EXPERIMENTAL RESEARCH ON THE STABILITY OF A SPRAY BOOM WITH AN ACTIVE AND PASSIVE PENDULUM SUSPENSION
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摆式主被动悬架喷雾机喷杆稳定性试验研究

Fang LI[1], Xiaohu BAI*[2]
[1] School of Information and Control Engineering, Liaoning Petrochemical University, Fushun/China;
[2] College of Engineering, Shenyang Agricultural University, Shenyang/China
E-mail: baixiaohu@syau.edu.cn
DOI: https://doi.org/10.35633/inmateh-72-46

Keywords: *Transient response, Dynamic response, Boom stability, Response surface method, Pendulum suspension*

ABSTRACT
When a sprayer is operating in the field, the uneven ground excitation causes the spray boom to move irregularly, significantly affecting the spray distribution uniformity and reducing the effectiveness of pesticide application. Installing a suspension between the vehicle and the boom is a crucial method to improve the boom stability. In this paper, experimental research on the stability of a boom with an active and passive pendulum suspension was carried out. The results of the transient response test of the passive suspension demonstrate that an increase in the suspension rotation damping coefficient reduces the overshoot of the system but slows down the response speed. Conversely, an increase in the suspension rotation stiffness coefficient speeds up the response speed. The results of the dynamic response test of the active suspension indicate that a smaller adjustment threshold of the control system for the boom inclination angle results in higher control accuracy. However, when the threshold is less than 1 cm, the boom becomes challenging to balance. The results of the combination experiments based on the response surface method reveal that the rotation stiffness coefficient, rotation damping coefficient, unit forward speed, and their interactions significantly impact the adjustment time of the boom and the variation coefficient of the boom inclination angle. Through contribution rate analysis, the influence order of each factor on the adjustment time and variation coefficient was obtained. Additionally, the analysis of variance results show that the established regression model fits the actual situation well, and has reference significance for the design and application of the suspension.

摘要
喷杆喷雾机田间作业时，田间不平地面的激励导致喷杆产生不规律运动，极大地影响雾滴分布均匀性，降低农药的施用效果。在车体与喷杆之间安装悬架是提高喷杆稳定性的重要途径。本文对安装摆式主被动悬架的喷杆稳定性进行了试验研究。被动悬架瞬态响应试验结果表明，悬架旋转阻尼系数增大，系统超调量减小，但响应速度变慢。悬架旋转刚度系数增加，系统响应速度加快。主动悬架动态响应试验结果表明，喷杆倾角控制系统调节阈值越小，控制精度越高。但当阈值小于1cm 时，喷杆难以平衡。基于响应面法的组合试验结果表明，旋转刚度系数、旋转阻尼系数、机组前进速度及其交互作用对喷杆调节时间、喷杆倾角变异系数影响显著。通过因素贡献率分析，得到了各因素对调节时间和变异系数的影响顺序。方差分析结果表明，建立的回归模型与实际情况高度拟合，对悬架的设计和应用具有参考意义。

INTRODUCTION
Plant protection equipment is one of the most important aspects influencing the chemicals spraying effect and utilization efficiency (*He, 2020*). Boom sprayers are widely used in agriculture for the application of chemical materials such as pesticides, herbicides and fertilizers due to their large widths and high efficiency (*He, 2022; Qiu et al., 2015*). When a sprayer runs over obstacles or uneven terrains, the spray boom oscillates both vertically and horizontally, impacting the spray distribution pattern. Previous research has shown that spray deposit distribution ranges between 0 and 800% as a result of spray boom vibrations (*Ooms et al., 2002*). Therefore, the stability of the boom has significant influence on spraying quality (*Lipinski et al.,* 2022). A stable boom can result in more uniform spray coverage and prevent the boom tips from touching the ground.

Fang Li, Lecturer, Ph.D.; Xiaohu Bai, Associate Prof., Ph.D.,Corresponding Author.

To address boom instability and enhance spray uniformity, manufacturers have equipped sprayers with various types of suspensions (*Cui et al., 2019*). The most commonly used suspension is the double-pendulum suspension, with the first pendulum serving as a passive suspension and the second pendulum functioning as an active suspension (*Tahmasebi et al., 2013*).

