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A Study on the Control Scheme of Vibration Isolator with Electrical Motor

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Abstract: In this study, a reliable control scheme with PID combined controller will be considered. The combined controller in this study is PID algorithm with parameters tuned by using ILC (iterative learning control) approach. The controller was applied to the vibration isolator using an induction motor which works as an actuator. This isolator is developed to eliminate the influence of vibration from rotating machineries on the small ship. The NI cRIO real time controller with FPGA is loaded to get or generate control signals. Crank mechanism which converts rotating energy into translational force is adopted and the relation between control force and torque generated from actuator is also analyzed. A Labview program is composed for controlling practice. Experimental results will be described to show the effectiveness of the proposed control schemes.

Key words: Vibration isolator, Crank mechanism, Electrical motor, Tuning, PID, ILC.

1. Introduction

In control, among all the known controllers, the proportional-integral-derivative (PID) controller is always the first choice for industrial control processes owing to the simple structure, good performance, and balanced control functionality under a wide range of operating conditions [1]. Although being widely used in industry, tuning PID parameters (gains) remains as a challenging issue and directly determines the effectiveness of PID control [2]. To address the PID design issue, much effort has been invested in developing systematic auto-tuning methods. These methods can be divided into three categories, where the classification is based on the availability of a process model and model type, (i) model free methods; (ii) non-parametric model methods and (iii) parametric model methods.

It should be noted that in many industrial control problems such as in process industry, the process is stable in a wide operation range under closed-loop PID, and the major concern for a PID tuning is the transient behaviors either in the time domain, such as peak overshoot, rise time, settling time, or in the frequency domain such as bandwidth, damping ratio and undamped natural frequency. From the control engineering point of view, it is one of the most challenges to directly address the transient performance, in comparison with the stability issues, by means of tuning control parameters. Even for a lower order linear time-invariant system process under PID, the transient performance indices such as overshoot could be highly nonlinear in PID parameters and an analytical inverse mapping from overshoot to PID parameters may not exist. In other words, from the control specification on overshoot we are unable to decide the PID parameters analytically.

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Besides that, in practice, when the process model is partially unknown, it would be difficult to calculate the PID parameters even if the nonlinear mapping between the transient specifications and PID parameters can be derived. In existing PID tuning methods, whether model free or model based, test signals will have to be injected into the process in order to find certain relevant information for controller parameter setting. This testing process may however be unacceptable in many real-time control tasks. On the other hand, many control tasks are carried out repeatedly, such as in batch processors.

This paper presents a novel control scheme in which the PID control parameters will be tuned by means of ILC approach. Iterative learning control (ILC) deals with a repeated control task without requiring the perfect knowledge such as the process model or parameters [3]. It learns to generate a control action directly instead of doing model identification. ILC learns to generate a corrected action from previous control actions and previous error signals. PID parameters will be updated whenever the same control task is repeated.

Proposed control scheme was applied to the control of vibration isolator. Experimental results to confirm the effectiveness of the controller will be introduced.

2. Iterative Learning Control Approach

In this section, the proposed PID controller using an ILC approach is described. The entire procedure was essentially carried out over two phases. In the first phase, a modified ILC procedure was carried out to yield the ideal input and output signals of the overall ILC-augmented control system. In the second phase, the signal derived from the first phase was applied to identify the best-fitting PID parameters with a standard least squares (LS) algorithm.

2.1 Phase 1: Iterative Refinement of Control

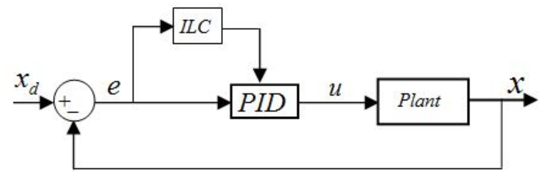


Figure 1: ILC added PID controller

An ILC component was added to the basic control system to iteratively obtain enhanced control signals for the tracking of the periodic reference signal.

