TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.5, May 2014, pp. 3416 ~ 3422
DOI: http://dx.doi.org/10.11591/telkomnika.v12i5.4914

Dynamic Characteristics for Leveling System of Mobile Elevating Work Platforms

Xue-peng Cao*[1,2] , Sheng-jie Jiao[1], Lei Cheng[2], Jun Zhang[1], Jin-ping Li[1]
[1]Highway Maintenance Equipment National Engineering Laboratory, Chang'an University
[2]Construction Machinery Co., Ltd. of XCMG, Middle of Naner Huan, Xi'an, Shannxi
*Corresponding author, e-mail: tiepeng2001@ chd.edu.cn

Abstract

Focused on revealing variations of dynamic characteristics of an auto-leveling system used in mobile elevating work platforms (MEWP) at large height, a unified mathematical model composited of a series of sub-models was built for the leveling systems. An effect on dynamic characteristics including the fast response and relative stability from varying-parameters was investigated. Results displayed the displacement-angle factor changing with work-conditions tended to cause fluctuations of the stability, while enlarging the amplifier gain would accelerate system response. Increasing the area ratio was conducive to leveling stability to be reinforced, but lead a different response speed for forward process or reverse leveling, which was harmful to overall stability. The findings would provide essential theory guidance for the design and manufacture of the leveling system devices of high altitude platform.

Keywords: *automatic leveling system, unified model, varying-parameters analysis, characteristics variations*

1. Introduction

Having good environmental adaptabilities and high operating efficiencies, mobile elevating work platforms (MEWP) with large height and big working space are obtained special value by markets and researchers. The leveling system of platform is one of key technologies of aerial work machineries, which directly affects the performances, such as safety of operating personals, operating flexibility and adaptability to environment [1-4]. The electro-hydraulic controlled leveling system with many strong points, such as running continuously and smoothly, high control accuracy and fast response speed, is adapted to a variety of MEWP [5].

The typical composition of electro-hydraulic leveling system is shown in Figure 1, which is a constant-value position control system. Previous studies focus on the modeling of electrical and hydraulic systems without considering impacts of link mechanisms for performance analysis [6], while a unity model of entire hydromechatronics system is proposed in this paper, and we analyze parameters-varying impacts on dynamic performances of leveling system, which will provide a useful guidance for actual leveling system designs.

2. Leveling Mechanism and Modeling

2.1. System Composition and Leveling Mechanism

The leveling system of MEWP is constituted of electro-hydraulic proportional valves 1, balance valves 2, asymmetric hydraulic cylinders 4, four-link transmission mechanisms 5, working platforms 6, inclination sensors 7 and amplifiers 8.shown as Figure 1. The leveling mechanism is expressed as: when outside interferences exerted on the platform from booms luffing and bending cause a certain inclining angle, the inclination sensor feedbacks a corresponding angle signal, which is compared with a referent input, and differential signal magnified by amplifier drives the proportional valve to produce a certain displacement. It controls pressure oil into the cylinder so that the cylinder rod has a telescopic amount, and impels linkage mechanism swinging to produce a displacement output opposite to the original inclination, which induces the platform to restore a horizontal state.

Received October 24, 2013; Revised December 5, 2013; Accepted December 24, 2013

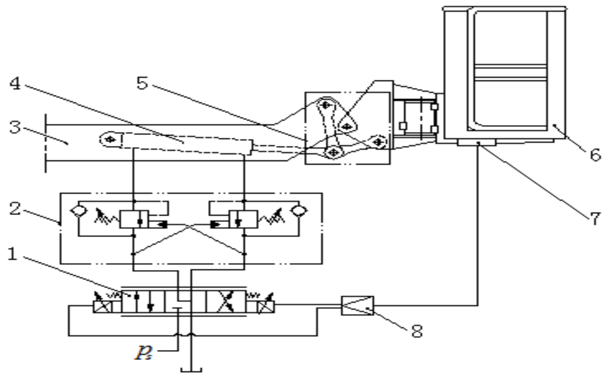

Figure 1. Compositions of Hydromechatronics Leveling System

2.2. Leveling System Unified Modeling

Based on the leveling system and automatic leveling composition as Figure 1 shown, the leveling control block diagram is constructed as Figure 2. In the next, each sub-model is built firstly, and then the unified modeling will be integrated.

