Int. J. Advanced Design and Manufacturing Technology, 2023, Vol. 16, No. 2, pp. 55-64

DOI: 10.30486/admt.2023.1965079.1373 ISSN: 2252-0406 https://admt.isfahan.iau.ir

Active Control of Shimmy Vibration in Aircraft Nose Landing Gear using Fuzzy and NARMA-L2 Controllers

Milad Yazdanpanah[1]
Department of Electrical Engineering,
science and research branch of Azad University, Iran
E-mail: miladyazdanp13@gmail.com

Alireza Nateghi[2]
Faculty of Electrical and Computer Engineering,
Shahid Sattari University of Aeronautical Engineering, Iran
E-mail: a_nateghi@sbu.ac.ir

Hassan Zare[3, *]
Department of Electrical Engineering,
Technical and Vocational University (TVU), Iran
Email: hszare@tvu.ac.ir
*Corresponding author

Received: 14 August 2022, Revised: 8 January 2023, Accepted: 18 January 2023

Abstract: In this paper, control of shimmy vibration of aircraft nose landing gear is presented. In this regard, the NARMA-L2 neural controller and a robust controller using a fuzzy method are designed and compared. The efficiency of these controllers was measured by comparing the results obtained from CTM and PID controllers. Using the NARMA-L2 neural controller, maximum effort and settling time are improved whereas using fuzzy controller overshoot of the vibration response improvement in the closed-loop system was observed. According to these results, a large part of the design requirements can be solved by the implemented controllers.

Keywords: Aircraft, Fuzzy Controller, NARMA-L2, Neural Controller, Suspension Oscillations

Biographical notes: Milad Yazdanpanah received his Master degree in Control Engineering at Babol Nooshirvani University in 2016. His career goal is to diagnose dynamic systems control. His research interests include optimization, system identification, and controller design. **Alireza Nateghi** is an Assistant Professor of Electrical engineering at the Shahid Sattari University of Aeronautical Engineering, Iran. He received his Ph.D. in Power Electrical engineering from the Shahid Beheshti University of Iran in 2013. His research interests focus on power converters and their application in renewable energy. **Hassan Zare** is an Assistant Professor of Power Electrical engineering at the Technical and Vocational University, Iran. He received his Ph.D. in Power Electrical engineering from the Semnan University of Iran in 2017. His research interests include Electrical Machines and Power Electronics.

Research paper

1 INTRODUCTION

Small vibrations (shimmy) are a very important and common phenomenon in the landing gear system when taking off or landing an aircraft. The energy required for this type of vibration is provided by the kinetic energy of the forward motion of the aircraft [1]. In the landing gear of an aircraft moving on the runway, the shimmy of the oscillating state is evoked by the reaction forces between the tire and the ground. In fact, shimmy is the oscillating motion of landing gear in torsional, lateral, and longitudinal directions; Which is due to the interaction between the tire dynamics and the landing gear with a frequency range of 10 to 30 Hz [2]. Shimmy not only leads to instabilities that impair comfort but can also affect the pilot's vision and lead to more dangerous consequences such as loss of control, excessive tire wear, failure of mechanical components, or even cause failure of the landing gear. The first attempts to reduce the destructive effects of these vibrations were to use passive methods. A damper was used to dampen these vibrations on Boeing 737 and Airbus A-320 aircraft as a standard preventive measure [3]. However, as noted in [4], poor damping requirements are often at odds with high-speed directional control. In addition, the structural parameters for vibration damping cannot be changed after the landing gear design is completed. One of the main disadvantages of dampers used in this method is the need for frequent maintenance and also increase temperature; Which causes the hydraulic fluid to expand and leak through the sealants, thereby reducing the damping efficiency of the device. Therefore, no other action can be taken when external disturbances or unknown parameters occur in the landing gear system. In some operating conditions, such as worn parts, severe weather, and rugged runway, an active control strategy can be effective in controlling shimmy vibrations.

