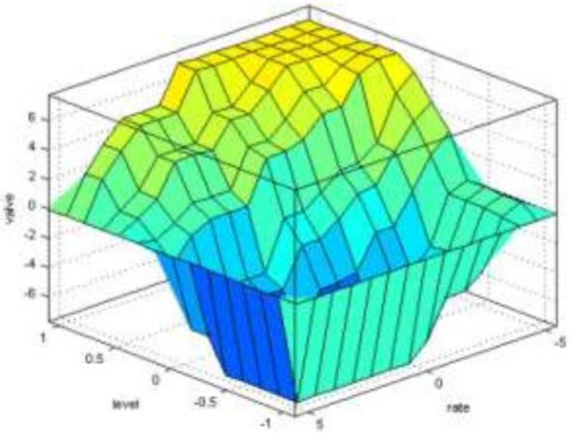

Figure 8. Surface view of rules (optimal trimf)

6. NUMERICAL SIMULATION RESULTS

A6 Intruder airplane with values according to Table 4 as case study is investigated. Dynamic equations for aircraft and landing gear system have nonlinear behavior and damping force is as semi-active control unit with input constraint for actuator controllable parameter of suspension system.

6. 1. Simulation With Uniform Runway Comparison between passive control and Fuzzy logic on the basis of Bees Algorithm for semi-active system is carried out in terms of different sinking speed (normal and hard).

TABLE 4. Data applied in numerical simulation process with MATLAB/SIMULINK

Shock Absorber	Value	Tyre	Value
P_0 (pa)	1.6e+06	k_t (N/m)	1.5e+06
V_0 (m^3)	6.88e-03	c_t (Ns/m)	2.6e+06
A (m^2)	1.376e-02	---	---
A_O (m^2)	6.412e-04	---	---
ρ (kg/m^3)	912	---	---
C_O	0.3	---	---
k_m (Ns/m)	0.7e+04	---	---
k_n (Ns2/m2)	0.1e+05	---	---
n	1.1	---	---

Figures 9 to 12 show that the vertical displacement of the aircraft and the air spring impact load to airframe are reduced using Fuzzy-Expert technique.

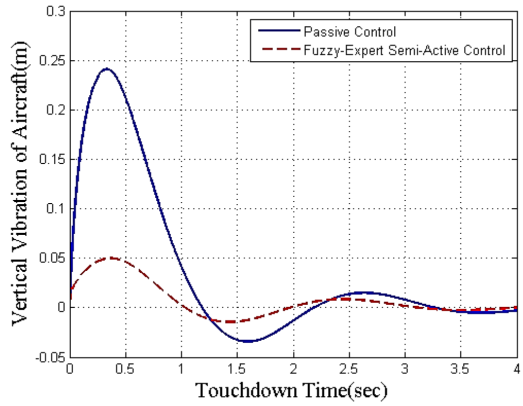

Figure 9. The vibration domain of aircraft under normal landing

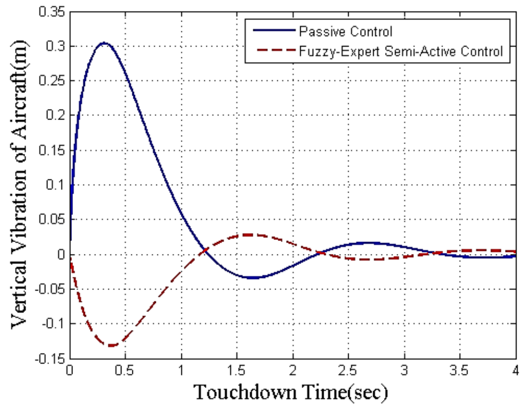

Figure 10. The vibration domain of aircraft under hard landing

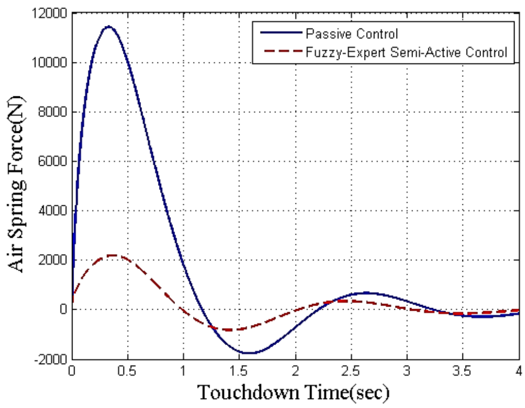

Figure 11. The impact force of aircraft under normal landing

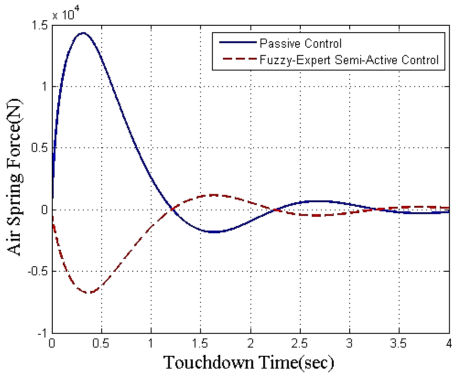

Figure 12. The impact force of aircraft under hard landing

Table 5 summarizes results and demonstrate that improvement percentage of Fuzzy-BA semi-active system is superior to passive system that leads to comfort of passengers and significant improvement over the performance of the passive system.

6. 2. Simulation With Uneven Runway Passive approach and Fuzzy controller is established upon expert knowledge as Bees algorithm for semi-active system. Contrast is presented in terms of various sinking speed (normal and hard).

Figures 13 to 16 show that there is decrease of the aircraft's displacement response and impact force for optimized fuzzy control strategy.

