STUDY ON HYDRAULIC ACTIVE SUSPENSION FOR WHEELED HYDRAULIC EXCAVATOR

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ABSTRACT

This paper deals with hydraulic active suspension for wheeled hydraulic excavator. In this study, a combined control method for both the posture keeping and the vibration elimination is proposed, and verified in experiment. The posture keeping control is realized by a variable stiffness control, and the vibration control is based on the skyhook damping theory. The result shows that the control can not only well eliminate the vibration on the body of the excavator during its high speed moving, but also well keep the posture of the chassis horizontal while the excavator is in digging or swing operation.

KEY WORDS

Suspension, Hydraulic system, Active damping, Stiffness control, Excavator

INTRODUCTION

Wheeled hydraulic excavator is appreciated for its mobility. However, the current model of this kind of excavator has no suspension system. The operator has to be frequently subjected to a large terrain-induced whole body vibration while the excavator is in moving.

To improve the operation performance and the condition of the operator, it is no doubt a good solution to add a suspension systems just like that used in the vehicle like truck or car. The ordinary vehicle often uses passive suspension system, and it is effective for eliminating the vibration. But for excavator, as its front system, i.e., boom, arm and bucket are moved and swung, its gravity center is changed in a large range, the passive suspension system can not adapt itself to such a large change, and so can not keep the attitude of chassis in horizontal during operation. And the gravity center of the excavator is rather high, the changing of the gravity center will increase the risk of overwhelm. For the reason above, active suspension system is found to be necessary for the wheeled excavator.

HYDRAULIC ACTIVE SUSPENSION

The wheeled excavator often use hydraulic system for its
front system operation, it is nature to use hydraulic active suspension in this study.

The experiment is executed with a wheeled hydraulic excavator of 10(t) class. Fig. 1 shows the whole side view of excavator and front view of suspension part. Suspension system is set between chassis and axle. Since the axle is attached directly to the chassis in the current model, it is necessary to detach the axle from the chassis to make the suspension system become effective. A link system is set between the chassis and the axle. The link system changes the force that acts at axle in axial direction, to that acts in vertical direction. As the result, it increases the stiffness between the chassis and the axle in the wheel axial direction. The suspension systems composed of leaf springs and hydraulic cylinder are set for all the four tires.

Fig. 1 Test model with active suspension

The function of the active suspension is implemented by the cylinder which is set between the chassis and axle. Fig. 2 shows the hydraulic circuit of active suspension system. Since large transient flow and quick valve response are needed for generating the enough damping force, a servo valve and accumulator are used for control the cylinder.

Fig. 2 Hydraulic circuit

Four acceleration sensors are separately fix on each wheel to detect the acceleration of each tire in the vertical direction, and pressure sensors are fixed in the bottom side of each cylinder. All signals are inputted into the controller as it shown in Fig. 3.

Fig. 3 controller

CONTROL THEORY

The suspension system of the excavator acts two functions, one is keeping the posture in certain state without suffering the influence of the movement of the gravity center, and another is to eliminate the vibration on the body during the excavator is in moving. Here a combined control method is proposed for controlling the cylinders in the suspension system to realize the two functions. The vibration control is based on the skyhook damping theory, which is well used in the mobile. And the posture control is realized through adjusting the stiffness in the four active suspensions to control the length of each cylinder. In the paper this posture control method is called stiffness control. Both kinds of controls are combined into one controller to control the four cylinders on tires. The detail will be introduced in following.

Stiffness Control

Fig. 4 shows a model for explanation of the principal of stiffness control in the control of the cylinder length, i.e.
the distance between the chassis and axle. In the model, a stiffness adjustable spring, which refers to one function of the cylinder, is set in parallel with a fixed spring-damper, which refers to the leaf spring in the suspension. Fig. 5 shows the block diagram of the control system for the stiffness control.

Fig. 4 Physical model for explaining the variable stiffness control

![Fig.4](image1)

Fig. 5 Block diagram of variable stiffness control

There are two control loops in Fig. 5, the inner one is pressure control and the outer one is the distance control. The distance between the chassis and axle is fed back, and eq(1) can be obtained

\[ P_{\text{ref}} = K \ast (L_{\text{ref}} - L_{\text{mes}}) \]  

(1)

where, \( P_{\text{ref}} \) is the reference pressure for the pressure control in the inner loop, \( L_{\text{ref}} \) is the reference distance determined according to the posture of the excavator. \( K \) is taken as the stiffness which can be adjusted by the controller, it can be expressed as (2).

\[ K = K_s / (1 + T_d S) \]  

(2)

Ks is adjusted according to the \( P_{\text{ms}}, L_{\text{mes}} \).

And the change of the \( P_{\text{ref}} \) causes the movement of the cylinder piston and so the distance between the chassis and axle can be adjusted.

