Improvement of ride quality for a wheel loader with semi-active cab isolation system via fuzzy self tuning of PID controller

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Received 2 Sep. 2023; Revised 12 Nov. 2023; Accepted 15 Nov. 2023; Published 10 Dec. 2023.
DOI: https://doi.org/10.54939/1859-1043.j.mst.FEE.2023.197-203

ABSTRACT

Improving driver ride comfort of a wheel loader is important to avoid potential health hazards from the whole-body vibration. A fuzzy self-tuning of PID controller is designed to control the damping coefficient of Semi-active cab isolation system (SCIS) for a wheel loader. A dynamic model of a wheel loader is establish under survey conditions for analysis and evaluation. The r.m.s acceleration responses of the vertical driver's seat and pitch angle of vehicle body according to ISO2631-1 (1997-E) are chosen as objective functions. The effectiveness of the proposed control strategy is analyzed through simulations involving excitations for a random road profile in time domain. The proposed SCIS is simulated and analyzed by Matlab/Simulink software in comparison with a passive cab isolation system (PCIS) under survey conditions. The achieved results indicate that ride comfort effectiveness of a wheel loader with SCIS is better than PCIS under survey conditions. In addition, the study results are the initial basis for optimizing controller parameters.

Keywords: Wheel Loader; Cab; Isolation system; Fuzzy-PID controller; Ride comfort.

1. INTRODUCTION

Wheel loaders are commonly used on construction sites. Their structural features are often not equipped with suspension systems to elastically connect the axle and chassis of vehicle. The vibration sources generated during operation are transmitted to driver's body through cab’s suspension system, and drive’s suspension system. On the other hand, wheel loaders are usually operated, wheel loader drivers are often exposed to high levels of whole body vibration. In short-term perspective these vibrations will affect operator comfort negatively and cause driver fatigue. A multibody dynamic model of a compact wheel loader was created**,** the dynamic model was verified by comparing the calculated results with the ground test results [1]. Accordingly, the influence of whole-body vibration in heavy equipment operators of a front-end loader was analyzed and the study mainly focused on role of task exposure and tire configuration with and without traction chains [2]. Two standards such as ISO 2631-1(1985) and ISO 2631-1 (1997) were used to assess the effect of wheel loader vibration on vehicle ride comfort [3]. However, the overall total values of vibration measured on the wheel loader in all operations were exceeded the ‘uncomfortable’ boundary specified in two standards and limited studies were carried out to evaluate the whole-body vibration (WBV) exposure experienced by operators of compact wheel loaders (CWLs) according to ISO 2631-1:1997 [4]. A wheel loader experiment was conducted and measured to analyze the vibration sources such as internal combustion engine (ICE), road surface and orther vibration transmitted to the cab and operator's seat. The experiment results were the basis for finding solutions to control vibration sources to improve vehicle ride comfort and reduce vehicle noise [5]. And, to solve this problem, the wheel loader suspension system was especially concerned by the researches [10]. Three characteristics of three hydropneumatic suspension systems were selected to analyze the ride comfort performance of the wheel loader under different survey conditions [6]. However, the vibration response was still very high according to the standard of ISO 2631-1, thus, it was uncomfortable for operators to control the wheel loader on the roadworks [13].

Nowadays, the control methods, such as Neuro-Fuzzy control with the fuzzy rules are successfully applied, it was shown that suspension with control can significantly enhance the ride comfort compared with the passive [7]. Thus, the cab's isolation system is one of the most important factors to improve the vehicle ride comfort, cabin comfort of excavators could be improved by changing the cab design (including dimensions, ingress/egress), view, reliability, and climate control [8]. The study for controlling the damping force or coefficients of the cab isolation system had been concerned [9]. Some control methods were presented quite thoroughly in the reference documents, which are the basis for designing control strategies [14, 15]. Van Quynh, L., et al [16-18] has many publications in the field of the cab isolation system for the earth-moving machinery. The goal of this paper is to establish a wheel loader ride comfort with the semi-active cab isolation system (SCIS) using Fuzzy Self Tuning of PID Controller compared to the passive cab isolation system (PCIS) under survey conditions. The r.m.s acceleration responses of the vertical driver's seat and pitch angle of vehicle body according to ISO2631-1 (1997-E) [13] are chosen as objective functions. Matlab/Simulink software is used for evaluation and comparison.