In [5], a PID controller was designed to eliminate the vertical vibrations of the aircraft wheel and the active control was compared with the semi-active control in the aircraft suspension system. NASA [6] started with a simplified model of the main landing gear, and implemented an external hydraulic system for active control in the vertical vibration damping of the aircraft wheels. Next, in [7], authors introduced a robust and optimal active controller for the shimmy vibrations of the aircraft landing gear. According to the results presented by that, the focus of the research is on the optimality of the controller and its high robustness to external disturbances has been neglected. This is well evident in the vibrational response of the system during external disturbances. Afterward, Zhang [8] addressed the dynamic modeling and control of shimmy phenomena in the aircraft landing gear. The controller implemented by him is the LQR type and its purpose is to increase the optimality of the control. While in a sensitive part such as the landing gear of an airplane, the speed of operation and robustness to disturbances are much more important than the optimality. Afterward, Burbano et al. [9] implemented an adaptive controller for aircraft landing gear shimmy vibration. But according to the results they obtained, the implemented controller, while acceptable, was not as robust to the incoming disturbances as desired, and the range of vibrations after applying the disturbance is negligible. After that, Orlando [10] addressed the control of shimmy vibrations using a modified simple adaptive controller. Despite the acceptable results, the implemented controller is not sufficiently robust against disturbances and the range of vibrations cannot be ignored. Next, Li and Zhao [11] optimized the vibration amplitude reduction for aircraft landing gear shimmy, using a semi-active control, considering the time delay. Considering that the operating time of the landing gear system is very short and must respond quickly to all commands, the system has been designed and implemented in such a way that it has the least possible delay. Therefore, it is not necessary to consider the delay in the implementation of the controller. In addition, in the system under study, the time response of actuators and robustness against disturbances are more important than optimality. Finally, Wang et al. [12] improved the performance of aircraft landing gear against shimmy vibration using a nonlinear feedback controller. In their research, by focusing on bifurcation, the controller was designed in such a way that the system remains stable in a limit cycle; This is while basically in controlling such a simple system (from a structural point of view), overcoming instability is only part of the work and the main focus is on the speed of reaching stability around the desired point. In this regard, due to the existing shortcomings, the implementation of two NARMA-L2 and fuzzy controllers was considered due to their high capabilities. NARMA-L2 control transforms nonlinear system dynamics into linear dynamics by canceling the nonlinearities. The controller is simply a rearrangement of the neural network plant model, which is trained offline, in batch form. The only online computation is a forward pass through the neural network controller. The drawback of this method is that the plant must either be in companion form, or be capable of approximation by a companion form model [13]. The NARMA-L2 controller uses neural networks to predict the behavior of a nonlinear device. The controller calculates the control inputs to increase the efficiency of the device on the time axis, and among the control models, it has minimum calculations that are taught in batches and offline [14]. The only online calculations are in the feedforward step of the neural network. The first step in using this controller is to define the system that should be controlled. In the neural network, to show the leading dynamics of the system, it is taught that the first step is to select the structure of the model used. Also, this controller simply rebuilds the model of the device [15]. In [16], a combination of fuzzy method and NARMA-L2 control idea was implemented to control the movement of a small helicopter and its efficiency was proved. Next, a method similar to that described was used to control the speed of a turbofan engine with unmodulated uncertainties in dynamic Equations [17]; And its effectiveness has been proven. The results of laboratory and theoretical research indicate the fact that to control the motion of systems that have complex or nonlinear motion dynamics; The use of fuzzy controllers is a powerful tool [18]. In addition, the use of this type of controller can increase the robustness of the system to changes in environmental conditions [19]. The proposed fuzzy controller tracks the desired path by overcoming the perturbations and tries to place the operators in that path. In this regard, the fuzzy control of a parallel robot was performed in the [20]. The results of the movement of this robot show very good control of the robot and its acceptable speed of movement. Pouly et al. [21], using a fuzzy method, implemented an adaptation law to control the feedback of shimmy vibration of landing gear. In their study, the fuzzy method is used only in the part of the adaptation law of control parameters, and the control law is extracted from the Lyapunov method. In another study, they used the fuzzy method to adapt the parameters required for the sliding-mode method application on shimmy vibrations control [22-23]. However, the fuzzy method can control this system by itself and has acceptable performance.

The main innovations of the article are as follows: 1- Reducing the amplitude of landing gear vibrations. 2- Damping the vibrations of the landing gear using fuzzy and NARMA-L2 controllers. 3- Robustness of the landing gear system to external disturbances with the help of the NARMA-L2 and fuzzy controllers. 4- Determination of the superiority of the NARMA-L2 and fuzzy controllers to each other. To achieve the above goals, the structure of this paper is as follows: In the second part, system modeling and dynamic formulation of landing gear are presented. The third part of this paper describes the modeling of CTM, NARMA-L2, and fuzzy controllers. In the fourth section, simulation and analysis of results are examined. Finally, the conclusion of the article is presented.

2 MODELING

A prerequisite for any research on the control of mechanical systems is to have a mathematical model of the dynamics of that system. For this reason, the dynamic modeling of the aircraft landing gear system was considered. A view of the aircraft suspension system at its nose and associated oscillations is shown in “Fig. 1”.

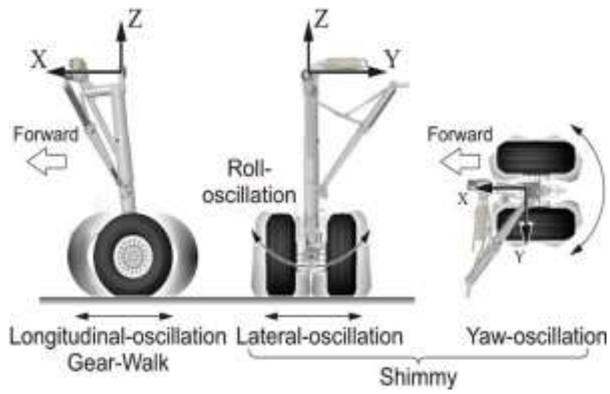

Fig. 1 A view of the oscillations of the aircraft nose system [24].

According to “Fig. 1”, the shimmy vibrations of the aircraft suspension are limited to three oscillations: longitudinal, lateral, and yaw. A prerequisite for any research on dynamic systems (here, aircraft suspension) is mathematical modelling. For this purpose, it is necessary to identify and introduce the parameters affecting the system dynamics. Figure 2 shows the parameters affecting the dynamics of the aircraft suspension.