Figure 1 shows the configuration with the ILC augmentation. In Figure 1, PID controller was considered as the basic feedback controller. It was not expected that this controller would achieve perfect performance without tracking error. Instead of the usual approach of refining the control signal that may not be permitted in the typical closed-architecture control system, the ILC component modified the desired reference signal through successive trials to improve the tracking performance. The ILC component was used to tune the PID controller parameters and then enable the output x to approach the actual desired trajectory x_d.

2.2 Phase 2: Identifying New PID Parameters

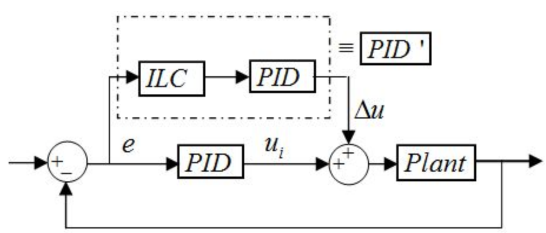


Figure 2: Equivalent representation of the ILC-Augmented control system

Here, PID controller parameters update procedure will be detailed. Based on work of [4], Figure 1 can be configured in the equivalent form as shown in Figure 2, where the ILC structure for enhancement of the reference signal can be revealed as a parallel learning controller to PID, combined an ILC component with PID parameter in series. PID' controller stands for group of ILC+PID. Finally PID controller of the system is obtained by the combination of PID and PID'. Control signal Δu of PID' controller can be derived as

$$\Delta u(t) = K_p^{'} e(t) + K_i^{'} \int_0^t e(t)dt + K_d^{'} \frac{de(t)}{dt} \quad (1)$$

In Figure 2, for PID controller, some recent approved tuning method [5-8] can be applied to get initial parameters (K_p, Ki, K_d). For PID', the standard LS algorithm was used to obtain the parameters. Eq. (1) can be written in the linear regression form as Eq. (2).

$$\Delta u(t) = \varphi^T(t) K \quad (2)$$

$$\text{where, } \begin{cases} \varphi^T(t) = [e(t) \quad \int_0^t e(t)dt \quad \frac{de(t)}{dt}] \\ K = [K_p^{'} \quad K_i^{'} \quad K_d^{'}]^T \end{cases}$$

Eq. (2) can be expressed in a general form

$$\Delta u(t) = A(p) e(t) K \quad (3)$$

Where, $A(p)=[1 \quad (1/p) \quad p]$, p = d/dt represents the differential operator.

With the additional filter H_f(p), Eq. (3) can be rewritten as

$$H_f(p)\Delta u(t) = H_f(p) A(p) e(t) K \quad (4)$$

where, the filter H_f(p) is a stable transfer function. Defining Δu_f, e_f as a combination of filter with Δu, e, then we have

$$\begin{cases} \Delta u_f(t) = H_f(p)\Delta u(t) \\ e_f(t) = H_f(p) e(t) \end{cases} \quad (5)$$

Thus, Eq. (5) can be written as

$$\Delta u_f(t) = K_p^{'} e_f(t) + K_i^{'} \int_0^t e_f(t)dt + K_d^{'} \frac{de_f(t)}{dt} \quad (6)$$

The regression vector becomes

$$\varphi_f^T(t) = [e_f(t) \quad \int_0^t e_f(t)dt \quad \frac{de_f(t)}{dt}]$$
$$= [H_f(p)e(t) \quad \frac{1}{\mathrm{p}} H_f(p)e(t) \quad \mathrm{p}H_f(p)e(t)] \quad (7)$$

Hence, the parameter vector remains as $K = [K_p^{'} \ K_i^{'} \ K_d^{'}]^T$.

In practical applications, the derivative signal is seldom obtained via direct measurement and measurement noise will be amplified if it is derived via direct differentiation. In this work, the differential filter was used to derive the derivatives [9].