Theoretical investigations and practical experiments have been conducted for improving the stability of a spray boom. To optimize the vertical suspension for a 39 m wide sprayer of John Deere, Anthonis et al. established a mathematical model of the suspension with an existing nonlinear damper. The standard deviation of the absolute boom rotation around the horizontal axis was minimized by applying several tracks based on power spectral densities of measurements in field conditions. The distance to the rotation point of the damper and the appropriate damping value were obtained (*Anthonis et al., 2005*). In order to investigate boom movements under excitation signals, Wu and Miao set up a model with four spring-damper modules between the boom and the frame, and obtained the ideal stiffness coefficient and damping coefficient (*Wu et al., 2012*). To acquire good responsiveness, stability and accuracy of the active suspension, Xue et al. developed a control algorithm based on adaptive fuzzy sliding model with the spray boom inclination angel as the control object. The test results indicated that the active suspension can effectively isolate the disturbing swing of the vehicle body and keep the spray boom stable (*Xue et al., 2018*). Aiming at the problem of poor stability caused by parameter uncertainties and random disturbances in the passive and active pendulum suspension, Cui et al. designed an adaptive robust controller, taking into account damping, stiffness, uncertain disturbances, Coulomb friction, and other parameters of the suspension (*Cui et al., 2020*). Zhuang carried out the performance test of cable-stayed spring, vertical spring, horizontal damper, and vertical damper. The results of transient response tests and field tests showed that the spring and damper had significant impacts on the transient vibration and the low-frequency vibration of the boom (*Zhuang, 2020*). Yan et al. studied the dynamic behaviour of the spray boom under step excitation, and analysed the effects of sprayer speed, boom length, and boom cross-section shape on boom vibration (*Yan, 2021*).

In this paper, experiments were conducted to test the transient response of the passive suspension and the dynamic response of the active suspension. The impacts of spring, damper, sprayer speed and their interactions on the adjustment time of the boom and the variation coefficient of the boom inclination angle were investigated by response surface analysis. The objective of this research is to provide references for the design and application of boom suspensions.

MATERIALS AND METHODS

Experimental setup

Figure 1 illustrates a schematic representation of the experimental setup. The spray boom, constructed from welded steel section, had a mass of 49 kg and a moment of inertia around the centre of mass of 93 kgm^2. The first pendulum rod of the suspension system was 0.45 m long, and the second one was 0.25 m long. A spring and a damper were connected between the first pendulum rod and the frame to inhibit boom oscillation. The damping coefficient of the damper was 1875 Ns/m. The stiffness coefficient of the spring was 730 N/m. The spring was installed inside a guide sleeve to ensure stability when compressed. An actuator, a 24V DC electric linear push rod, was used to adjust its length in response to signals from the control system. Additionally, two ultrasonic sensors were employed to measure the distance between the boom end and the ground surface. The prototype of the experimental setup is shown in Figure 2.

To generate the required excitation signal, wooden boards of varying heights were placed on the ground to simulate a field slope, as shown in Figure 3. Considering the boom length and the wheel-track of the tractor, the angle of the simulated slope was set at 1.5° (*Qiu et al., 2012, Wei et al., 2015*).

Method of transient response tests of the passive pendulum suspension

Attach the frame to the three-point hitch linkage of the tractor, and unfold the spray boom. Then lift one side of the boom to a position with an inclination angle of about 5°. Turn off the control system for the boom inclination angle and release the boom. Subsequently, record the distance from the ultrasonic sensors at the left and right ends of the boom to the ground, and then calculate the inclination angle of the boom during oscillation.

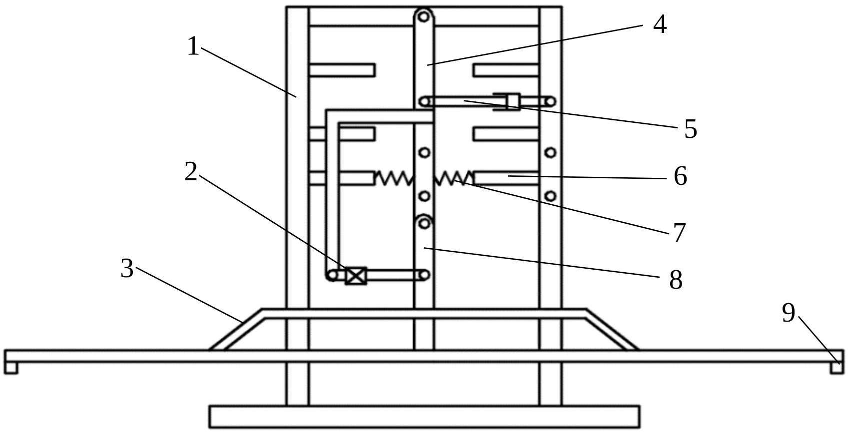


Fig. 1 - Schematic of the experimental setup

1- frame; 2- actuator; 3- spray boom; 4- first pendulum rod; 5- damper; 6- guide sleeve; 7- spring; 8- second pendulum rod 9- ultrasonic sensor

Fig. 2 - Prototype of the experimental setup

Fig. 3 - Simulated slope for experiments

Method of dynamic response tests of the active pendulum suspension

Level the spray boom to a height of 80 cm from the ground. Then place a box with a height of 40 cm beneath the right ultrasonic sensor to mimic a sloped terrain (*Herbst et al., 2018*). Activate the control system for the boom inclination angle, which adopts a fuzzy PID control algorithm based PSO (*Li et al., 2023)*. Record the distance from the ultrasonic sensors at the left and right ends of the boom to the ground.