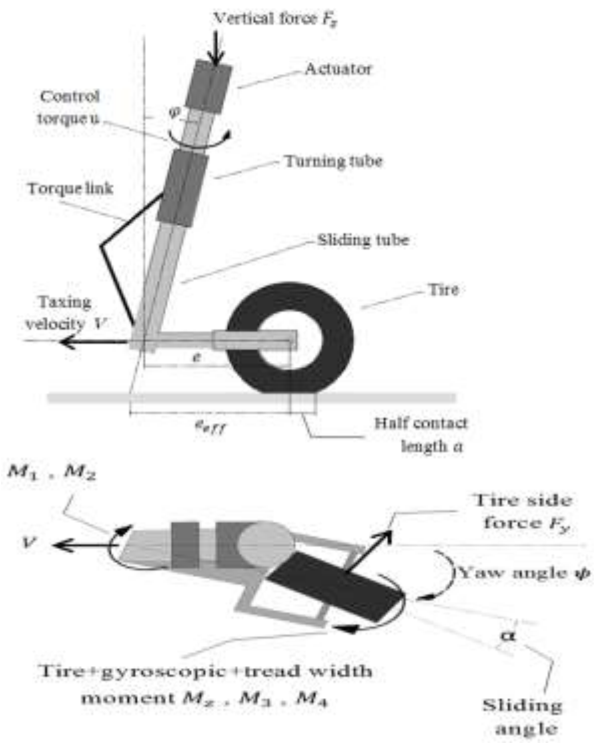

Fig. 2 Schematic of aircraft nose suspension parameters [7].

The nonlinear model of shimmy vibrations includes the torsional dynamics of the landing gear, the force and torques applied to the cart from various sources, and the elastic deformation of the wheel, or so-called wheel mechanics. Figure 2 shows a nose landing gear that must be controlled to handle the M_5 control torque. Using Newton's second law, the differential Equation of the shimmy vibrations can be obtained.

For movement in the direction of the rotation angle of the landing gear (ψ) we have [4]:

$$\ddot{\psi} = \frac{1}{I_z}(c\psi + K\dot{\psi} + \frac{\kappa}{V}\cos(\varphi)\dot{\psi} + M_3 + M_5) \quad (1)$$

The kinematic relationship between the transverse displacement of the wheel (y_1) and the rotational angle of the landing gear is expressed as follows:

$$\dot{y}_1 + \frac{V}{\sigma}y_1 = V\cos(\varphi)\psi + (e_{eff} - a)\cos(\varphi)\dot{\psi} \quad (2)$$

Where, α is half the length of the tire's contact with the ground and σ is the length of the tire's relaxation. We have the following:

$$\alpha \approx \tan(\alpha) = \frac{y_1}{\sigma} \quad (3)$$

Therefore, by selecting the state variables $X = [\psi \ \dot{\psi} \ y_1]^T$, the shape of the state space of the Equations of motion is as follows:

$$\begin{cases} \dot{X} = AX + Bu + d \\ y = CX \end{cases} \quad (4)$$

Where we have:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{c}{I_z} & \frac{K}{I_z} + \frac{\kappa}{VI_z}\cos(\varphi) & 0 \\ V\cos(\varphi) & (e_{eff} - a)\cos(\varphi) & -\frac{V}{\sigma} \end{bmatrix}, \ B = \begin{bmatrix} 0 \\ \frac{1}{I_z} \\ 0 \end{bmatrix}, \quad (5)$$

$$u = M_5, \ d = \frac{M_3}{I_z}, \ C = [1 \ \ 0 \ \ 0].$$

3 CONTROLLER DESIGN

In this section, to control the studied system, implementation of the RCTM, NARMA-L2, and fuzzy controllers, was considered. It is important to use the above method in estimating a suitable initial conjecture for the application of control forces. This optimal initial conjecture, which is obtained by using the Equations of motion of the system and the error of position and velocity, prevents the application of inappropriate control forces and follows the smoothness of the path. Using the obtained model and controller designed for this system, any unwanted vibration can be repelled; Even if there is an initial error in locating and measuring the location of the operators. In other words, with the use of this controller, the advantages of two control methods of feedback and feedforward can be used simultaneously, and in addition to applying a suitable control signal for a nonlinear system, disturbances and uncertainties can be eliminated with the help of feedback terms.

3.1. Control using Robust RCTM Controller

The schematic of the CTM controller in the joint space is as shown in “Fig. 3” [25]:

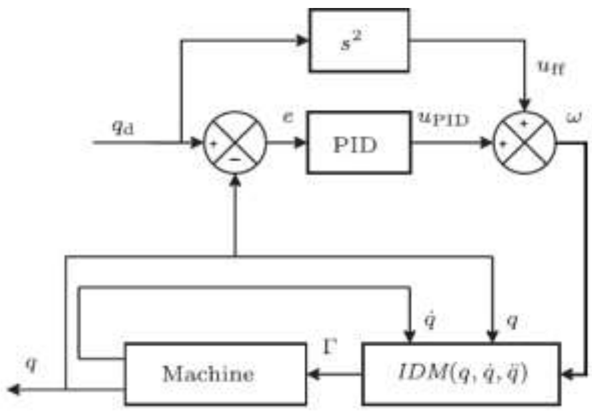

Fig. 3 General schematic of CTM controller in the joint space [25].