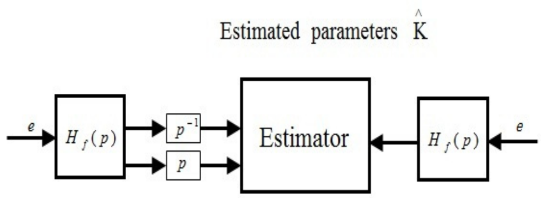


Figure 3: Equivalent representation of the ILC-Augmented control system

Figure 3 shows the block diagram of the estimator with filter $H_f(p)$.

Regression form of control inputs and errors can be represented as

$$\begin{cases} U = [\Delta u_f(1) \ \Delta u_f(2) \ldots \Delta u_f(n)]^T \\ \Phi = [\varphi_f^T(1) \ \varphi_f^T(2) \ldots \varphi_f^T(n)]^T \end{cases} \quad (8)$$

where, n is the number of data used in the estimation. Thus, the LS(least square) estimation of the parameters can be determined efficiently as

$$\hat{K} = (\Phi^T \Phi)^{-1} \Phi^T U \quad (9)$$

Once the best-fit PID' controller was identified, then the final PID controller can be written as

$$u(t) = (K_p + K_p^{'})e(t) + (K_i + K_i^{'})\int_0^t e(t)dt + (K_d + K_d^{'})\frac{de(t)}{dt}$$
$$= K_{pf}e(t) + K_{if}\int_0^t e(t)dt + K_{df}\frac{de(t)}{dt} \qquad (10)$$

where K_{pf}, K_{if} and K_{df} are the three overall parameters of the final PID controller. In this way, the PID controller was tuned in the closed loop.

3. Experimental System

3.1 System Overview

To confirm the effectiveness of the proposed control scheme we designed and developed 1 DOF vibration isolator as shown in Figure 4.

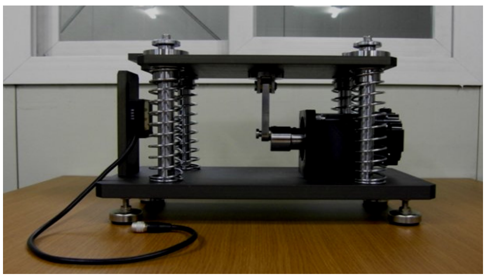


Figure 4: Developed vibration isolator

The vibration isolator is composed with upper plate, actuator to isolate vibration signal, sensors to measure analog and digital signals and controller to control the actuator. Outline of system components is shown in Table 1.

Table 1: System components

Passive isolation stage	Springs, Dampers, Mass
Actuator	Electric motor Mitsubishi HC-KFS73
NI cRIO 9022	NI cRIO Real-time controller
Laser sensor	ANR 1251 of SUNX

3.2 Actuator Mechanism

The actuator consisting of motor and crank mechanism is shown in Figure 5. From this mechanism, the relation between required motor torque and control force can be calculated as follows.

$$\tau = rF_1 = \frac{rF}{\cos\theta} \qquad (11)$$

Substituting $\cos\theta = \sin\alpha$ into Eq. (11), then we have

$$F = \frac{\tau \sin\alpha}{r} \qquad (12)$$

where, $\sin\alpha = \frac{\sqrt{(r+l+x)(-r+l+x)(r-l+x)(r+l-x)}}{2rx}$

and, F is control force, l is connecting rod length, r is crank length, θ is angle between F_1 and vertical, and α isangle between crank and vertical axis.

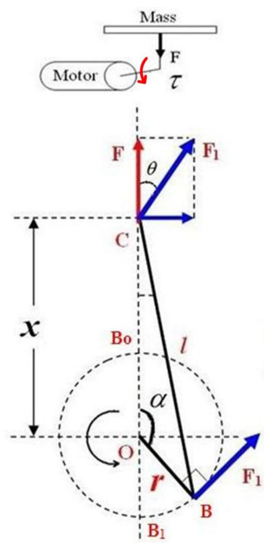


Figure 5: Actuator mechanism

3.3 Control algorithm

The control object as shown in Figure 4 can be represented by mechanical components in Figure 6. That is a single degree of freedom vibration isolator composed with spring k, mass m and damper c. AC motor works as system actuator which generates control force f(t) and x(t) means displacement of mass.