TABLE 5. Comparison of the dynamic response without runway disturbance excitation

Landing condition	Controller	Overshoot (m)	Force (N)
	Passive	0.24	11400
Normal	Fuzzy-Expert (BA)	0.05	2200
	Percent (%)	79	80
	Passive	0.3	14300
Hard	Fuzzy-Expert (BA)	0.13	7000
	Percent (%)	56	51

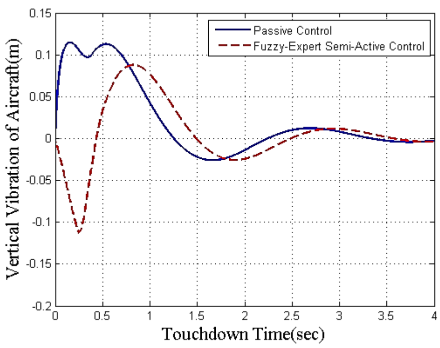

Figure 13. The vibration domain of aircraft under normal landing

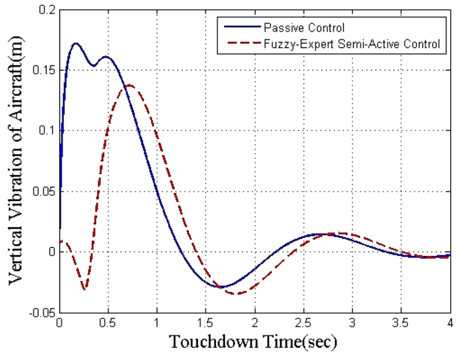

Figure 14. The vibration domain of aircraft under hard landing

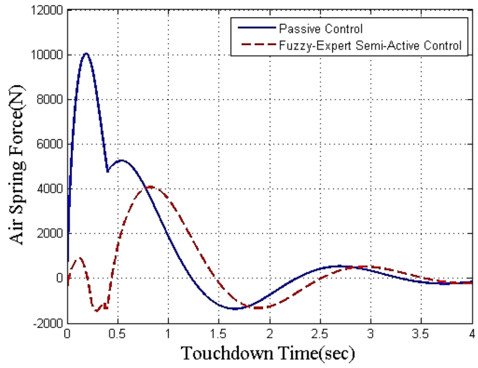

Figure 15. The impact force of aircraft under normal landing

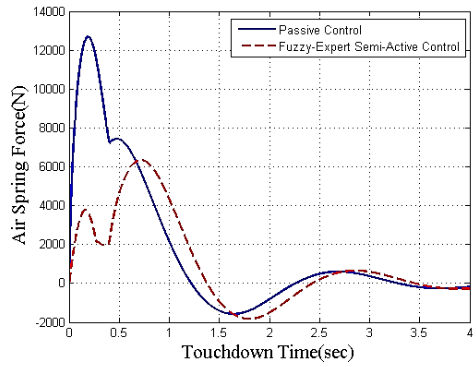

Figure 16. The impact force of aircraft under hard landing

From Table 6, it can be claimed that fuzzy semi-active system based on Bees Algorithm is superior to passive system that deduces to increase in structure's fatigue life.

TABLE 6. Comparison of the dynamic response with runway disturbance excitation

Landing condition	Controller	Overshoot (m)	Force (N)
Normal	Passive	0.1147	10000
	Fuzzy-Expert (BA)	0.1125	4000
	Percent (%)	2	60
Hard	Passive	0.1718	12700
	Fuzzy-Expert (BA)	0.1372	6400
	Percent (%)	20	50

7. CONCLUSION AND FUTURE WORK

This semi-active approach modifies the damping quality by adjusting the size of the orifice area in shock absorber subsystem as nonlinear oleo-pneumatic suspension system. This research shows betterment of passengers' comfort and fatigue life by decreasing vibration domain and impact force. Therefore, it can be deduced that the efficiency of semi-active landing gear for fussy logic based on Bees algorithm is increased compared with passive system. However, the use of optimization algorithm to optimize the membership functions in fuzzy logic, make it an effective method for system performance improvement. In next research, full aircraft model as more complete and complicated vibration model for case study will be investigated and for evaluation and comparison of other intelligent algorithms, Fuzzy logic can be combined with other algorithms such as Genetic Algorithm, Ant Colony, and Particle Swarm.

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چکیده

ضربه فرود و ناهمواری باند روی عملکرد سیستم ارابه فرود اثر مستقیمی داشته و منجر به ناراحتی سرنشینان و کاهش توانایی خلبان جهت کنترل هواپیما می گردد. نهایتا"، ارتعاشات ایجاد شده توسط این عوامل منجر به خستگی سازه می گردد. کنترلر منطق فازی به دلیل سادگی در طراحی و اجرا به طور مکرر در کاربردهای مختلف استفاده شده است. در مقاله حاظر، این شیوه کنترلی با بهره گیری از روش حداقل خطای بحرانی و الگوریتم زنبور عسل به عنوان تکنیک بهینه سازی برای مدل سیستم تعلیق نیمه فعال که عملکرد میرایی ضربه گیر در لحظه برخورد را هدف کنترل روی ارابه فرود درنظر گرفته، پیاده سازی شده و بازده آن نسبت به کنترل غیرفعال مورد ارزیابی قرار گرفته است. نتایج شبیه سازی عددی با نرم افزار متلب/سیمولینک حاکی از آن است که نیروی وارده بر بدنه و ارتعاش عمودی سازه اصلی بهبود قابل ملاحظه ای (۶۰٪ و ۵۰٪) برای روش هوشمند فازی بهینه شده با الگوریتم زنبور عسل در مقایسه با عملکرد غیرفعال داشته است که این امر موجب افزایش در کیفیت فرود، راحتی مسافران و عمر خستگی سازه در شرایط عملیاتی مختلف گردیده است.

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