2. DYNAMIC MODEL OF WHEEL LOADER

2.1. Dynamic model

In this study, a dynamic model of a wheel loader with 6 degrees of freedom [16] is shown in Fig.1 which including the driver seat, the cabin, and the vehicle body.

In Fig. 1, z_s, z_c and z_k are the vertical displacements at centre of gravity of driver's seat, cab, front and rear vehicle body; φ_c and φ_{fr} are pitch angle displacements at centre of gravity of cab, and rear vehicle body; m_s, m_c and m_k are the masses of driver's seat, cab, front and rear vehicle body; c_{ctr} are control inputs to cab isolation system, and it is difined as actuator forces to produce the control forces; q_{t1} and q_{t2} are the excitations of the road surface roughness, (k = ff, fr)

Based on wheel loader dynamic model and by using Newton's law, the motion equations of the driver's seat, cab are given as follow:

$$\begin{cases} m_s\ddot{z}_s = -F_s \\ m_c\ddot{z}_c = F_s - \sum\limits_{i=1}^{2} F_{ci} \\ I_c\ddot{\varphi}_c = F_{c1}l_{c1} - F_{c2}l_{c2} - F_s l_s \\ m_{fr}\ddot{z}_{fr} = \sum\limits_{i=1}^{2} F_{ci} - \sum\limits_{j=1}^{2} F_{tj} \\ I_{fr}\ddot{\varphi}_{fr} = F_{t2}l_{t2} + F_{c2}l_{fr} + F_{c1}l_{ff} - M_t \\ m_{ff}\ddot{z}_{ff} = -F_{t1} \end{cases} \tag{1}$$

Where:

$$F_s = [k_s\left(z_s - z_{cs}\right) + c_s\left(\dot{z}_s - \dot{z}_{cs}\right)];$$

$$F_{t1} = k_{t1}\left(z_{ff} - q_{t1}\right) + c_{t1}\left(\dot{z}_{ff} - \dot{q}_{t1}\right);$$

$$F_{t2} = k_{t2}\left(z_{fr0} - q_{t2}\right) + c_{t2}\left(\dot{z}_{fr0} - \dot{q}_{t2}\right);$$

$$M_t = \left[k_{t1}\left(z_{ff} - q_{t1}\right) + c_{ct1}\left(\dot{z}_{ff} - \dot{q}_{t1}\right)\right]l_{t1}$$

The equation of the dynamic forces of cab hydraulic isolation system is determined by

$$
\begin{aligned}
F_{ci} &= k_{ci} z_i + c_{ci} \dot{z}_i && \text{Passive} \\
F_{ci} &= k_{ci} z_i + c_{ci} \dot{z}_i + c_{ctr} \left| \dot{z}_i \right| \dot{z}_i && \text{Control}
\end{aligned}
\tag{2}
$$

where, z_i and $\dot{z}_i$ are the relative displacement and velocity of the cabin and rear vehicle body.

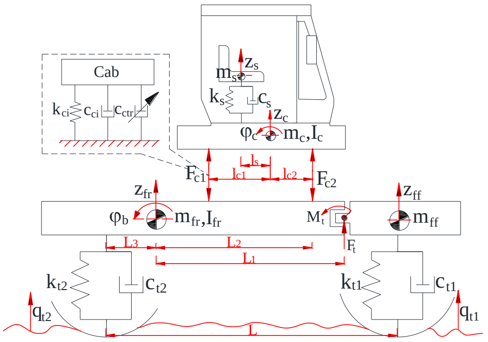


Figure 1. *Dynamic model of a wheel loader.*

2.2. Road Excitation Profile

The road profile of the road surface roughness can be determined by the experimental formula [12]:

$$
G_q(n) = G_q(n_0)\left(\frac{n}{n_0}\right)^{-\omega} \tag{3}
$$

where $G_q(n_0)$ is the displacement power spectral densit (PSD) for the roughness of the road; $n_0 = 0.1$ m^{-1} is a reference spatial frequency, $\omega = 2$ is the frequency index which determines the frequency configuration of the PSD of the road surface. Road surface roughness is assumed to be a zero-mean stationary Gaussian random process. It can be generated through an inverse Fourier transformation:

$$
q(t) = \sum_{i=1}^{N} \sqrt{2G_q(n_i)\Delta n} \cos\left(2\pi n_k t + \varphi_i\right) \tag{4}
$$

Where: N is the number of intervals; $\Delta n = 2\pi / L$ with L as the length of the road segment; φ_i is a random phase uniformly distributed from 0 - 2π.