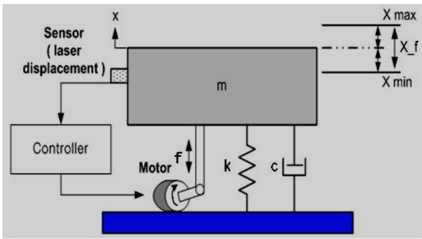


Figure 6: System modeling

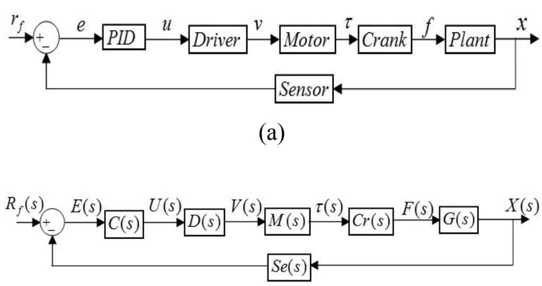
System dynamics is described by Eq. (13).

$$m\,\ddot{x}(t) + c\,\dot{x}(t) + k\,x(t) = f(t) \tag{13}$$

Its transfer function will be Eq. (14).

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2 + cs + k} \tag{14}$$

Block diagram of system including control components is shown in Figure 7. Where, r_f means set-point value, and e is an error variable between set-point value and real displacement, and u is control signal from controller, and τ is the torque generated by motor, and f implies control force value.



(a)

(b)

Figure 7: Block diagram of control

ILC method is applied to the PID controller in Figure 7. As mentioned above, initial parameters of the controller will be obtained by Matlab. Then ILC approach will be applied to get optimal parameters of controller.

Initial PID parameters were obtained by Matlab. The instruction of this work is available in [6]. In sequence, obtained initial PID parameters are $K_p=2.26, K_i=1.16, K_d=0.28$.

Next, the ILC scheme, as discussed in Section 2, was applied to the system for tuning the PID controller with the above initial values of parameters.

In real system, $m = 3.2$ kg, $c = 0.1$ Ns/m, $k = 200$ N/m, l = 78 mm, r = 8 mm then

$$G(s) = \frac{1}{3.2s^2 + 0.1s + 200} \tag{15}$$

And,

$$C(s) = \frac{K_p s + K_i + K_d s^2}{s}, \quad D(s) = \frac{20}{s},$$

$$M(s) = \frac{0.72}{s}, \quad C_r(s) = \frac{K_\alpha}{s}$$

where, $K_\alpha \cong \sin\alpha / r$ means constant value during control duration.

Control block diagram in Figure 7 is equivalent to Figure 8.

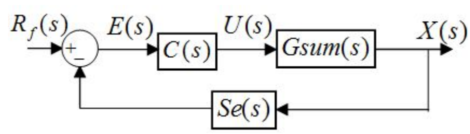


Figure 8: Equivalent block diagram

In Figure 8,

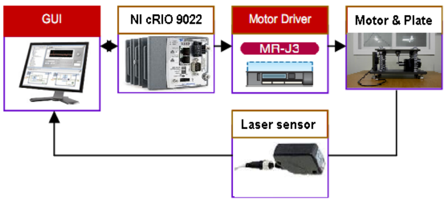
$$\begin{aligned} Gsum(s) &= D(s)M(s)Cr(s)G(s) \\ &= \frac{1800\,K_\alpha}{s^3(3.2s^2 + 0.1s + 200)} \end{aligned} \tag{16}$$

Based on the approach in the previous section, PID parameters are determined as $K_{pf} = 1.2$, $K_{if} = 0.63$, $K_{df} = 0.33$.

3.4 Experimental system composition

We applied proposed control algorithm to the developed vibration isolator. Figure 9 shows experimental system composition. Laptop PC, real time controller, motor driver, its power supply, vibration isolator and laser sensor are shown in Figure 9 (a).

Figure 9 (b) shows the photo of the real experiment system.