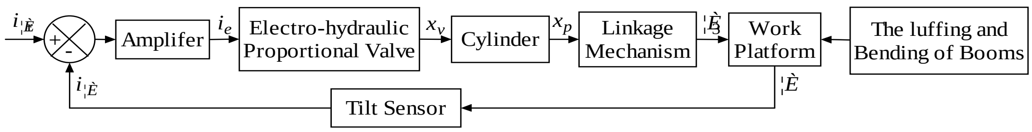

Figure 2. Block Diagram of Auto-leveling Control System of MEWP

1) Tilt sensor

The tilt sensor works as a proportional part, whose conversion relationship can be expressed as:

$$i_\theta = K_a \theta \tag{1}$$

Where i_θ , θ , K_a respectively denote feedback signal, tilt angle of platform, and proportional coefficient.

2) Comparison amplifier

Time constant is very small (t_T<1 ms), the amplifier can be considered as a difference with proportional factor [7].

$$i = K_e (i_\theta - i_{\theta_{ref}}) \tag{2}$$

Where K_e is proportional factor of amplifier.

Combining above equations, the feedback- compared can be expressed as Laplace function.

$$W_I(s) = \frac{I(s)}{\theta(s)} = K_a K_e \tag{3}$$

3) Electro-hydraulic proportional valve

From the reference [5], the relationship between spool-displacement output and input current of the proportional valve is conveyed as:

$$W_V(s)=\frac{X_V(s)}{I(s)}=\frac{K_v}{\frac{s^2}{\omega_v^2}+\frac{2\zeta_v}{\omega_v}s+1} \tag{4}$$

Where ω_v , ζ_v are the hydraulic natural frequency and hydraulic damping ratio of the valve, and K_v is valve gain.

4) Asymmetrical hydraulic cylinders controlled by four-way valves

From literatures [8] and Figure 3, the transfer function comprised of asymmetrical hydraulic cylinder and four-way valve can be denoted as:

$$X_p=\frac{\frac{K_q}{A_p}X_V-\frac{K_{ce}}{A_p^2C}(1+\frac{V_t}{T\beta_eK_{ce}}s)(F_L-\frac{\lambda-1}{1+\lambda^2}A_2P_s)}{\frac{m_tV_t}{T\beta_eA_p^2C}s^3+(\frac{m_tK_{ce}}{A_p^2C}+\frac{B_pV_t}{T\beta_eA_p^2C})s^2+(1+\frac{B_pK_{ce}}{A_{p1}^2C}+\frac{KV_t}{T\beta_eA_p^2})s+\frac{KK_{ce}}{A_p^2C}} \tag{5}$$

There is no elastic load; meanwhile the viscous damping coefficient is very small. So output of piston displacement and input of spool moving are given as:

$$W_h(s)=\frac{X_p(s)}{X_V(s)}=\frac{K_q/A_p}{s(\frac{s^2}{\omega_h^2}+\frac{2\zeta_h}{\omega_h}s+1)} \tag{6}$$

Where λ, A_p are area ratio and equivalent area, $\lambda=A_1/A_2$, $A_p=(A_1+A_2)/2$; K_q, K_{ce} are flow rate gain and total flow rate-pressure coefficient of the valve, $K_{ce}=K_c+C_{tp}$; T, C are effective modulus varying coefficient resulted from symmetry cylinders and equivalent area varying coefficient of load flow rate, $T=2(1+\lambda^2)/\lambda$, $C=2(1-\lambda+\lambda^2)/(1+\lambda^2)$; β_e, V_t are the effective bulk modulus and total volume of the cylinder. ω_h, ζ_h are hydraulic natural frequency and hydraulic damping ratio, $\omega_h=\sqrt{T\beta_eA_p^2C/m_tV_t}$, $\zeta_h=K_{ce}\sqrt{T\beta_em_t/V_tC}/2A_p$.