In order to make the CTM controller resistant to disturbance and initial conditions, we write the error dynamic Equations as follows:

$$\dot{E} = AE + BT_{RC}$$
$$E = \begin{bmatrix} e^T & \dot{e}^T \end{bmatrix}^T, \ e = \psi - \psi_d \quad (6)$$

Where, T_{RC} is the torque applied by the resistor. Matrices A, B are equal to:

$$A = \begin{bmatrix} 0 & 1 \\ -k_p & -k_d \end{bmatrix}, \ B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \quad (7)$$

Now by choosing a Q matrix and solving the Lyapunov Equation, we find the P matrix:

$$A^T P + PA + Q = 0,\ \ Q = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{8}$$

From which it can be written:

$$Z = B^T PE \tag{9}$$

Using Z and the following Equation, the robust control input is determined:

$$T_{RC} = \begin{cases} -\rho \operatorname{sgn}(Z) & \|Z\| > \delta \\ -\dfrac{\rho Z}{\delta} & \|Z\| \leq \delta \end{cases} \tag{10}$$

Where the parameters ρ and δ were selected using the following definition:

$$\begin{aligned} &\delta : \delta > 0 \\ &\rho : \|\omega - T_{RC}\| \leq \rho \\ &\delta = 0.01, \quad \rho = 15 \end{aligned} \tag{11}$$

The input of the inverse dynamic will be equal to:

$$\begin{cases} \ddot{\theta} = \omega + T_{RC} \\ \omega = \ddot{\psi}_d - T_{PD} \end{cases} \rightarrow IDM \rightarrow T_{RCTM} \tag{12}$$

And the control input of the system in the presence of disturbance is as follows:

$$T = T_{RCTM} \tag{13}$$

3.2. Artificial Neural Control using NARMA-L2

The NARMA-L2 controller uses neural networks to predict the behavior of a nonlinear device. The controller calculates the control inputs to increase the efficiency of the device on the time axis, and among the control models, it has the least calculations, which are taught in batches and offline. The only online computing is in the feedforward step of the neural network.

The first step in using this controller is to define the system that needs to be controlled. The neural network is trained to represent the leading dynamics of the system, the first step being to select the structure of the model used. Also, this controller simply rearranges the system model. A standard model used in discrete nonlinear systems is as follow [26]:

$$\begin{aligned} y(k+d) &= N\left[y(k),\, y(k-1),\, \ldots,\right. \\ &\left. y(k-n+1), u(k),\, u(k-1),\, \ldots,\, u(k-n+1)\right] \end{aligned} \tag{14}$$

Where, u (k) is the input of the system and y (k) is its output. In the definition phase, we can train the neural network to estimate the nonlinear function N, and if we want the system output to follow a reference trajectory (y (k + d) = y_r (k + d)), the next step is developing a nonlinear controller.

$$\begin{aligned} u(k) &= G\left[y(k),\, y(k-1), \ldots, y(k-n+1),\right. \\ &\left. y_r(k+d),\, u(k-1),\, \ldots,\, u(k-m+1)\right] \end{aligned} \tag{15}$$

Where. the G function minimizes the sum of the squares error. The problem with this type of controller is that if the neural network needs to be trained to create the G function, dynamic propagation must be used, and this is done very slowly. One solution to this problem is a model estimation. The controller used here is based on the estimation model.

$$\begin{aligned} \hat{y}(k+d) &= f\left[y(k),\, y(k-1),\, \ldots,\right. \\ &\left. y(k-n+1),\, u(k-1),\, \ldots\, u(k-m+1)\right] \\ &+ g\left[y(k),\, y(k-1),\, \ldots,\right. \\ &\left. y(k-n+1),\, u(k-1),\, \ldots,\, u(k-m+1)\right] u(k) \end{aligned} \tag{16}$$

So, with the NARMA-L2 controller, the following controller can be created, (See "Fig. 4").

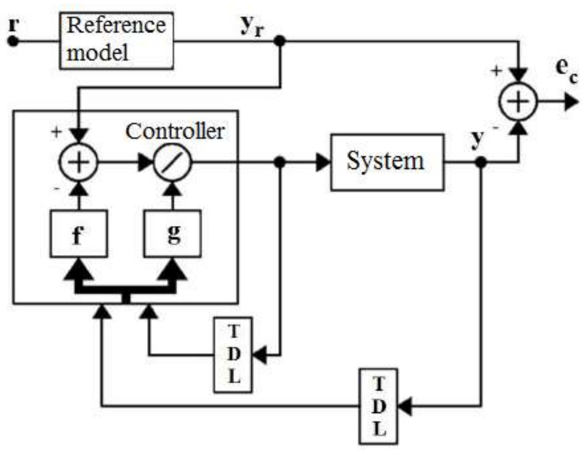

Fig. 4 NARMA-L2 controller [27].

And we have:

$$u(k+1) = y_r(k+d) - \frac{f\left[y(k) \ldots y(k-n+1), u(k), \ldots, u(K-n+1)\right]}{g\left[y(k) \ldots y(k-n+1), u(k), \ldots, u(K-n+1)\right]} \tag{17}$$

Where $d \geq 2$.

3.3. Fuzzy Controller Design

Fuzzy controllers have acceptable efficiency and performance in controlling the nonlinear systems as well as performing special maneuvers. One way to design a fuzzy controller is to break down complex system behaviors into multiple movements within the actuators. After designing a suitable control algorithm for each section, their corresponding actions can be combined. In this paper, the fuzzy controller is designed in such a way that it can stabilize the system around its stable point well by determining the appropriate control force and has good robustness to disturbances. This controller is designed according to the if-then rules in the following form:

$$\text{If "e" is A and "de" is B, then "u" is C} \tag{18}$$

The "and" and "or" operators are defined as follows:

$$\mu_{A\cup B} = \max(\mu_A(u), \mu_B(u)) \tag{19}$$

$$\mu_{A\cap B} = \min(\mu_A(u), \mu_B(u)) \tag{20}$$

In the proposed controller, Mamdani-based fuzzy inference was used along with the centroid defuzzification method. In the first step, the fuzzy controller, after receiving the inputs, performs the fuzzifying process, then, based on Equation (26) and Mamdani inference, the membership functions are combined using the fuzzy operators. In the next step, the values of the membership functions are combined based on relation 19 with the "and" operator and the fuzzified outputs calculated. The input of the fuzzy system was selected as an error (e) and an error derivative (de) of the desired value at a given time. The membership functions of these inputs were considered as Gaussian functions as follow:

$$f(x;\sigma,c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \tag{21}$$

Where, c is an arbitrary real constant and σ is non-zero. Position and velocity errors were selected as five membership functions [- - 0 + ++]; Where the position error change interval [-0.1 0.1] and the velocity error change interval [-10 10] were selected. According to the Mamdani inference, the membership functions of the outputs were considered as Gaussian functions too. Membership functions for the fuzzy system inputs and outputs are shown in "Fig. 5". Finally, a set of fuzzy rules was chosen to extract the appropriate control force as shown in "Table 1". The general algorithm of implementing a fuzzy controller is as follows:

- Inputs: "e", "de" - crisp numerical values.
- Output: "u" - crisp numerical value.

BEGIN:
Step 1. Fuzzification of the inputs,
Step 2. Application of the fuzzy operators (AND or OR) in the antecedent of the rules according to (19) and (20),
Step 3. Implication from the antecedent to the consequent using of the AND operation according to (19),
Step 4. Aggregation of the consequents across the rules using the OR operation according to (20),
Step 5. Defuzzification to the output variable.
END

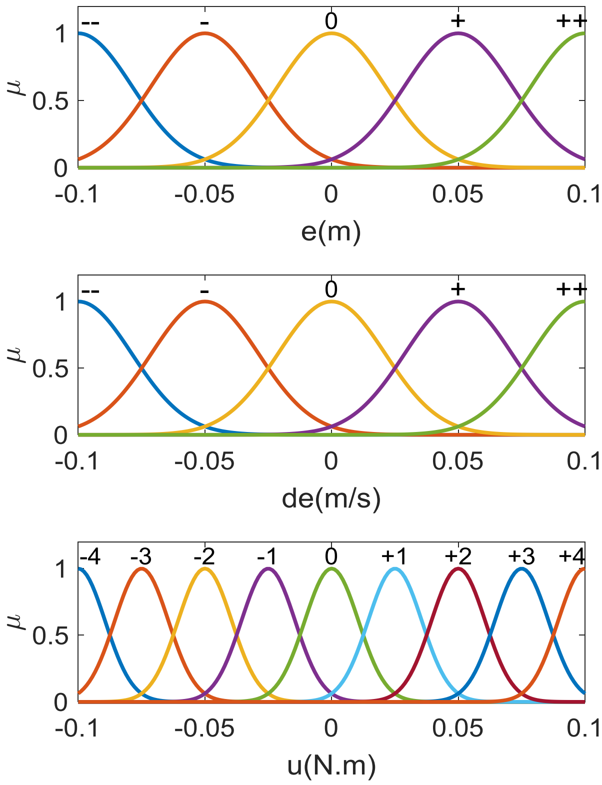

Fig. 5 Input and output membership functions of Mamdani fuzzy system.

Table 1 Fuzzy Rules

number	Fuzzy rules					
1	If "e" is	--	and "de" is	--	then "u" is	+4
2		--		-		+3
3		--		0		+2
4		--		+		+1
5		--		++		0
6		-		--		+3
7		-		-		+2
8		-		0		+1
9		-		+		0
10		-		++		-1
11		0		--		+2
12		0		-		+1
13		0		0		0

14		0		+		-1
15		0		++		-2
16		+		--		+1
17		+		-		0
18		+		0		-1
19		+		+		-2
20		+		++		-3
21		++		--		0
22		++		-		-1
23		++		0		-2
24		++		+		-3
25		++		++		-4

4 SIMULATION STUDY

In this study, after modeling the dynamics of small vibrations (shimmy) of aircraft landing gear, it was controlled by the NARMA-L2 and fuzzy controllers, and its results were compared with the results of RCTM and PID controllers. The parameters of the PID controller used in this section were determined using the Simulink optimization section as follows (“Table 2”).

$$PID\ \ Transfer\ Function = P + I\,\frac{1}{s} + D\,\frac{N}{1+N\,\dfrac{1}{s}} \tag{22}$$

Table 2 PID controller block parameters

Controller coefficients	Value
P	-314035
I	-35344169
D	-442
N	1677

The values in “Table 3” are used to simulate the mentioned system. The fuzzy and NARMA-L2 neural control systems were simulated in the Simulink software environment, as described in Section Three. Where the NARMA-L2 controller parameters in Table 4 were shown. One of the important issues that the controller has to deal with is the different initial conditions. To measure the performance of the implemented controllers about the error, the following conditions were considered as initial conditions:

$$\begin{bmatrix}\psi & \dot{\psi}\end{bmatrix}_{t=0} = \begin{bmatrix}-0.1 & 10\end{bmatrix} \tag{23}$$

Table 3 Parameters used for simulation [19]

Parameter	Description	Value	Units
e	Structure parameters Caster length	0.12	M
C	Torsional stiffness of strut	$-1e5$	$N.m.rad^{-1}$
K	Torsional damping of strut	-45	$N.m.rad^{-1}$
I_Z	Moment of inertia of strut	1	$kg\ m^2$
φ	Rake angle	0.1571	rad
$\mathcal{R}$	Tire parameters Radius of nose wheel	0.362	m
α	Contact patch length	0.1	m
K	Damping coefficient of elastic tyre	-270	$N\ m^2\ rad^{-1}$
CM_α	Self- aligning coefficient of elastic tyre	-2	m /rad
CF_α	Restoring coefficient of elastic tyre	20	rad^{-1}
σ	Relaxation length	0.3	m
δ	Restoring force limit	0.087	rad
α_g	Self- aligning moment limit	0.1745	rad
F_z	Vertical force on the gear	9000	N
$\mathcal{V}$	Forward velocity	75	ms^{-1}