In this study, typical road surface roughness is adopted according to the standard ISO 8068 [12] and computer simulation result of the typical road surface roughness ISO 8068 class D is shown in Fig.2.

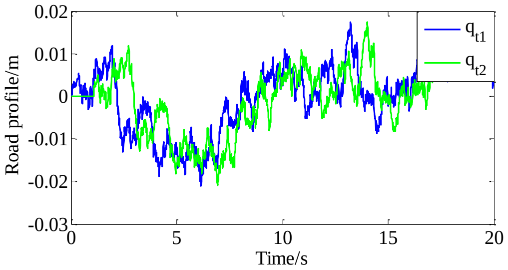


Figure 2. *Typical road surface roughness according to the standard ISO 8068 class D.*

3. Designs Fuzzy- PID control for SCIS

The fuzzy controller is included in the control structure in Fig.3, in order to provide the value $\{K_p^{'}, K_i^{'}, K_d^{'}\}$ to the PID controller, based on the current condition of {e, ce}.

Controller PID controller is the popular. Due to its design simplicity PID can be easily incorporated in both linear and nonlinear systems. The definition of PID control is as follows

$$c_{ctr} = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t) \tag{5}$$

Where K_p, K_i and K_d are called the Proportional, Integral and Derivative gains, respectively. Ziegler-Nichols method one of the good online caculation methods of tuning. The variable ranges of PID controller parameters[15] are defined below

$$\begin{aligned} K_p^{'} &= \frac{K_p - K_{p\min}}{K_{p\max} - K_{p\min}} = \frac{K_p - K_{p\min}}{\Delta K_p} \\ K_i^{'} &= \frac{K_i - K_{i\min}}{K_{i\max} - K_{i\min}} = \frac{K_i - K_{i\min}}{\Delta K_i} \\ K_d^{'} &= \frac{K_d - K_{d\min}}{K_{d\max} - K_{d\min}} = \frac{K_d - K_{d\min}}{\Delta K_d} \end{aligned} \tag{6}$$

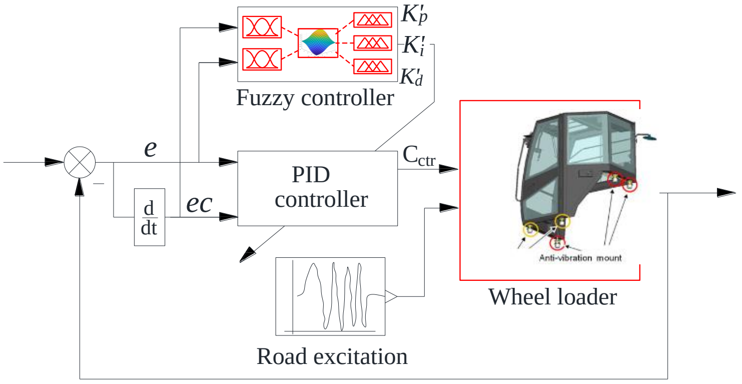


Figure 3. *Block diagram of Fuzzy –PID controler.*

Hence, we obtain:

$$\begin{aligned} K_p &= K_p^{'}.\Delta K_p + K_{p\min} \\ K_i &= K_i^{'}.\Delta K_i + K_{i\min} \\ K_d &= K_d^{'}.\Delta K_d + K_{d\min} \end{aligned} \tag{7}$$

Where $K_p^{'}, K_i^{'}$ and $K_d^{'}$ are the control parameters of the Fuzzy control in the variable ranges of the PID control of $\{K_{p\min} \le K_p \le K_{p\max}\}$, $\{K_{i\min} \le K_i \le K_{i\max}\}$; $\{K_{d\min} \le K_d \le K_{d\max}\}$. The range of each parameters are: $\{100 \le K_p \le 2100\}$, $\{10 \le K_i \le 100\}$, their values are then replaced into Eq. 8 as follows:

$$\begin{aligned} K_p &= 2000K_p^{'} + 100 \\ K_i &= 99K_i^{'} + 10 \\ K_d &= 9.9K_d^{'} + 0.1 \end{aligned} \tag{8}$$