For example, if the difference \( L_{\text{ref}} - L_{\text{mes}} \) is positive, the stiffness \( K \) is then increased, that causes the increase of the reference pressure \( P_{\text{ref}} \) in hydraulic cylinder. Since the reference pressure \( P_{\text{ref}} \) is proportional to the force acting between chassis and axle, the increase of \( P_{\text{ref}} \) will increase the \( L_{\text{ms}} \), and so decrease the \( L_{\text{ref}} - L_{\text{mes}} \). The \( K \) will be increased as \( L_{\text{ref}} - L_{\text{mes}} \) is positive. As to \( L_{\text{ref}} - L_{\text{mes}} \) is negative, the reverse is the case.

Ordinarily, the increase of the stiffness will make the damping condition serious, to improve the vibration condition, another control loop is added.

**Damping Control**

Fig. 6 shows the block diagram of the vibration control algorithm. That is based on the skyhook damping theory, and its function can be understood through the physical model shown in model in Fig. 7. The control of the cylinder acts as the function of a damper in the up of the spring-damper. The detail about the control method can be referred to [1].

![Fig.6](image2)

Fig. 6 Block diagram of damping control system

![Fig.7](image3)

Fig. 7 Physical model for explaining the damping control

**Combination of the stiffness control and the damping control**

Fig. 8a shows the block diagram of the combining control of stiffness control and damping control system. The Fig. 8b shows its equivalent physical model.
Ordinarily, the stiffness control, which is used for posture adjusting, is conflicted with the damping control in function. In practice, the vibration of the excavator is often appeared around its resonant frequency, say, in the range from 1 Hz to 4 Hz, and the posture adjusting is effected in the range less than that. So by shifting the effective frequency range of the two control loops, both the posture and vibration can be well controlled.

The effective of the active suspension system and its control method has been verified in experiment.

**EXPERIMENTAL APPRECIATION**

The active suspension system is experimentally appreciated in several aspects.

Firstly to investigate the dynamic performance of the suspension system, the step response tests are carried out for all the four suspensions including the control parts.

**Step response of the control system**

To investigate the dynamic performance of the suspension, the response of the suspension to the step change of reference input \( L_{ref} \) is measured for all the four suspensions, Fig. 9 is one of typical results. The flat parts are found both as cylinder is stretched, and shortened in the response of the piston movement. That is considered as the influence of the hysteresis of leaf spring which is in parallel with the cylinder.

**Posture control performance in swing**

The performance of posture control system in swinging operation is an important item for appreciating the suspension system of the wheeled hydraulic excavator. The excavator is different with the car, because that during the front of the excavator is in swing or in digging operation, the gravity center of the whole body is changed a lot. If the suspension system can not keep the posture of the body against the change, the suspension is not able to be adapted to the excavator.

The comparison of the suspension systems with and without active suspension control are carried out.

Fig. 10 shows the dynamic response of both the front-left and front-right cylinders movement during the swing operation without the active suspension control. And Fig. 11 shows that with the active suspension control.

Fig. 13 is a picture show the posture of the excavator without the active suspension control system. According to the picture it can be found, as the front turns a 90 degree, with the boom and arm in fully stretched state, the chassis state is greatly changed. In the case operator will feel danger, and he not continue his normal operation.

For reference, Fig. 14 shows the picture of the current model's posture which has no any suspension system.
Vibration Elimination performance experiment(1)
(Drop and catch test)
To appreciate the damping performance of the active suspension system, a drop and catch test is carried out. The test can be explained with the Fig.15. The inertial state of the excavator front is shown as Fig.15(a). The boom, arm and bucket are firstly stretched in full scale as Fig.15(c), and then drop the boom in full speed, as the tip of the bucket near to the ground, make a sudden stop of the boom operation. That will cause the vibration of the excavator body.

The comparison are made among the three cases, those are the passive suspension only, the posture control (stiffness control) only active suspension, and the combination control of posture and damping control. The acceleration in the direction perpendicular to the ground is measured at the center of chassis.

Fig.16(a),(b),(c) show records of the experiment in three cases, and the Fig.17 shows the FFT analysis results of the three records.

According to Fig.17, the posture control only case has higher vibration level than the two other cases, that is because the posture control increase the stiffness of the suspension, and make worse the damping performance. The combination control overcomes the shortcoming of the stiffness control, and well improve the damping performance to the same extend of the passive suspension.
Vibration Elimination performance experiment (2) (moving test)

The vibration on the chassis during movement of the excavator is another item to examine the performance of the suspension system. Three cases are experimentally compared, those are current model without suspension system, model with passive suspension system, and model with active suspension system.

Fig. 18 shows the comparison of the frequency analysis results of three cases, as the excavator is moved in 30 km/h on a flat road.

According to Fig. 18, the active suspension system shows best performance among the three type of cases.

CONCLUSIONS

A damping and posture combination control method is proposed for the active suspension system of the wheeled excavator. The damping control is based on the skyhook damping theory and the posture control use a stiffness control principle. As the effective frequency ranges of two kind of controls are reasonably shifted, both the vibration elimination and posture control can be well implemented. The experiments show:

1) The posture control performance of the model with the active suspension system can be obtained to the same extend as that of the current model of excavator, which has no suspension system.

2) The vibration Elimination performance of the model with the active suspension system is much improved compared with the current model.

REFERENCES

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