Method of experiments of the boom stability

Based on the structure and working principle of the pendulum suspension, three main factors affecting the boom stability were selected: unit forward speed, suspension rotational damping coefficient, and suspension rotational stiffness coefficient. The suspension rotational damping coefficient can be calculated from the damping coefficient and the damper's installation position, while the suspension rotational stiffness coefficient can be determined from the stiffness coefficient and the spring's installation position (*Cui et al.,2017a*, *Cui et al.,2017b*). According to the working requirements of the sprayer, the unit forward speed was set at 2~4 km·h^{-1}, the suspension rotational damping coefficient at 100~300 Nms·rad^{-1}, and the suspension rotational stiffness coefficient at 20~100 Nm·rad^{-1}. Factors and levels of the experiments are presented in Table 1.

Table 1

Factors and levels

Levels \ Factors	Unit forward speed	Suspension rotational damping coefficient	Suspension rotational stiffness coefficient
	[km·h^{-1}]	**[Nms·rad^{-1}]**	**[Nm·rad^{-1}]**
-1	2	100	20
0	3	200	60
1	4	300	100

To evaluate the speed of the spray boom in tracking the ground slope and its stability after reaching steady state, the adjustment time of the boom and the variation coefficient of the boom inclination angle were chosen as experimental indicators. The adjustment time of the boom is the time from when the tractor begins to drive up a slope to when the boom reaches a steady state. The variation coefficient of the boom inclination angle is the ratio of its standard deviation to the average value after the boom achieves a steady state.

Since many nonlinear factors affect the boom inclination angle, quadratic or higher-order models are commonly used to estimate the boom response (*Jeon et al., 2004*). The Box-Behnken combination experimental design based on response surface method was employed. A three-factor and three-level scheme was designed, with 5 replicates of the central point, resulting in a total of 17 experiments.

RESULTS

Transient response of the passive pendulum suspension

Maintain the initial angle of the boom and change the damping effect by adjusting the installation position of the damper. When the damper was placed at positions 0.23 m, 0.326 m, and 0.4 m away from the hinge point of the first pendulum rod and the frame, the corresponding suspension rotational damping coefficients were 100 Nms·rad^{-1}, 200 Nms·rad^{-1}, and 300 Nms·rad^{-1}, respectively.

The impact of three different rotational damping coefficients on the inclination angle changes of the boom is demonstrated in Figure 4. It reveals that the rotational damping coefficient notably influences the peak value of the transient response of the boom. When *C* is 100 Nms·rad^{-1}, the peak time is approximately 2 s, with a 50% overshoot, and the boom angle stabilizes within 10% of the initial value at around 6.5 s. For *C* at 200 Nms·rad^{-1}, the peak time is roughly 2.1 s, with an 18.37% overshoot, and the boom angle stabilizes within 10% of the initial value at approximate 3.2 s. With *C* at 300 Nms·rad^{-1}, the peak time extends to about 3.1 s, and the overshoot is 3.7%. It is obvious that increasing the damping coefficient decreases the overshoot, but if the damping coefficient is too large, the peak time will increase, leading to a slower system response.

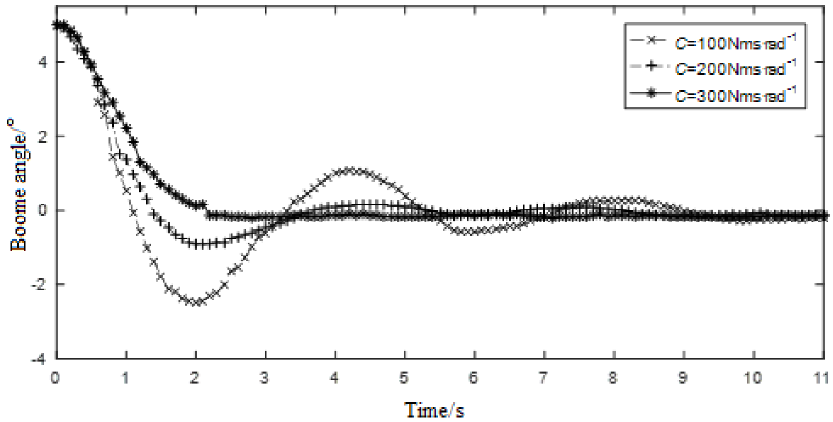


Fig. 4 – Transient response of the boom with different rotational damping coefficients

The variations in the inclination angle of the boom with three different rotational stiffness coefficients are shown in Figure 5. When *K* is 20 Nm·rad^{-1}, 60 Nm·rad^{-1}, and 100 Nm·rad^{-1}, the peak time is approximately 1.6 s, 1.9 s, and 2.0 s, respectively. It can be inferred that the peak time of transient response of the suspension decreases with a larger rotational stiffness coefficient, indicating a faster response speed.