By replacing Eq. (8) into Eq. (5), the PID’s transfer function is rewritten by

$$c_{ctr} = \left(2000K_p^{'} + 100\right)e(t) + \left(99K_i^{'} + 10\right)\int e(t)dt + \left(9.9K_d^{'} + 0.1\right)\frac{d}{dt}e(t) \tag{9}$$

The fuzzy controller is fed with two inputs error and derivative of error and the fuzzy controller output is used to adjust the PID parameters. Fuzzy inference block of the controller design is shown in Fig.4 below.

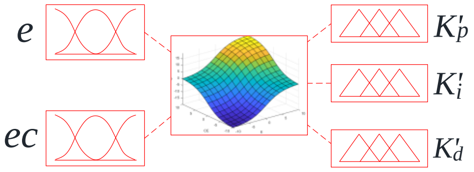


Figure 4. *Fuzzy inference block.*

Put the input membership functions of e and ec as linguistic labels. The inputs are {Negative Big, Negative medium, Negative small, Zero, Positive small, Positive medium, Positive Big}, and are referred to in the rules bases as {NB, NM, NS, ZE, PS, PM, PB}, and the linguistic labels of the outputs are {Negative Big, Negative medium, Negative small, Zero, Positive small, Positive medium, Positive Big} and referred to in the rules bases as {NB, NM, NS, ZE, PS, PM, PB}. There are 49 rules in the rule base used as presented in table 1.

Table 1. *Control rules of Fuzzy- PID control [14].*

$\{K_p', K_i', K_d'\}$		**ce**						
		NB	NM	NS	ZE	PS	PM	PB
e	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

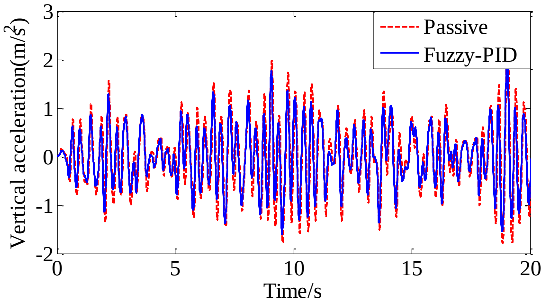
4. RESULTS AND DISCUSSION

In order to evaluate the ride comfort effectiveness of the wheel loader with the semi-active cab isolation system (SCIS) using Fuzzy Self Tuning of PID Controller compared to the passive cab isolation system (PCIS) under survey conditions, Matlab/simulink software was used for simulation and evaluation of their effectiveness with a set of reference data [19]. The comparison results of the time domain acceleration responses with SCIS compared to PCIS when the vehicle moves on the ISO class E road surface (very poor condition) at the vehicle speed of 5 km/h and empty vehicle load are shown Fig.5 and Fig. 6. From the results of Fig.5 and Fig.6, we show that the peak amplitude values of the time domain acceleration response of the vertical driver's seat and cab's pitch angle with SCIS using Fuzzy-PID controller respectively reduce in comparison with PCIS which indicates that the ride comfort efficiency of with SCIS using the Fuzzy-PID controller has greatly improved the ride comfort of vehicle compared to PCIS under large amplitude and low frequency excitations of ground surface.

From the results of Fig.5 and Fig.6, the values of the root-mean-square (RMS) vertical acceleration responses of the vertical driver's seat (a_{ws}) and cab's pitch angle (a_{wcphi}) according to International Standard ISO 2631-1[16] are determined by Eq.(10), when vehicle moves on the poor ground surface condition (ISO class E) at the vehicle speed of 5 km/h and empty vehicle load, as shown is table 2. The root-mean-square (RMS) vertical acceleration responses of vehicle body according to International Standard ISO 2631-1 is determined by:

$$a_w = \left[\frac{1}{T}\int_0^T a^2(\mathrm{t})\,\mathrm{dt}\right]^{\frac{1}{2}} \tag{10}$$

Where: a(t) is the weighted acceleration (translational and rotational) as a function of time, m/s^2; T is the duration of the measurements.