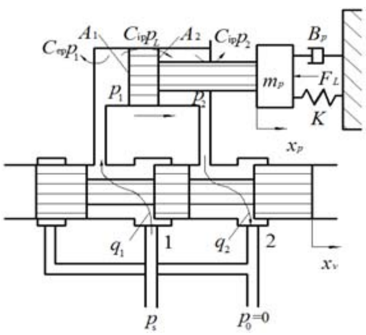

Figure 3. The Schematic Diagram of Asymmetrical Hydraulic Cylinders Controlled by Four-way Valves

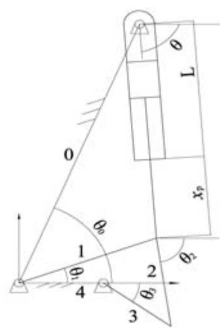

Figure 4. The Vector Chart of Leveling Mechanism

5) Driving mechanisms

Driving mechanisms can be expressed by two closed polygons (Figure 4), using the vector equation and Euler's formula, which can be described as:

$$\begin{cases} l_1\cos\theta_1+l_0\cos\theta_0=(L+x_p)\cos\theta \\ l_1\sin\theta_1+l_0\sin\theta_0=(L+x_p)\sin\theta \end{cases} \tag{7}$$

$$\begin{cases} l_1\cos\theta_1 + l_2\cos\theta_2 = l_4 + l_3\cos\theta_3 \\ l_1\sin\theta_1 + l_2\sin\theta_2 = l_3\sin\theta_3 \end{cases} \tag{8}$$

Where L、l_0、l_1、l_2、l_3、l_4 represent length of cylinder, rack 0, pendulum rod 1, link 2, rocker 3, fixed hinge points of the boom 4, respectively. θ, θ_i (*i*=0,1,...,4) are angle between each component and X-axis positive.

Solving above equation, we could acquire expressions among output displacement, rocker displacement and input straight-line displacement.

$$\begin{cases} \theta_1 = \arcsin\dfrac{bc \pm \sqrt{b^2c^2 - (a^2+b^2)(c^2-a^2)}}{a^2+b^2} \\ \theta_3 = 2arc\tan\dfrac{A \pm \sqrt{A^2+B^2-C^2}}{B-C} \end{cases} \tag{9}$$

Where $a = 2l_0l_1\cos\theta_0, b = 2l_0l_1\sin\theta_0, c = \left(L + X_p\right)^2 - l_0^2 - l_1^2$, $A = 2l_1l_3\sin\theta_1, B = 2l_3(l_1\cos\theta_1 - l_4),$ $C = l_2^2 - l_1^2 - l_4^2 + 2l_1l_4\cos\theta_1$.

Since θ_0 relies on given location of hinge points and keeps a constant. Therefore, movement regularities expressed by (9) between θ_3 and x_p are indicated as a complex trigonometric relationship. In other words, strong nonlinearities are displayed between the output and the input. To facilitate the modeling analysis, relevant parameters are substituted into (9), and the both moving relationship is shown Table 1.

Table 1. The Moving Relationship between Cylinder Piston and Work Platform

Variable	Value						
Piston displacement x_p /mm	0	66.6	128.2	197.5	280	372. 6	464.5
Platform displacement θ_3 /°	0	30	60	90	120	150	180

Using third-order polynomial fitting method to analyze above data, we can obtain:

$$\theta_3 = a_0x_p^3 + b_0x_p^2 + c_0x_p + d_0 \tag{10}$$

Where $a_0 = 1\times10^{-7}, b_0 = -3\times10^{-4}, c_0 = 0.5126, d_0 = -0.9606$.

Due to the value of a_0 and b_0 is far less than c_0, which illustrates the higher order parts are much smaller compared with the first order for impact on displacement transfer performance, so linear fitting method can be used.

$$\theta_3 = K_l x_p + m \tag{11}$$

Doing Laplace transform, a transmitting function for driving mechanisms is given as:

$$W_l(s) = \frac{\Theta_3(s)}{X_p(s)} = K_l \tag{12}$$

From (3), (4), (6) and (12), the unified open-loop transfer function of leveling system is built as:

$$W(s) = \frac{\Theta_3(s)}{\theta(s)} = \frac{K}{s\left(\dfrac{s^2}{\omega_v^2} + \dfrac{2\zeta_v}{\omega_v}s + 1\right)\left(\dfrac{s^2}{\omega_h^2} + \dfrac{2\zeta_h}{\omega_h}s + 1\right)} \tag{13}$$