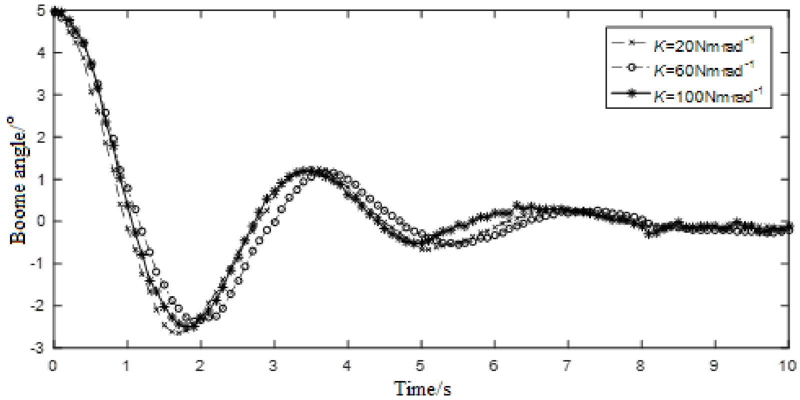


Fig. 5 – Transient response of the boom with different rotational stiffness coefficients

Dynamic response of the active pendulum suspension

When the boom is in a horizontal position, the distance between the left sensor and the ground is 80 cm, and the distance between the right sensor and the box is 40 cm. This results in a 40 cm difference between the two sensors and the target, prompting the control system to decrease the distance difference. The adjustment process is shown in Figure 6 and Figure 7. At the outset, with the distance difference at 40 cm and a zero-distance change rate, the control system outputs a 20% duty cycle for the electric push rod. As the distance difference and the distance change rate alter, the duty cycle is consistently modified, reaching 30% at 0.3 s. At the same time, the right end of the boom rises while the left end descends. By 2 s, the boom reaches its initial equilibrium position, and the duty cycle is reduced to zero. However, due to the change in the position of the gravity centre, the boom continuous to swing, and the duty cycle becomes relatively small. After 5.6 s, the boom reaches its final equilibrium position, with the distance between the left sensor and the ground at 61 cm, and the distance between the right sensor and the box at 59 cm. The steady-state error of the control system is 1 cm.