Table 4 Parameters used in NARMA-L2 controller block

Parameter	Value
Number of hidden layers	5
Number of input delays	3
Number of output delays	3
Sampling time	0.001 (s)
Maximum of outputs	0.5 (rad)
Minimum of outputs	-0.5 (rad)
Maximum of inputs	10000 (N.m)
Minimum of inputs	-10000 (N.m)
Number of training samples	10000

The results of the simulation of the mentioned controllers are as follows:
As shown in “Fig. 6”, the overshoot of response in the system controlled by NARMA-L2 in the time interval from zero to 0.03 seconds is up to 30% less than in the PID and CTM controllers' case whereas the fuzzy controller overshoot is zero; And then, these three

controllers have reached a stable state in the same time. As shown in “Fig. 7”, the neural controller operated by applying a controlled force at a smaller amplitude and greater oscillations than other controllers.

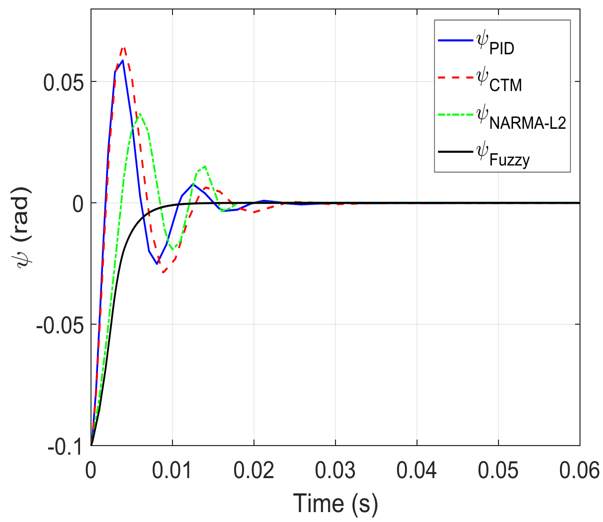

Fig. 6 Angle φ is driven by controllers designed without the presence of external disturbance.

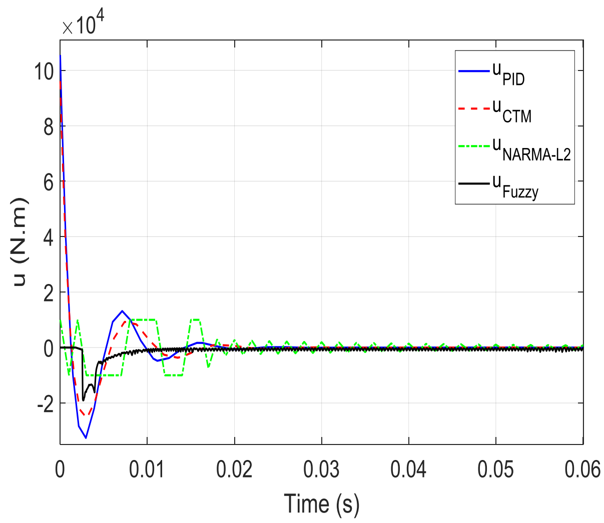

Fig. 7 The amount of control torque applied by the implemented controllers without the presence of external disturbance.

The maximum amplitude of control force for the neural controller is up to 90% less than that applied by the CTM and PID controllers. This value for the fuzzy controller is 50% less than the same controllers. To measure the robustness of the controllers to environmental disturbances, a disturbance signal with the following schematic was used (“Fig. 8”).

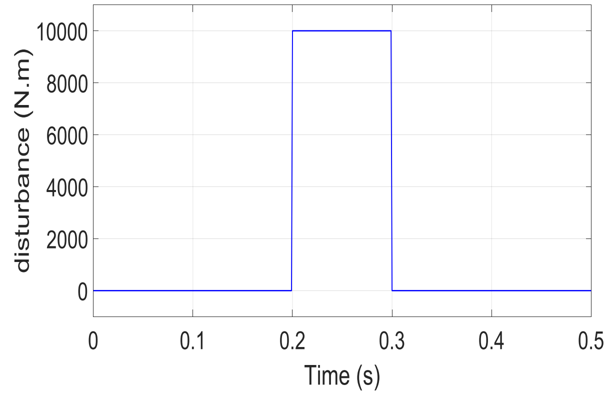

Fig. 8 Disturbance signal applied to the system.

The disturbance was modeled as an external torque applied to the aircraft wheels and applied to the system. The initial conditions considered in this section are as follows:

$$\begin{bmatrix}\psi & \dot{\psi}\end{bmatrix}_{t=0} = \begin{bmatrix}0.1 & 0\end{bmatrix} \tag{24}$$

As shown in “Fig. 9”, the overshoot of the response in the system controlled by NARMA-L2 from zero to 0.03 seconds is equivalent to those used by the PID and CTM controllers; Whereas for the fuzzy controller, overshoot is zero. But at the onset of the disturbance pulse, the neural controller vibrates less and stabilizes faster than PID and CTM controllers; But the superiority of the neural controller at the end of the disturbance pulse is obvious. The controller maintains the balance of the system well during this period and prevents unwanted vibrations caused by the change of the disturbance pulse. System vibrations in this case are less than a quarter of the system vibrations when PID and CTM controllers are used. While the vibrations amplitude of the fuzzy controller is almost zero in the whole domain of disturbance; this phenomenon clearly shows the robustness of the fuzzy controller.