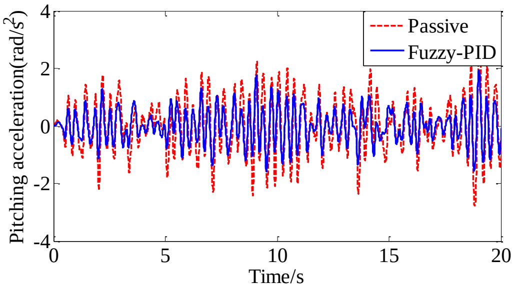


***Figure 5.** Time domain acceleration response of the vertical driver's seat.*

***Figure 6.** Time domain acceleration response of cab's pitch angle.*

***Table 2.** The values of a_{ws} and a_{wcphi} under survey conditions.*

Parameters	a_{ws}(m/s^2)	a_{wcphi}(rad/s^2)
PCIS (Passive)	0.71	0.93
SCIS (Fuzzy – PID)	0.57	0.67
Reduction	19,72%	27,96%

From the results of table 2, we show that the values of a_{ws} and a_{wcphi} with SCIS using Fuzzy-PID controller respectively decreased by 19.72% and 27,97% compared to PCIS that leads to a significant improvement in ride comfort of wheel loader under survey conditions.

5. CONCLUSIONS

In this study, a wheel loader ride comfort with the semi-active cab isolation system (SCIS) using Fuzzy Self Tuning of PID Controller was proposed to evaluate the ride comfort effectiveness of its SCIS compared to the passive cab isolation system (PCIS) under survey conditions. The major conclusions that can be drawn from the evaluation results as follows: (i) The peak amplitude values of the time domain acceleration response of the vertical driver's seat and cab's pitch angle with SCIS using Fuzzy-PID controller respectively reduce in comparison with PCIS which indicates that the ride comfort efficiency of with SCIS using the Fuzzy-PID controller has greatly improved the ride comfort of vehicle compared to PCIS under large amplitude and low frequency excitations of ground surface; (2) The values of a_{ws} and a_{wcphi} with SCIS using Fuzzy-PID controller respectively decreased by 19.72% and 27,97% compared to PCIS that leads to a significant improvement in ride comfort of wheel loader under survey conditions. The study results are an interesting reference for the researchers and manufacturers for further considerations during the improved design in the design of cab isolation system of earth-moving machinery.

***Acknowledgement:** The authors wish to thank the Thai Nguyen University of Technology for supporting this work. The authors would like to thank Assoc. Prof. Le Van Quynh for help with scientific ideas.*

REFERENCES

[1]. NikolayPavlov et al, *"Study of the wheel loader vibration with a developed multibody dynamic model,"* MATEC Web of Conferences, **Vol.133**, 02007, (2017).

[2]. Ryan P. Blood et al, *"Whole-body vibration in heavy equipment operators of a front-end loader: Role of task exposure and tire configuration with and without traction chains,"* Journal of Safety Research **Vol.43**, pp.357–364, (2012).

[3]. Zhao X. et al, *"Assessment of wheel loader vibration on the riding comfort according to ISO standards,"* Vehicle System Dynamics, **Vol. 51**(10), pp.1548-1567, (2013).

[4]. Zhao X., Schindler C., *"Evaluation of whole-body vibration exposure experienced by operators of a*

compact wheel loader according to ISO 2631-1:1997 and ISO 2631-5:2004," International Journal of Industrial Ergonomics, **Vol. 44** (6), pp. 840-850, (2014).

[5]. F. Chi, J. Zhou et al, *"Avoiding the health hazard of people from construction vehicles: a strategy for controlling the vibration of a wheel loader,"* International Journal of Environmental Research and Public Health, **Vol.14** (3), pp. 275, (2017).

[6]. X. Li, W. Lv, W. Zhang, and H. Zhao, *"Research on dynamic behaviors of wheel loaders with different layout of hydropneumatic suspension,"* Journal of Vibroengineering, **Vol.19**(7), pp. 5388–5404, (2017).

[7]. S. Wang et al, *"Active control of hydropneumatic suspension parameters of wheel loaders based on road condition identification,"* International Journal of Advanced Robotic Systems, **Vol.15** (6), (2018).