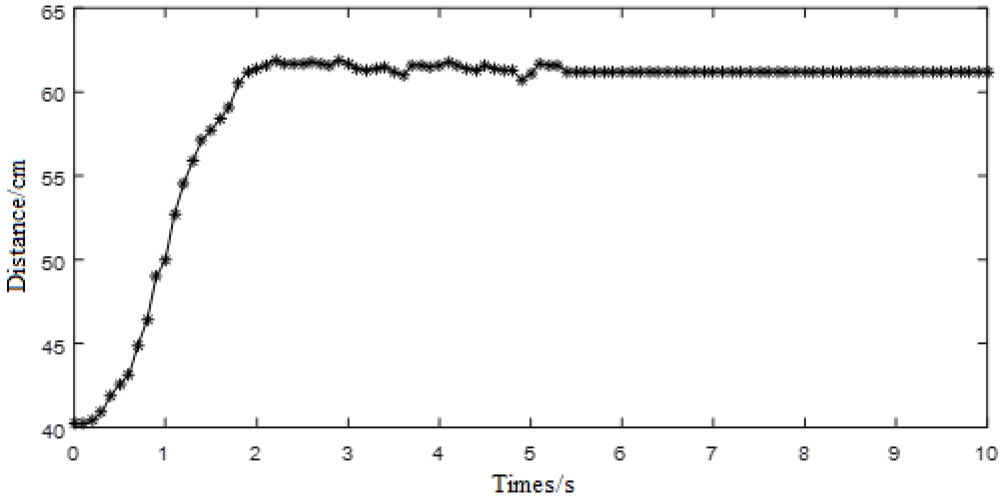


Fig. 6 – Distance between the right sensor and the target

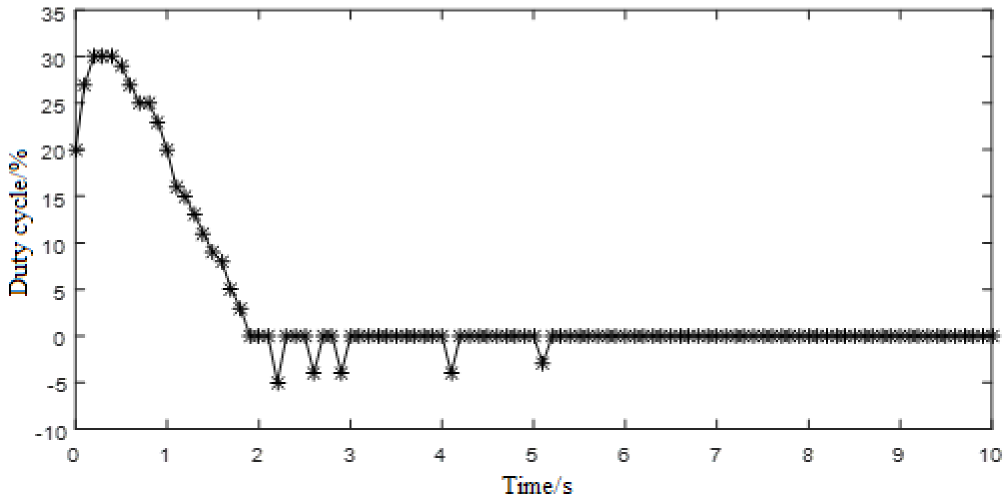


Fig. 7 – Duty cycle output by the control system

To test the effect of the boom height threshold on control performance, various thresholds of 10 cm, 7 cm, 5 cm, 3 cm, 2 cm, and 1 cm were set. The results are presented in Table 2. Upon setting the threshold above 2 cm, the control system can effectively adjust the boom height at both ends to the ground, and successfully confine the height error within the prescribed threshold for both ends. However, with the threshold set at 1 cm, the electric push rod continues to be active, preventing the boom from achieving equilibrium.

Table 2

Results of threshold test

Boom height before balance [cm]		Threshold [cm]	Boom height after balance [cm]	
Left end	Right end		Left end	Right end
80	40	10	63.8	56.2
		7	62.0	57.2
		5	57.5	62.1
		3	61.0	58.5
		2	59.5	61.2
		1	—	—

Stability of the spray boom

The experimental scheme and results are shown in Table 3.

Table 3

Experimental scheme and results

No.	Factors and levels			Experimental indicators	
	Rotational stiffness coefficient	Rotational damping coefficient	Unit forward speed	Adjustment time	Variation coefficient
	X_1	X_2	X_3	Y_1/s	Y_2/%
1	0	-1	-1	6.6	10.71
2	0	0	0	5.4	10.29
3	1	0	1	5.9	11.86
4	1	1	0	7.4	11.45
5	1	-1	0	7.1	11.43
6	0	0	0	5.3	10.27
7	0	1	-1	7.0	10.63
8	-1	1	0	7.7	11.36
9	0	-1	1	6.8	10.86
10	0	0	0	5.4	10.19
11	1	0	-1	5.9	11.29
12	-1	0	-1	5.2	11.28
13	0	0	0	5.4	10.28
14	-1	0	1	5.6	11.41
15	-1	-1	0	6.3	11.12
16	0	1	1	7.6	11.15
17	0	0	0	5.5	10.18

Regression Model Establishment and Significance Test

The statistical analysis software Design Expert 8.0.5 was applied to process the data in Table 3, and the results are shown in Table 4.

The *P* values of the model terms related to the adjusting time Y_1 and variation coefficient Y_2 are all less than 0.0001, indicating a high degree of significance for the regression model. Furthermore, the *P* values of the lack of fit terms corresponding to these two indicators are 0.2564 and 0.9527, both greater than 0.05, suggesting a strong fit of the regression model to the actual circumstances. The significance of the quadratic terms X_1^2、X_2^2、X_3^2, and interaction terms X_1X_2、X_1X_3、X_2X_3 indicates that there is a quadratic nonlinear relationship and interaction among the three factors and the experimental indicators.

Consequently, response surface quadratic polynomial regression models for the adjusting time Y_1 and variation coefficient Y_2 were established, as depicted in equations (1) and (2).

$$Y_1=5.4+0.23X_1+0.33X_2+0.15X_3-0.2X_1X_2-0.1X_1X_3+0.1X_2X_3+0.15X_1^2+1.5X_2^2+0.1X_3^2 \quad (1)$$

$$Y_2=10.24+0.11X_1+0.059X_2+0.17X_3-0.055X_1X_2+0.11X_1X_3+0.093X_2X_3+0.86X_1^2+0.24X_2^2+0.36X_3^2 \quad (2)$$

Table 4

Results of analysis of variance

Variance source	Adjustment time Y_1				Variation coefficient Y_2			
	Square sum	Degree of freedom	F value	P value	Square sum	Degree of freedom	F value	P value
Model	11.52	9	179.21	<0.0001**		4.65	9	302.28
X_1	0.41	1	56.70	0.0001**		0.092	1	54.13
X_2	0.85	1	118.30	<0.0001**		0.028	1	16.17
X_3	0.18	1	25.20	0.0015**		0.23	1	137.37
X_1X_2	0.16	1	22.40	0.0021**		0.012	1	7.08
X_1X_3	0.04	1	5.60	0.0499*		0.048	1	28.34
X_2X_3	0.04	1	5.60	0.0499*		0.034	1	20.04
X_1^2	0.095	1	13.26	0.0083**		3.12	1	1824.5
X_2^2	9.47	1	1326.3	<0.0001**		0.24	1	139.36
X_3^2	0.042	1	5.89	0.0456*		0.54	1	315.53
Residual	0.05	7				0.012	7	
Lack of fit	0.03	3	2.00	0.2564		0.001	3	0.11
Error	0.02	4				0.011	4	
Sum	11.57	16				4.66	16	

Note: P<0.01 means highly significant (**), and P<0.05 means significant (*).

