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A closed-loop detection and open-loop control strategy for booms of truck-mounted concrete pump

Xiaojie Sun *, Hua Ye, Shumin Fei

School of Automation, Southeast University, Jiangsu Nanjing 210096, Key Laboratory of Measurement and Control of CSE, Ministry of Education, China

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ABSTRACT

In this paper, we have proposed a closed-loop detection and open-loop control strategy for the booms of truck-mounted concrete pump. During pumping, vibration inevitably appears in the operation of long and lightweight booms. The vibration cannot be easily weakened and it may even be captured by the controller, which leads to poor work efficiency and quality. In order to solve this problem, we firstly compare the open-loop control with the closed-loop control and reveal that the open-loop control has a stable output but contains a steady error. This defect can be fixed by our proposed strategy using the closed-loop detection via correcting the planning start and the open-loop gain. Furthermore, we establish the filtering and curve fitting for the collected angle values by sensors, which greatly reduce the interference originated from vibration. Lastly, our simulation results verify the effectiveness of the proposed strategy.

1. Introduction

As a large engineering machinery used for concrete pouring, the truck-mounted concrete pump has wide applications in constructions of high-rise buildings, bridges, highways and in water conservancy projects. Because the use of suitable concrete pump may improve productivity and increase the quality of products and services, more construction sites are considering the selection of concrete pumps [1] and pay attention to the pumping quality control method [2]. For all these reasons with the expanding of construction scale and range, the design of truck-mounted concrete pump has been rapidly advanced. The boom system, an important component of a truck-mounted concrete pump, lends support to the conveying pipes where the concrete is pumped into. This design enables the end of the conveying pipes conveniently moving with the booms. The operation of the booms can directly affect the work efficiency, stability, reliability and service life of a truck-mounted concrete pump.

The current trends for the design of boom system include large in size, various structures and intelligent operation. At this standard, the long and lightweight multi-boom serves well to meet the high demanding of construction. Nonetheless, the control for this type of booms always appears to be problematic [3–6]. In addition, the hydraulic impact, the boom deformation and the unpredicted environmental changes may cause the vibration and the imprecise end-positioning. At present, the majority of truck-mounted concrete pumps can only be operated manually, which is still labor intensive, technique demanding and dangerous. This places a high priority on developing automatic operation with a main objective to reduce/eliminate the vibration and its interference with the controller.

In recent years, many publications have focused on the design of automatic operation and the methods to reduce vibration. Among them, the concept of automation vs. robotics in construction has been proposed and developed [7]. Xia and Elton et al. have visually demonstrated the models and dynamic characteristics of the booms by using various software-development environments and finite element analysis [8,9], which are valuable contribution to the boom research. Despite the fact that the differential equation of rigid motion of the booms is deduced by the multi-body dynamic theory and the Lagrange equation [10–12], the flexible model [13–15] is more accurate and more complex under the assumption mode since deformation occurs in pouring process. In control strategies, particle swarm optimization is applied to calculate the final value of every joint point, and adaptive robust PD is used for tip trajectory synthesis with gravity compensation [18,19]. The sensors to detect the angle values are installed for a kind of intelligent boom system [20] but with some conditions limited to the boom moving. Two different types of devices for reducing the vibration have been introduced by X. Yi and W. Yi et al. [21,22]. X. Yi et al. have invented the anti-vibration hydraulic cylinder and its control unit while W. Yi and colleagues have obtained the vibration amplitude through the detector module and through controlling the piston position of the boom hydraulic cylinder. However, both methods mentioned above require

* Corresponding author. Tel.: +86 25 83792719.
E-mail address: sunny@seu.edu.cn (X. Sun).

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new equipments with higher weight and volume of truck-mounted concrete pump which would remarkably increase the cost for the machinery.

Therefore, our goal is to develop an automatic control method for the boom system which would be minimally disturbed by the vibration. Moreover, this method can also be implemented in programmable logic controller (PLC) of truck-mounted concrete pump without assistance from any other equipment in real time. To fulfill this purpose, we have formulated a closed-loop detection and open-loop control strategy which offers better performances including a stable output inherited from the open-loop control and a corrected tracking by the closed-loop detection. With the application of this strategy, the vibration will be further reduced by the filtering and curve fitting for the collected angle values.

In Section 2 of this paper, we describe the models to be discussed; in Section 3, we firstly compare the closed-loop control with the open-loop control, and then propose a closed-loop detection to reduce the steady error caused by the open-loop control; in Section 4, the filtering and curve fitting algorithm is presented and discussed; Section 5 contains the simulation results and control effects from four control methods, including the open-loop control, the closed-loop control, the open-loop control with closed-loop detection and additional filtering and curve fitting; Finally, a conclusion is drawn in Section 6.