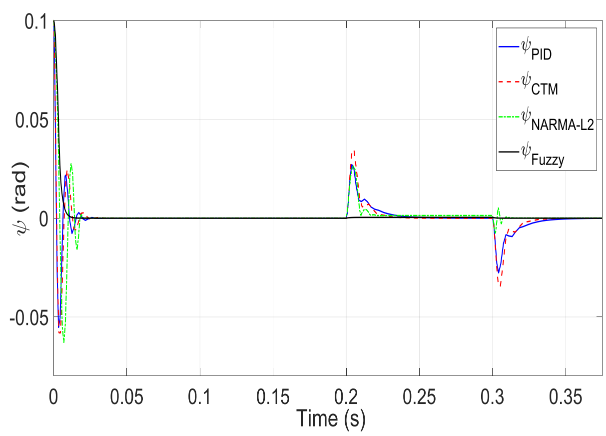

Fig. 9 Angle φ driven by controllers designed in the presence of external disturbance.

As shown in “Fig. 10”, the neural controller exerts a controlled force equal to One-tenth of the control force exerted by the CTM and PID controllers from zero to 0.03 seconds. This value for the fuzzy controller is half of the same controllers. At the end of the disturbance pulse, the neural controller in the same amplitude as the other designed controllers used more oscillations to apply the control force. Finally, these more fluctuations in the application of the control force have led to a reduction in the amplitude of the vibrations at the angle φ.

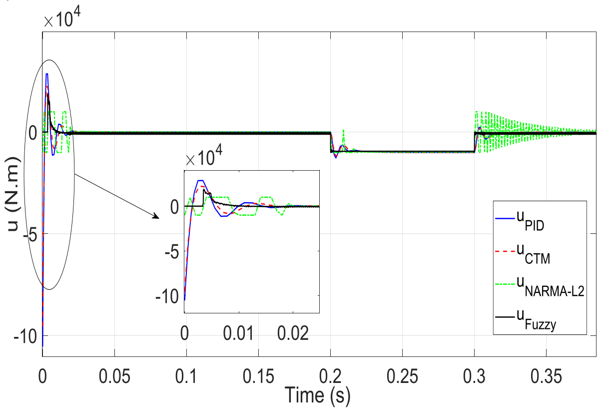

Fig. 10 The amount of control torque applied by controllers implemented in the presence of external disturbance.

All of the above will demonstrate the superiority of the NARMA-L2 neural controller over the PID and CTM controllers. But the comparison between two controllers, NARMA-L2 and fuzzy, is a bit more difficult. To better investigate, the efficiency of the control methods implemented in “Table 5” is compared.

Table 5 Comparison of the efficiency of the control methods used

Control method	Overshoot	maximum effort	settling time
PD	0.06	1e5	0.020
CTM	0.07	1e5	0.023
NARMA-L2	0.03	1e4	0.019
Fuzzy	0	5e4	0.020

As can be seen, the NARMA-L2 controller had less settling time and maximum effort than other controllers. This is a good indication of the high performance of the designed controller compared to PID and CTM controllers. whereas the fuzzy controller overshoot is zero and is the best controller in this area.

5 CONCLUSIONS

In this paper, in order to solve the challenge of small vibrations of the aircraft landing gear, after mathematical modeling of the mentioned system, a NARMA-L2 neural controller and a robust controller using a fuzzy method are designed and implemented. The efficiency of these controllers was measured by comparing the results obtained from CTM and PID controllers. Using the NARMA-L2 neural controller, maximum effort and settling time improved whereas using fuzzy controller, overshoot of the vibration response improvement in the closed-loop system was observed. The maximum effort in the neural controller is one-tenth of this value in the CTM and PID controllers. This value for the fuzzy controller is half that in the mentioned controllers. The amount of overshoot in the neural controller is less than half of this amount in the CTM and PID controllers. This value is exactly zero for the fuzzy controller. Also, the settling time of the four controllers is close to each other, but the neural controller is somewhat better.

REFERENCES

[1] Rahmani, M., Behdinan, K., On the Effectiveness of Shimmy Dampers in Stabilizing Nose Landing Gears, Aerospace Science and Technology, Vol. 91, No. 1, 2019, pp. 272-286.

[2] Rahmani, M., Behdinan, K., Structural Design and Optimization of A Novel Shimmy Damper for Nose Landing Gears, Structural and Multidisciplinary Optimization, Vol. 62, No. 5, 2020, pp. 2783-2803.

[3] Haddadpour, H., Bornassi, S., The Shimmy Vibration Analysis of Aircraft Landing Gear, Journal of Aeronautical Engineering, Vol. 13, No. 2, 2011, pp. 59-69.

[4] D’Avico, L., Tanelli, M., and Savaresia, S. M., Experimental Validation of Landing-Gear Dynamics for Anti-Skid Control Design, IEEE European Control Conference, Vol. 1, 2018, pp. 2751-2756.

[5] Zhao, K., Okolo, P., Neri, E., Chen, P., Kennedy, J., and Bennett, G. J., Noise Reduction Technologies for Aircraft Landing Gear-A Bibliographic Review, Progress in Aerospace Sciences, Vol. 112, No. 1, 2020, pp. 1-23.