Impact of Factors on Response Values

The impact of each factor on the model can be compared using the contribution rate K (*Xie et al., 2019, Shen et al., 2019*). A larger K value indicates a greater impact. The calculation method for the contribution rate is shown in equations (3) and (4), and the results are presented in Table 5.

$$\delta=\begin{cases}0, & F\leqslant 1\\ 1-\dfrac{1}{F}, & F>1\end{cases} \quad (3)$$

$$K_{X_i}=\delta_{X_i}+0.5\sum\delta_{X_iX_j}+\delta_{X_i^2} \qquad i,j=1,2,3 \quad i\neq j \quad (4)$$

Where:

K_{Xi} is the contribution rate of the factor X_i, F is the F-value of each regression term in the model, δ is the assessment value corresponding to the F-value.

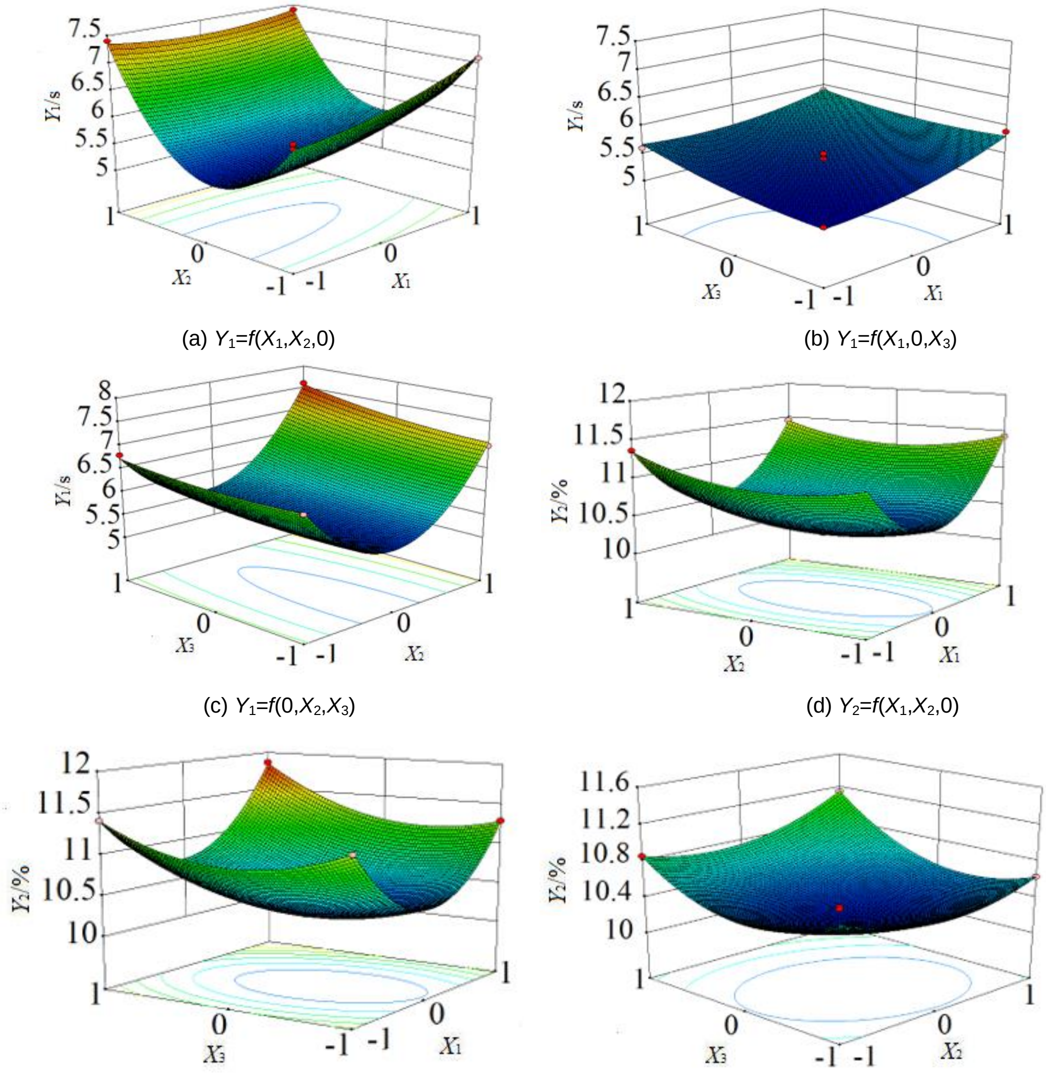
Table 5

Analysis of contribution rate of factors

Indicators	Contribution rate			Order of contribution rate
	Rotational stiffness coefficient X_1	Rotational damping coefficient X_2	Unit forward speed X_3	
Adjustment time	2.795	2.879	2.612	$X_2>X_1>X_3$
Variation coefficient	2.893	2.835	2.947	$X_3>X_1>X_2$