[8]. L. Evers, F. Krause, and P. Vink, *"Aspects to improve cabin comfort of wheel loaders and excavators according to operators,"* Applied Ergonomics, **Vol.34**(3), pp.265–271, (2003).

[9]. T. Wei, L. Zhiqiang, *"Damping Multimode Switching Control of Semiactive Suspension for Vibration Reduction in a Wheel Loader,"* Shock and Vibration, **Vol.2019**, Article ID 4535072,11 pages.

[10]. Rehnberg A., Drugge L., *"Ride comfort simulation of a wheel loader with suspended axles,"* International Journal of VehicleSystems Modelling and Testing, **Vol.3** (3), pp.168-188, (2008).

[11]. R. Fales, E. Spencer et al, *"Modeling and control of a wheel loader with a human-in-the-loop assessment using virtual reality,"* Journal of Dynamic Systems, Measurement, and Control, **Vol.127**(9), pp.415–423, (2005).

[12]. ISO 8068, *"Mechanical Vibration-Road Surface Profiles – Reporting of Measured Data"*, (1995).

[13]. ISO 2631-1, *"Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole Body Vibration-Part 1: General Requirements,"* (1997).

[14]. A S. Emam, *"Fuzzy Self Tuning of PID Controller for Active Suspension System,"* Advances in Powertrains and Automotives, Vol.1(1), pp.34-41, (2015).

[15]. N. Ebrahimi, A.Gharaveisi, *"Optimal Fuzzy Supervisor Controller for an Active Suspension System,"* International Journal of Soft Computing and Engineering (IJSCE), **Vol.2**(4), (2012).

[16]. Van Quynh, L., Viet Ha, D., et al, *"Improvement of ride comfort quality for an earth-moving machinery with semi-active cab isolation system,"* E3S Web Conf. **Vol.304**, 02012, (2021).

[17]. Van Quynh, L. et al, *"Optimal Design of Cab's Isolation System for a Single-Drum Vibratory Roller,"* Lecture Notes in Networks and Systems, **Vol.178**, pp. 619–627, (2021).

[18]. Van Cuong, B. et al, *"Effects of Design Parameters of Cab's Suspension System on an Agricultural Tractor Ride Comfort,"*. Lecture Notes in Networks and Systems, **Vol 602**, pp 881–886, (2023).

[19]. Tran Thang Quyet, *"Study on the ride effectiveness of hydraulic isolation system for construction machine cab,"* Master of Science thesis, Thai Nguyen University of Technology, (2022).

TÓM TẮT

Nâng cao chất lượng êm dịu cho máy xúc lật với hệ thống đệm cách dao động bán chủ động cabin sử dụng bộ điều khiển Fuzzy-PID

Nâng cao độ êm dịu người điều khiển máy xúc lật là quan trong để tránh các nguy cơ sức khỏe tiềm ẩn do rung động toàn thân gây ra, Một bộ điều khiển Fuzzy-PID được thiết kế để điều khiển hệ hệ số giảm chấn của hệ thống đệm cách dao động bán chủ động cab (SCIS) cho máy xúc lật. Một mô hình động lực học máy xúc lật được thiết lập dưới điều kiện khảo sát cho phân tích và đánh giá. Giá tốc bình phương trung bình phản ứng của ghế ngồi người điều khiển theo phương thẳng đứng và góc lắc dọc cabin theo tiêu chuẩn quốc tế ISO2631-1 (1997-E) được chọn như là các hàm mục tiêu. Hiệu quả của chiến thuật điều khiển đề xuất được phân tích dưới kích thích ngẫu nhiên của mặt đường theo thời gian. SCIS đề xuất được mô phỏng và phân tích bằng phần mềm Matlab/Simulink so sánh với hệ thống đệm cách dao động bị động cabin (PCIS) dưới các điều kiện khảo sát. Các kết quả khảo sát chỉ ra rằng hiệu quả êm dịu của máy xúc lật với SCIS là tốt hơn PCIS dưới các điều điều kiện khảo sát. Ngoài ra, các kết quả nghiên cứu là cơ sở ban đầu cho việc tối ưu các thông số điều khiển.

Từ khoá: Máy xúc lật; Cabin; Hệ thống đệm cách dao động; Bộ điều khiển Fuzzy-PID; Độ êm dịu.