[6] Horta, L. G., Daugherty, R. H., and Martinson, V. J., Modeling and Validation of a Navy A6-Intruder Actively Controlled Landing Gear System, NASA, 1999.

[7] Tourajizadeh, H., Zare, S., Robust and Optimal Control of Shimmy Vibration in Aircraft Nose Landing Gear, Aerospace Science and Technology, Vol. 50, No.1, 2016, pp. 1-14.

[8] Zhang T., Dynamic Modeling and Control Strategies for Shimmy in Aircraft Landing Gears, M.S. Thesis, 2016.

[9] Burbano, L. D. A., Coraggio, M., Di-Bemardo, M., Garofalo, F., and Pugliese, M., Adaptive and Quasi-Sliding Control of Shimmy in Landing Gears,

European Control Conference, Vol. 1, 2018, pp. 1-20.

[10] Orlando, C., Modified Simple Adaptive Control of Aircraft NLG Shimmy, AIP Conference Proceedings, Vol. 1, 2020, pp. 34-43.

[11] Li, F., Zhao, Y., Amplitude Reduction Optimization of Time Delay Semi-Active Control for Aircraft Landing Gear Shimmy, Journal of Physics: Conference Series, Vol. 34, 2022, pp. 87-100.

[12] Wang, Y., Jin, X., Yin, Y., Using Nonlinear Feedback Control to Improve Aircraft Nose Landing Gear Shimmy Performance, Meccanica, Vol. 57, No. 9, 2022, pp. 2395-411.

[13] Pukrittayakamee, A., De Jesús, O., and Hagan, M. T., Smoothing the Control Action for NARMA-L2 Controllers, Midwest Symposium on Circuits and Systems, Vol. 3, 2002, pp. 1-20.

[14] El Hamidi, K., Mjahed, M., El Kari, A., Ayad, H., and El Gmili, N., Design of Hybrid Neural Controller for Nonlinear MIMO System Based on NARMA-L2 Model, IETE Journal of Research, Vol. 50, No. 1, 2021, pp. 1-14.

[15] El Hamidi, K., Mjahed, M., El Kari, A., Ayad, H., and El Gmili, N., Design of Hybrid Neural Controller for Nonlinear MIMO System Based on NARMA-L2 Model, IETE Journal of Research, Vol. 50, No. 2, 2021, pp. 1-14.

[16] Al-Fallooji, N. S., Abbod, M., Helicopter Control Using Fuzzy Logic and Narma-L2 Techniques, International Journal of Intelligent Systems & Applications, Vol. 12, No. 5, 2020, pp. 1-20.

[17] Lu, F., Yan, Z., Tang, J., Huang, J., Qiu, X., and Gao, Y., Iterative Learning NARMA-L2 Control for Turbofan Engine With Dynamic Uncertainty in Flight Envelope, Proceedings of the Institution of Mechanical Engineers, Vol. 1, 2021, pp. 124-140.

[18] Derdiyok, A., Soysal, B., Arslan, F., Ozoglu, Y., and Garip, M., An Adaptive Compensator for A Vehicle Driven by DC Motors, Journal of the Franklin Institute, Vol. 342, No. 3, 2005, pp. 273-283.

[19] Chwa, D., Fuzzy Adaptive Tracking Control of Wheeled Mobile Robots with State-Dependent Kinematic and Dynamic Disturbances, IEEE transactions on Fuzzy Systems, Vol. 20, No. 3, 2011, pp. 587-593.

[20] Vermeiren, L., Dequidt, A., Afroun, M., and Guerra, T. M., Motion Control of Planar Parallel Robot Using the Fuzzy Descriptor System Approach, ISA Transactions, Vol. 51, No. 5, 2012, pp. 596-608.

[21] Pouly, G., Huynh, T. H., Lauffenburger, J. P., and Basset, M., Active Shimmy Damping Using Fuzzy Adaptive Output Feedback Control, 10th International Conference on Control, Automation, Robotics and Vision, Vol. 1, 2008, pp. 16-22.

[22] Pouly, G., Huynh, T. H., Lauffenburger, J. P., and Basset, M., Indirect Fuzzy Adaptive Control for Active Shimmy Damping, IFAC Proceedings Volumes, Vol. 41, No. 2, 2008, pp. 15058-15063.

[23] Pouly, G., Huynh, T. H., Lauffenburger, J. P., and Basset, M., State Feedback Fuzzy Adaptive Control for Active Shimmy Damping, European Journal of Control, Vol. 17, No. 4, 2011, pp. 370-393.

[24] Tourajizadeh, H., Zare, S., Optimal Control of Shimmy Oscillation in Aircraft Nose Landing Gear, Modares Mechanical Engineering, Vol. 15, No. 8, 2015, pp. 207-215.

[25] Heydarzadeh, M., Karbasizadeh N., Tale Masouleh M., and Kalhor A., Experimental Kinematic Identification and Position Control of a 3-DOF Decoupled Parallel Robot, Journal of Mechanical Engineering Science, Vol. 233, No. 5, 2019, pp. 1841-55.

[26] Celikel, R., Aydogmus, O., NARMA-L2 Controller for Single Link Manipulator, International Conference on Artificial Intelligence and Data Processing, Vol. 1, 2018, pp. 1-6.

[27] Bustamante, R. D., Bastos, B. S., De Oliveira, J. S., and Santos, B. F., Nonlinear Autoregressive-Moving Average-L2 (NARMA-L2) Controller for Multivariable Ball Mill Plant, Chemical Product and Process Modeling, Vol. 23, No. 1, 2021, pp. 1-15.