Impact of Interactions on Response Values

The software Design Expert 8.0.5 was utilized to create response surfaces and analyse the impact of interactions on the adjustment time and variation coefficient, as shown in Figure 8.



(a) $Y_1=f(X_1,X_2,0)$ (b) $Y_1=f(X_1,0,X_3)$

(c) $Y_1=f(0,X_2,X_3)$ (d) $Y_2=f(X_1,X_2,0)$

(e) $Y_2=f(X_1,0,X_3)$ (f) $Y_2=f(0,X_2, X_3)$

Fig. 8 – Impact of interactions on the adjustment time and variation coefficient

When the unit forward speed is set to zero level, at all levels of the rotational stiffness coefficient, the adjustment time initially decreases and then increases as the rotational damping coefficient increases. This indicates that under damping causes the overshoot of the boom angle to be too large and slows down the transient component attenuation when the damping coefficient is too low. Conversely, an excessively high damping ratio makes the connection between the pendulum and the frame almost rigid, making it easy for high-frequency excitation signals to be transmitted to the boom. When the rotational stiffness coefficient is set to zero level, at a lower level of the rotational stiffness coefficient, the adjustment time gradually increases as the unit forward speed increases. This suggests that excessive forward speed generates stronger excitation on the boom, and the reaction force generated by the spring intensifies the oscillation of the boom.

When the unit forward speed and rotational damping coefficient are each set to zero level, the variation coefficient demonstrates a trend of initially decreasing and then increasing as the rotational stiffness coefficient increases. This indicates that a spring with too low stiffness exerts a weak inhibitory effect on boom vibration. However, if the spring stiffness is excessive, it leads to a higher resonance frequency in the suspension, allowing disturbances in a wider frequency range to be transmitted to the boom, thus resulting in poor stability. The influence of the rotational damping coefficient on the variation coefficient is generally consistent with its impact on the adjustment time, albeit changing at a slower rate.

CONCLUSIONS

The results of transient response tests of the passive suspension indicate that increasing the rotational damping coefficient leads to a decrease in system overshoot. However, if the damping coefficient is excessively large, the system response becomes slower. Furthermore, a higher rotational stiffness coefficient results in a shorter peak time and faster response speed.

The results of dynamic response tests of the active suspension reveal that the control system for the boom inclination angle can effectively respond and adjust the height difference on both ends of the boom, with a short response time and small steady-state error. Moreover, reducing the threshold enhances control accuracy. However, if the threshold is excessively small, the boom may fail to achieve balance.

The effects of the rotational stiffness coefficient, rotational damping coefficient, and unit forward speed on the boom adjustment time and the boom angle variation coefficient were investigated using the Box-Behnken combination experimental design based on response surface. A quadratic regression model was established and analysis of variance was conducted. The contribution rate analysis revealed that the order of the effects of all factors on the adjustment time as follows: rotational damping coefficient, rotational stiffness coefficient, and unit forward speed. Similarly, the order of the effects of all factors on the variation coefficient was determined as: unit forward speed, rotational stiffness coefficient, and rotational damping coefficient. Through analysis of the response surfaces, the impacts of all factors and their interactions on the experimental indicators were studied.

ACKNOWLEDGEMENT

This research was supported by talent scientific research fund of Liaoning Petrochemical University (No.2021XJJL-024).

REFERENCES

[1] Anthonis, J., Audenaert, J., Ramon, H. (2005). Design optimization for the vertical suspension of a crop sprayer boom. *Biosystem Engineering*, 90(2), 153–160.

[2] Cui, L., Xue, X., Ding, S., Qiao, B., Le, F. (2017a). Analysis and test of dynamic characteristics of large spraying boom and pendulum suspension damping system (大型喷杆及其摆式悬架减振系统动力学特性分析与试验). *Transactions of the Chinese Society of Agricultural Engineering*, 33(9), 69–76.

[3] Cui, L., Xue, X., Ding, S., Gu, W., Chen, C, Le, F. (2017b). Modeling and simulation of dynamic behavior of large spray boom with active and passive pendulum suspension (双钟摆主被动悬架式大型喷雾机喷杆动力学仿真与试验). *Transactions of the Chinese Society of Agricultural Machinery*, 48(2), 82–90.

