CHEMICAL ENGINEERING TRANSACTIONS

VOL. 46, 2015

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www. aidic. it/cet

Guest Editors: Peiyu Ren, Yanchang Li, Huiping Song

ISBN 978-88-95608-37-2; **ISSN** 2283-9216

DOI: 10.3303/CET1546192

Research and Design of Control System for Vibration Transmission Machine

Jian Chu*[a], Guoyu Wang[b]

[a] Tianjin University of Technology and Education: Joint Lab of Information Sensing & Intelligent Control,
[b] School of mechanical engineering, Tianjin University of Technology and Education, Tianjin, 300222, China.
chujian6@126.com

Currently, the vibration transmission machines are widely used in mining, metallurgy, coal, chemical, building material, light industry, food, and machinery manufacturing industries. Inertia vibrator is divided into two categories - non-resonant and resonant. The former has the following advantages: simple structure, conveniently manufactured, and stable working state. That is why non-resonant inertia vibrators are mostly used in engineering practices. The biggest disadvantage of non-resonant type is bigger power consumption. In contrast, the resonant type is durable, has compact structure and has less energy consumption. But it is difficult to adjust the working status; small frequency drift will cause large amplitude fluctuation. In order to improve energy efficiency and stability, we used vibration velocity as a closed-loop feedback signal and microcomputer technology to control resonance conveyor. In the control unit we utilized quadratic optimal control algorithm of PID parameter optimal tuning to maximize the automatic frequency tracking and achieved steady state of resonance and optimal energy efficiency.

1. Introduction

Material handling equipment plays an irreplaceable role in industrial automation. Resonance conveyor is a mechanical vibration system controlled by inertia vibrator. Although the resonance type vibrating machine has high efficiency, the slope of the response curve is very deep. While the system running, small changes in the load or other parameters can cause the output to alter significantly. In normal operation, the load of the vibration can be changed from 0 to 100%, sometimes it can be overloaded. The number of motor revolutions can also fluctuate. The gradual change of the stiffness of the main vibration spring is also hard to avoid. All of these would cause changes in the natural frequency. Therefore, the mechanical vibration system directly controlled by the inertial vibration exciter is seldom used in engineering.
In order to solve the issues, we used the vibration velocity of the phase inverted signal for closed-loop feedback, namely using PLC for acquisition and processing of feedback signal to realize the frequency automatic tracking to achieve system resonance balance. Because of high reliability strong anti-interference ability, PLC can be a good candidate for achieving process control automation. This not only can improve the efficiency and quality of the integrated control, but also can improve the working environment. In the future development of vibration transmission machine will improve the performance and reliability of components, to move towards standardization, serialization, generalization and improve vibration transmission machine control, regulation performance, reduce power consumption, reduce noise, achieve more environmentally friendly and humanized design.

2. Working Principle

The resonant type inertia transfer machine belongs to the single degree of freedom vibration system. With high efficiency and energy saving resonance, we can complete task of large power motor with small power motor [Sa'ed A. Musmar and T awfeeq Al-kanhal (2014)]. The benefit of energy saving are more obvious for large and medium resonance type. The structure diagram of the system is shown in Figure 1:

Please cite this article as: Chu J., Wang G.Y., 2015, Research and design of control system for vibration transmission machine, Chemical Engineering Transactions, 46, 1147-1152 DOI:10.3303/CET1546192