Where K is open-loop gain, $K = K_a K_e K_l K_v K_q / A_p$

The corresponding closed-loop transfer function can be written as:

$$G(s) = \frac{W(s)}{1+W(s)} = \frac{K}{s(\frac{s^2}{\omega_v^2} + \frac{2\zeta_v}{\omega_v}s+1)(\frac{s^2}{\omega_h^2} + \frac{2\zeta_h}{\omega_h}s+1)+K} \quad (14)$$

3. Dynamic Characteristics Analysis

More attention is focused to investigate parameters affecting on dynamic characteristics of leveling system, such as four-linkage mechanisms, asymmetrical cylinders and amplifiers. Based on the open-loop transfer function and classic control theory, these varying-parameters are analyzed as follow. The amplifier gain value depends on system stabilities, other parameters are shown as Table 2.

Table 2. Basic Parameters of Leveling System

Components	Parameters	Symbols	Values	Unit
Tilt sensor	Sensor coef.	K_a	0.8×10^{-3}	[A/°]
Amplifier	Prop. coef.	K_e	283	-
Proportional valve	Valve gain	K_v	5×10^{-4}	$[\mathrm{m/s\cdot A}]$
	Natural frequency	ω_v	69	[rad/s]
	Damping ratio	ζ_v	0.7	-
	Flow rate gain	K_q	2.4	[m^2/s]
	Flow rate-pressure coef.	K_c	4.0×10^{-12}	$[\mathrm{m^5 / N\cdot s}]$
Four-way valve and cylinder	Total equivalent mass	m_t	800	[Kg]
	Effective bulk modulus	β_e	1.0×10^{9}	[Pa]
	Big chamber area	A_1	5.0×10^{-3}	[m^2]
	Small chamber area	A_2	2.7×10^{-3}	[m^2]
	Internal leak-coef.	C_{ip}	5.0×10^{-13}	$[\mathrm{m^5 / N\cdot s}]$
	External leak-coef.	C_{ep}	0	$[\mathrm{m^5 / N\cdot s}]$
	Total volume	V_t	2.3×10^{-3}	[m^3]
Four-link mechanism	Displacement-angle coeff.	K_l	3.9×10^{2}	[°/m]

1) The displacement-angle coefficient of four-link mechanism varies

Keeping the gain K_e unchanged and changing the displacement-angle coefficient K_l from 100 to 390, dynamic response curves are shown as Figure 5. When it becomes greater, system response gets faster, but overshoot is increasing. Due to K_l varies with work conditions, when employing a constant amplifier gain, which easily causes dynamic performances fluctuating. Although using four-bar linkages could expand angular displacement for leveling output, variation ranges of this coefficient should be constrained within permissible area to ensure system stability.

2) The area ratio of asymmetric cylinder varies

Keeping big chamber area A_1 unchanged, the area ratio coefficient λ is taken as 1, 1.85,3, and dynamic response curves are shown as Figure 6. Larger area ratio could induce smaller overshoot and better stability. Considering actual states, the larger inevitably leads to a thicker cylinder rod, which can strengthen rod stability and make the force transmitting smoothly, but will bring about the rod with quite different speed between outstretch and retracting, which would create the platform having a distinct response speed at forward leveling or reverse process and not allow for overall stability of leveling system. Therefore, selecting area ratio needs to consider the both impacts to get better performances under the entire work process.

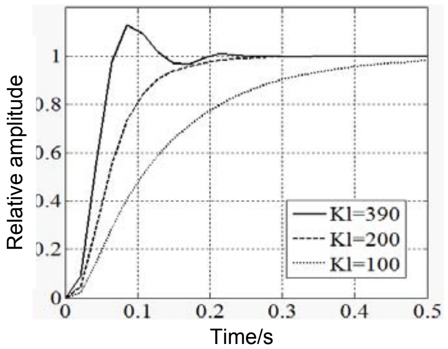

Figure 5. The Curves under Different Displacement-angle Coefficients of Four-links