(a)

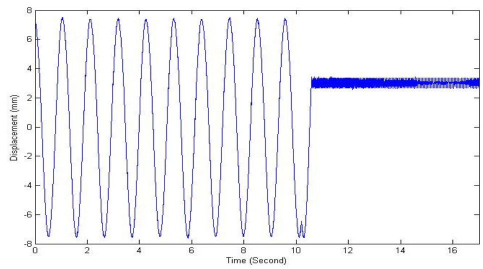
(b)

Figure 9: System composition

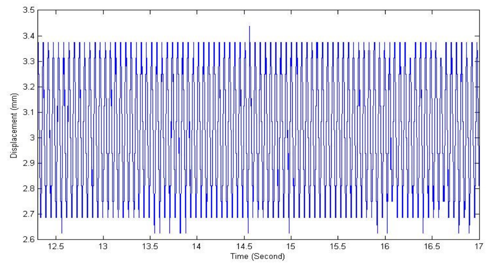
4. Experiment Results

Experiments were done on real set up system for verifying research result. Figure 10 illustrates experiment result when PID controller is tuned by Matlab wizard and Figure 11 shows the result in case PID controller is tuned based on ILC approach.

Set-point of plate displacement is 3 mm in both cases of experiment. At beginning, motor rotates freely around 11 seconds, plate of model moves up and down in range of (-8, 8) mm. After that, motor is controlled to isolate vibration of the plate and keeps it stable to the set-point. By comparison of experimental results as shown in Figure 10 (b) and Figure 11 (b), it is easy to conclude that PID controller tuned by ILC approach shows good performance than tuned by Matlab only.

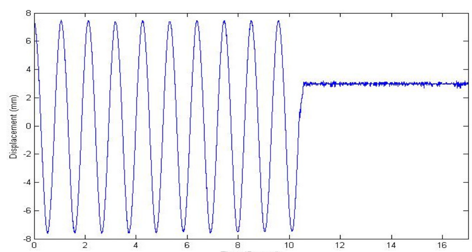


(a) State variable with time

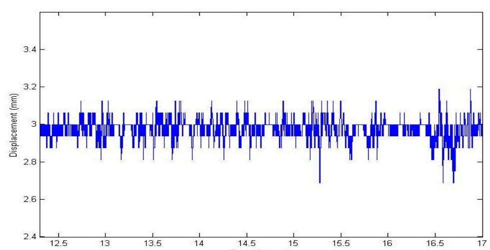


(b) Steady state (set-point 3 mm)

Figure 10: Experiment results with Matlab tuning only



(a) State variable with time



(b) Steady state (set-point 3 mm)

Figure 11: Experiment results with ILC tuning algorithm

5. Conclusion

In this study, a novel tuning method for PID controller based on ILC approach and experimental result applying proposed controller were introduced. Even though PID controller is widely used because of its simple structure and good performance, selection of adequate PID parameter is an important and difficult work. We applied ILC approach to get suitable PID parameters by tuning method. In this tuning approach, ILC learns to generate a corrected action from previous control actions and previous error signals then PID parameters will be updated whenever the same control task is repeated. This approach could be applied to the control task without requiring the perfect knowledge of process model or parameters.

To confirm the effectiveness of the proposed control scheme we developed 1 DOF vibration isolator composed with mass, spring and actuator. The actuator is an electrical motor that generates control torque and this torque was converted to control force through crank mechanism. It is reasonable way for archiving translation motion to introduce crank mechanism. The relation between control force and torque from actuator was also analyzed. System consisting of GUI, controller, driver, sensor and isolator was set up for real experiment.

PID parameters for vibration isolator were easily derived by proposed ILC approach. We applied the PID controller to the experiment to isolate vibration signal and the experiment was accomplished with reliable results. Proposed control scheme was compared with experiment result in case of PID controller being tuned by Matlab wizard. It was clear that the experimental results obtained by proposed tuning method is better than the Matlab tuning approach.

From the experimental results we confirm that proposed control method is useful for real system because of its facilities and reliability.

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