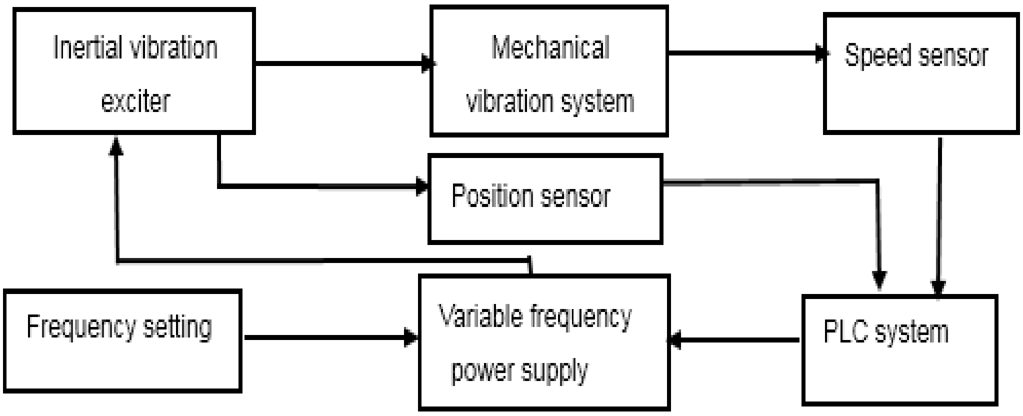

Figure 1: structure diagram of vibration transmission system

Because the system uses the vibration speed sensor, it is possible to make the closed-loop feedback system to become self excited system of negative resistance. To achieve this, it must meet the following conditions:
(1) The working frequency of the frequency conversion power supply shall be set to Ω.

$$\Omega = (1.05 \pm 0.05)\omega_n$$

The frequency setting is easy to implement, and it is actually wider for the synchronization range.
the forced vibration equation of a degree of freedom vibration system:

$$Mx'' + fx' + kx = F_0 \sin \omega_0 t$$

In the formula: M--Quality; X--Displacement; K--Spring rigidity; f--Coefficient of friction; F0--Exciting force
Equation solution:

$$x = A\sin(\omega_0 t - \alpha)$$

The equations can be obtained by the above equation:

$$(k - m\omega_0^2)A - f_0 \cos\alpha = 0$$

$$f\omega_0 A - F_0 \sin\alpha = 0$$

Can be obtained:

$$A = \beta_0 \cos\alpha / m\omega_0^2$$

$$\alpha = tg^{-1} f\omega_0 / k - m\omega_0^2$$

Voltage output is

$$v = A\omega_0 \cos(\omega_0 t - \alpha)$$

Therefore, the output voltage of the PLC is used to control the frequency power, so that the frequency conversion power and its phase locked synchronization work, you can achieve a stable vibration state, that is $\omega_0 \cong \omega_n$.
(2) If the system is to show the negative resistance self - excited state, the method is to be $\omega_0 < \Omega$. When debugging the system, cut off the frequency Ω of the feedback observation set, and to connect with the feedback observation ω_0.

3. Control Scheme Design

For control system we selected S7-200 SIEMENS as the control center of the system. In terms of data acquisition we used electromagnetic induction vibration speed sensor to detect mechanical vibration velocity.

For inertial vibrator position detection we used infrared position sensor. For sensor and frequency converter simulation data input and output. We used module EM235 and S7-200 combination [O. Badran, H. And B. Alomour (2012)].
By changing frequency of the converter, the vibration amplitude was transmitted to PLC through the sensor and was recorded. In the process of vibrating body movement cycle when the input voltage is increased to the maximum, the vibration cycle T was obtained by PLC through a timing and vibration angular velocity ω_1 and eccentric block angular velocity ω_2 were detected. The PID controller was used to adjust the real and theoretical value of the four detection time of the eccentric block. At the same time, the two time optimal control algorithm was adopted to achieve the optimal tuning of PID parameters. According to the requirement of control system in the selected PLC, we used STEP7 Micro/WIN as a process control software development environment. PLC ladder diagram language was used to complete the design and debugging of PLC control program. We used WinCC as computer monitoring system, and touch screen monitor at lower machine for on-site monitoring. The main module functions were: human-computer interaction, data acquisition, control, protection, communication, etc.
We used the linear quadratic optimal control algorithm for the optimal tuning of PID parameters, so that the system can achieve optimal efficiency and energy saving when the resonance is reached. We set the performance index function as J, to optimize the system by adjusting the two performance index to reach the maximum.

$$J = \frac{1}{J_1} + J_2$$

$$J_1 = \int_{t0}^{t1} \begin{bmatrix} X^T(t)A(t)X(t) + 2U^T(t)E(t)X(t) + U^T(t)D(t)U(t) \\ +2X^T(t)D(t)U(t) + 2X^T(t)a(t) + 2U^T(t)b(t) \end{bmatrix} dt + X^T(t_1)G(t_1)X(t_1)$$

$$J_2 = \int_{t0}^{t1} E(t)I(t)dt$$

In the form of J_1, the displacement is the smallest, and the energy of J_2 is the largest and the performance index is the largest. In the form of J_1, X is an n-dimensional state vector, A, B and G are n x n, C is n x r, E is r × n, D is R x R matrix of order a n-dimensional, b is r-dimensional vector and their elements are a continuous function of t and D is a symmetric positive definite matrix, A and G is a symmetric matrix. In the form of J_2, E for electromagnetic electromotive force, I for the current.