[4] Cui, L., Xue, X., Le, F., Mao, H., Ding, S. (2019). Design and experiment of electro hydraulic active suspension for controlling the rolling motion of spray boom. International *Journal of Agricultural and Biological Engineering*, 12(4), 72–81.

[5] Cui, L., Xue, X., Le, F., Ding, S. (2020). Adaptive robust control of active and passive pendulum suspension for large boom sprayer (大型喷杆喷雾机钟摆式主被动悬架自适应鲁棒控制研究). *Transactions of the Chinese Society of Agricultural Machinery*, 51(12), 130–141.

[6] Herbst, A., Osteroth, H., Stendel, H. (2018). A novel method for testing automatic systems for controlling the spray boom height. *Biosystems Engineering*, 174(8), 115–125.

[7] He, X. (2020). Research progress and developmental recommendations on precision spraying technology and equipment in China (中国精准施药技术和装备研究现状及发展建议). *Smart Agriculture*, 2(1), 133–146.

[8] He, X. (2022). Research and development of efficient plant protection equipment and precision spraying technology in China: a review (高效植保机械与精准施药技术进展). *Journal of Plant Protection*, 49(1), 389–397.

[9] Jeon, H.Y., Womac, A.R., Gunn, J. (2004). Sprayer boom dynamic effects on application uniformity. *Transactions of the American Society of Agricultural Engineers*, 47(3), 647–658.

[10] Lipinski, A.J., Lipinski, S., Burg, P., Sobotka, M. S. (2022). Influence of the instability of the field crop sprayer boom on the spraying uniformity. *Journal of Agriculture and Food Research*, 10, 1–4.

[11] Li, F., Bai, X., Su, Z., Tang, S., Wang, Z., Li, F., Yu, H. (2023). Development of a control system for double-pendulum active spray boom suspension based on PSO and fuzzy PID. *Agriculture-Basel*, 13(9), 1660.

[12] Ooms, D., Lebeau, F., Ruter, R., Destain, M.F. (2002) Measurements of the horizontal sprayer boom movements by sensor data fusion. *Computers and Electronics in Agriculture*, 33, 139-162
[13] Qiu, B., Yang, N., Xu, X., Guan, X., Wu, C. (2012). Ideal spray Boom response extraction with front and rear tires excited by step track (喷雾机前后轮相继激励下喷杆理想运动响应提取). *Transactions of the Chinese Society of Agricultural Machinery*, 43(2), 55–60.
[14] Qiu, B., Yan, R., Ma, J., Guan, X., Ou, M. (2015). Research progress analysis of variable rate sprayer technology (变量喷雾技术研究进展分析). *Transactions of the Chinese Society of Agricultural Machinery*, 46(3), 59–72.
[15] Shen, G., Wang, G., Hu, L., Yuan, J., Wang, Y. (2019). Development of harvesting mechanism for stem tips of sweet potatoes (甘薯茎尖收获机研制). *Transactions of the Chinese Society of Agricultural Engineering,* 35(9), 46–55.
[16] Tahmasebi, M., Rahman, R.A., Mailah, M., Gohari, M. (2013). Active force control applied to spray boom structure. *Applied Mechanical Material*, 315, 616–620.
[17] Wu, J., Miao, Y. (2012). Dynamic characteristic analysis of boom for wide sprayer with different exciting sources (不同激励源下宽幅喷雾机喷杆的动态特性分析). *Transactions of the Chinese Society of Agricultural Engineering*, 28(4), 39–44.
[18] Wei, X., Shao, J., Miao, D., Li, L., Xie, X. (2015). Online control system of spray boom height and balance (喷杆式喷雾机喷杆高度及平衡在线调控系统). *Transactions of the Chinese Society of Agricultural Machinery*, 46(8), 66–71.
[19] Xie, J., Zhang, F., Chen,X., Han, Y. Tang, W. (2019). Design and parameter optimization of arc tooth and rolling bundle type plastic film residue collector (弧形齿滚扎式残膜回收机的设计及参数优化). *Transactions of the Chinese Society of Agricultural Engineering,* 35(11), 26–37.
[20] Xue, T., Li, W., Du, W., Mao, E. Wen, H. (2018). Adaptive fuzzy sliding mode control of spray boom active suspension for large high clearance sprayer (大型高地隙喷雾机喷杆主动悬架自适应模糊滑模控制). *Transactions of the Chinese Society of Agricultural Engineering,* 34(21), 47–56.
[21] Yan, J., Xue, X., Cui, L., Ding, S., Gu, W., et al. (2021). Analysis of dynamic behavior of spray boom under step excitation. *Applied Science*, 11(21), 10129.
[22] Zhuang, T. (2020). *Theoretical analysis and experimental research on boom vibration of large-scale high clearance sprayer* (大型高地隙喷雾机喷杆振动理论分析与试验研究) [Doctoral dissertation, Chinese Academy of Agricultural Mechanization Sciences).