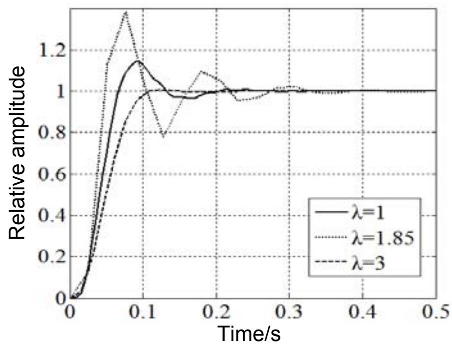

Figure 6. The Curves under Different Area Ratio Coefficients of Asymmetric Cylinder

3) Amplifier gain varies

When the gain K_e separately is 100,283 and 400, dynamic characteristics curves are shown as Figure 7. The more amplifier gain increases, the faster leveling system responds, but the overshoot gets larger and arouses greater oscillation. At the expression of open-loop gain $K = K_a K_e K_l K_v K_q / A_p$,sensor coefficient K_a and valve coefficient K_v are not changing with working conditions, while flow gain coefficient K_q and displacement-angle coefficient K_l are varying with spool opening and output angular displacement, respectively. In order to maintain the control characteristics invariable, the gain K_e should vary synchronously with the both parameters. Considering the feasibility and effectiveness of actual operations, sectional gain adjustment could be adopted with conditions changing, which has advantages for better performances within varying-parameters.

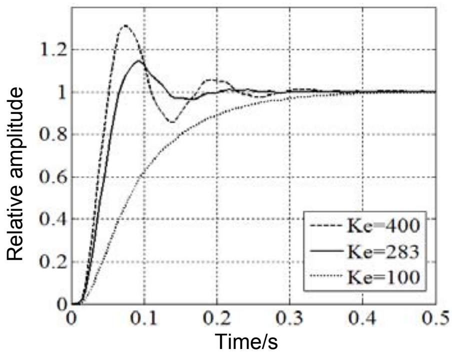

Figure 7. The Curves under Different Amplifier Gains

4. Conclusion

A unified model was built for the hydromechatronics leveling system of MEWP, and several variations of dynamic characteristics was revealed as follows, which will provide a useful guidance for actual leveling system designs.

(1) The displacement-angle coefficient of four-link mechanism becomes greater, system response gets faster, but overshoot would be more obvious. For the leveling system with a constant amplifier gain, the coefficient easily causes dynamic performances fluctuating, so this change should be constrained within permissible ranges.

(2) An increment of the area ratio of asymmetric cylinder area ratio can induce smaller overshoot and better stability, but overlarge value will make the platform have a completely different response speed at forward leveling or reverse process, which is not conducive to overall leveling stability.

(3) Increasing the amplifier gain makes system respond faster, but inclines to cause system oscillation. It is suitable to adopt a sectional gain adjustment with conditions changing for parameter-varying leveling course.

Acknowledgements

The Special Fund for Basic Scientific Research of Central Colleges, Chang'an University (Grant No.CHD2011TD017, CHD2011ZD016)

References

[1] Schimaneckf, Merrifield D. Aerial work platforms: safety, liability & the rental center. *Professional Safety*. 1998; 73(1): 25-28.
[2] Smith A. Things looking up for aerial work platforms. *Diesel Progress*. 2005; 71(1): 12-14.
[3] Xia Xiu-feng. Development of China's aerial platform vehicle. *Construction Mechanization*. 2010; (9): 33-35.
[4] Cao Xue-peng, Cheng Lei, Jiao Sheng-jie, et al. Technical Status and trends of Aerial work platform. *World Sci-Tech R&D*. 2012; 34(10): 801-804.
[5] Bora Eryilmaz, BrueeH. Wilson. Unified modeling analysis of a proportional valve. *Journal of the Franklin Institute*. 2006: 48-68.
[6] Wang xin, Song Xiao-guang, Teng Ru-min, et al. Simulation and Research in Aerial Work Platform Electro-hydraulic Proportional leveling system based on matlab. *Machine tool and hydraulic*. 2008; 36(4): 162-164.
[7] Zhang Li-ping. Design manual of hydraulic and pneumatic system. Beijing: Machinery Industry Press. 1997: 453-454.
[8] Meng Zheng-zheng. Analysis and establishment of the transfer function for asymmetric hydraulic cylinders controlled by four-way valves. *Journal of Hefei University* (Natural Sciences). 2006; 16(2): 23-27.