2. System description

Our research object is a 46-meter-long five-boom system, including the rotary mechanism, five booms, the hydraulic cylinders, the conveying pipes and the hose at the terminus. The function of the hydraulic cylinders is to stretch out or draw back the booms. When the piston of the hydraulic cylinder is completely out, the boom reaches the maximum angle. The whole boom system moves freely within the range and transports the concrete in the accessible range. The rotary mechanism enables the working range of the booms fixed at a certain point to be a large, spheroidic pouring space.

2.1. Model of hydraulic system

Hydraulic cylinder controlled by pulse width modulation (PWM) high speed ON/OFF valve (HSV) has been widely used in construction machinery due to its simple structure, low cost, minimal oil pollution and digital control. HSV is usually utilized as a pilot valve because of its small allowable flow while hydraulic-operated directional valve is often employed as HSV's power amplifier stage. The final control of the hydraulic system is realized via changing the displacement of directional valve through adjusting the duty cycle of PWM HSV. Based on the characteristic equations of HSV, directional valve and hydraulic cylinder [23,24], the mathematic model for the hydraulic system can be achieved as

$$Y(s) = \frac{K_{q1} A_v K_x \omega_n^2}{A_m s (s^2 + 2\xi_n \omega_n s + \omega_n^2)(A_v^2 s + K_v K_{c1})} D(s) \tag{1}$$

where y is the displacement of hydraulic cylinder, d is the duty cycle of PWM, and $Y(s)$ and $D(s)$ are the Laplace transform of y and d, respectively; K_{q1} and K_{c1} are the flow gain and the flow-pressure coefficient of HSV, respectively; A_v, K_v and K_x are the valve core's area, the valve core-spring elasticity coefficient and the flow gain of directional valve, respectively; A_m is the average area of cylinder's piston; and ξ_n and ω_n are the related parameters of hydraulic cylinder. From the mathematic model (1), we deduce that the position of hydraulic cylinder y can be controlled by the duty cycle d.

2.2. The link between displacement of hydraulic cylinder and joint angle

Next, we delineate the relationship between the displacement of hydraulic cylinder and the joint angle. Since all of the booms can only move in one plane, the space coordinates may be obtained by rotating the plane coordinates. The structural diagram of five booms is shown in Fig. 1. Assume the booms are homogeneous. θ_i, $i=1,\ldots,5$ represents the angle of two neighboring booms.

The vibrating portion of truck-mounted concrete pump is a complicated fluid–solid coupling system composed of the boom flexibility and the concrete pulsation. Wang and Chen et al. have done deep research on the vibration mechanism of boom system [25,26]. Finite element model of booms has been built and the corresponding damped vibration response has been obtained by test. Schematic of the flexible booms is shown in Fig. 2. Assume P_i is the tip of the ith boom. The tip's longitudinal displacement y_{pi} has the damped vibration form as

$$y_{pi} = A_i \sin(2\pi t / T_i) e^{-\delta_i t}, \quad i = 1, \ldots, 5. \tag{2}$$

From Fig. 2, y_{pi} and the angle change ω_i of the ith boom have the following relation

$$y_{pi} = (l_i + \Delta l_i)\omega_i, \quad i = 1, \ldots, 5 \tag{3}$$

where l_i is the length of the ith boom and Δl_i is the length change from the origin to the tip due to the boom vibration. Since the vibrating displacement is much smaller than the pouring movement of the booms,

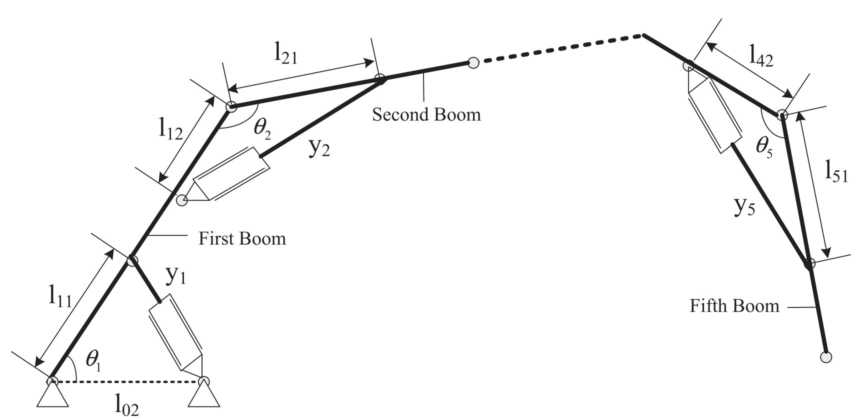

Fig. 1. Structural diagram of five booms.