The optimal control solution for the minimum value of J_1 is the maximum value of $\frac{1}{J_1}$. The minimum value of J_1 is:

$$V(X(t_0), t_0) = k_0(t_0) + 2X^T(t_0)k_1(t_0) + X^T(t_0)K_2(t_0)X(t_0)$$

Where $K_2(t)$, $k_1(t)$, and $k_0(t)$ are calculated by the following equation:

$$\cdot\dot{K}_2(t) = \left(E + C^T K_2\right)^T D^{-1}\left(E + C^T K_2\right) - A - K^2 B - B^T K_2$$

$$\dot{k}_1(t) = \left(E + C^T K_2\right)^T D^{-1}\left(b + C^T k_1\right) - a - B^T k_1$$

$$\dot{k}_0(t) = \left(b + C^T k_1\right)^T D^{-1}\left(b + C^T k_1\right)$$

$K_2(t_1) = G(t_1)$, $k_1(t_1) =$ zero vector, $k_0(t) = 0$

The optimal control for the minimum value of J_1 is:

$$u^* = -D^{-1}\left[\left(E + C^T K_2\right)X + \left(b + C^T k_1\right)\right]$$

Optimal control for the maximum value of J_2, Euler equations can be obtained by $\delta J_2 = 0$, The values of the extreme values can be obtained by the J_2 Euler equation. According to the conditions to determine the maximum value of $\frac{\partial F}{\partial y} - \frac{d}{dx}\left(\frac{\partial F}{\partial y'}\right) = 0$, when $\delta J_2 = 0, \delta^2 J < 0$ gets maximum value, when $\delta J = 0, \delta^2 J > 0$ gets minimal value, objective functional J reaches maximum value, which makes the system to achieve the maximum energy efficiency. We can analyze the power saving of our optimization design by comparing the power usage of before and after optimization design. In practice, the system needs the power of 11kw, through the optimal control only need 3KW, energy efficiency is 72.73%. From the results we can see the energy saving effect is obvious. Program flow chart of the system is shown in Figure 2:

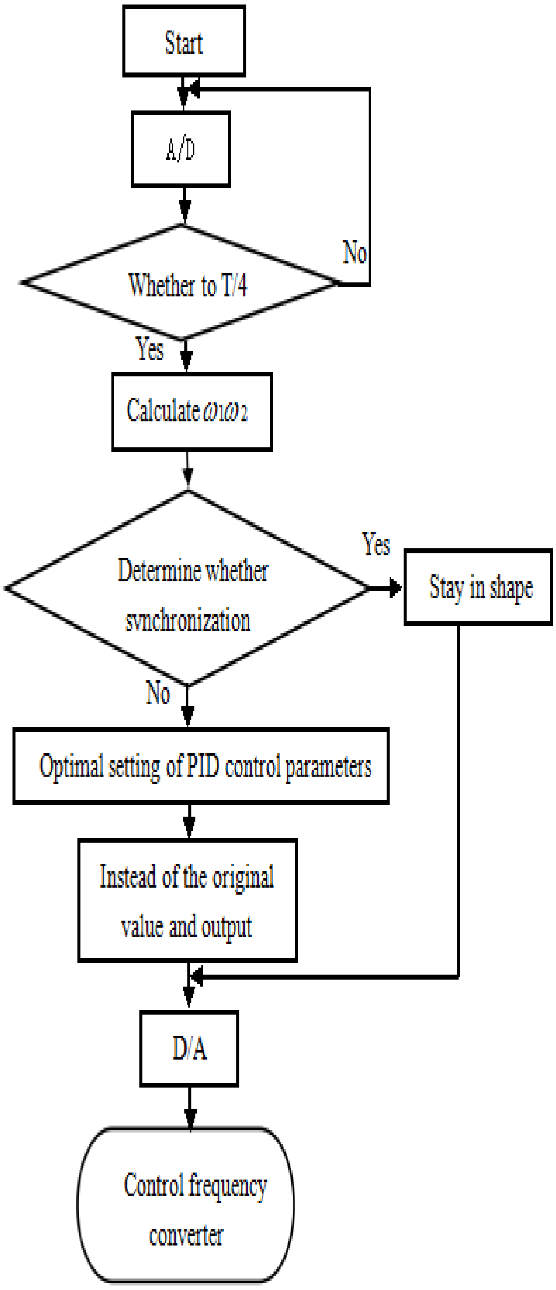

Figure 2: System program flow chart

4. System Processes

(1) Searching for synchronization frequency:
The above calculation shows that the frequency of the converter is about 40 Hz at the time of resonance. We gradually increased the frequency by 0.2 Hz at a time, and recorded the amplitude of the vibration body from generating type magnetic sensor to magnifier to PLC. Due to the inertia of the mechanical device, each frequency increase to a new level should delay 3 cycles.
(2) Resonance operating control:
After finding the same frequency, the procedures of vibration body movement cycle were determined, that is the process - T1 for input voltage changing to its maximum. In this process, the vibration cycle T was obtained through timing by PLC, and then the angular velocity ω_1 of the vibration body is detected.
Similarly angular velocity of the eccentric block can be measured. The signal of the two diodes installed on the outer orbit of the eccentric block was received by PLC. The conducting time interval between the two adjacent receiving diodes is T2/4. Then angular velocity ω_2 can be obtained through the time recoded by PLC.
Output voltage control:
The position of the eccentric block was detected four times in one cycle T1 through encoder at T1/4, T1/2, T3/4, and T1. The values were compared with the theoretical value. If the two values were the same, no adjustment were needed; otherwise, the optimal control algorithm was used to tune the PID parameters. The input signal to the digital regulator was altered by "discrete quantization". Digital regulator output signals must be sent to the "recovery" of zero order holder, which recovers the discrete signal to continuous signal. This way the object can be effectively controlled. Figure 3 is a block diagram of the digital control:

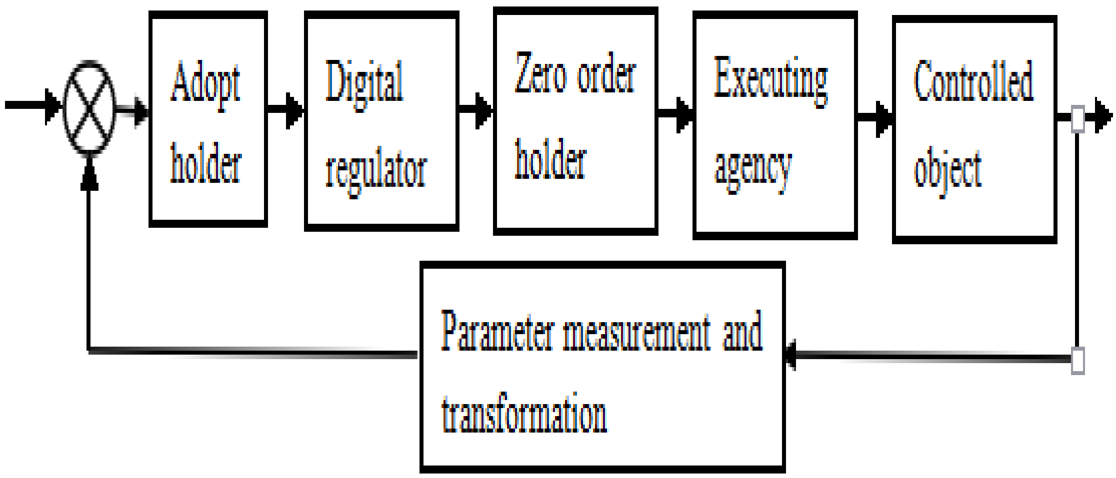

Figure 3: Digital control principle

After the optimal setting of PID parameters, the output of the D/A converter was sent to the frequency converter. When the speed of the motor was controlled to the same speed and same phase with the vibrating body, the system was in the resonance state.

5. Conclusions

After the overall design of the vibration transmission system, PLC, frequency converter, vibrating body, exciter and advanced control algorithm are the key components for the vibration transmission and control system. The vibration type transmission machine is a mechanical vibration system which is controlled by the inertia vibration exciter, to achieve high efficiency and energy saving, and increase the system control ability by using resonance. The microcomputer control technology is used to control the resonant transmission to realize the resonance state of the automatic frequency tracking. PID parameters are adjusted through the optimal control algorithm, therefore the vibration system is always running with high efficiency and the energy saving effect is obvious. Along with the progress of science and industry, the resonant transmission machine will be widely used in the industry.

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