CLOSED LOOP IDENTIFICATION OF SYSTEMS WITHIN CASCADE CONNECTED CONTROL STRATEGIES

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Abstract
A brief review of the background to the Phase-Locked Loop (PLL) method of non-parametric system identification is presented. This introduces the idea of performing the non-parametric identification for any point on the frequency response curve of a process. The PLL identification method is then extended to perform the non-parametric identification of the component parts of a cascade connected control system. An advantage of the method is that the non-parametric identification is performed with the cascade control system connected in closed loop. An example demonstrating the identification method is given.

1 Introduction

It has been sixty years since Ziegler and Nichols published a method that allowed PID controllers to be satisfactorily tuned without the requirement to have a process model available. One of their methods relied on being able to identify the frequency where the process frequency response has a phase angle of $-\pi$ (rad). This frequency is termed the ultimate frequency. With this frequency value and the magnitude of the process frequency response at the ultimate frequency as data, Ziegler and Nichols (1942) presented a rule based method for PID controller tuning.

The method of ultimate period is still used to tune PID controllers in the process industries. The method requires that the control loop is closed and in proportional control only. The proportional controller term is increased until the process exhibits a stable limit cycle. By making measurements of the process response signal frequency and the controller gain at the sustained oscillation point, the data that the rule based controller tuning method of Ziegler and Nichols requires can be extracted.

A key practical difficulty of this method is the need to bring the closed loop process to the point of marginal stability. In the early 1980's there was a change from analogue to digital techniques of PID controller implementation and industrial practitioners were keen to see an advance being made in PID controller tuning methods. Hagglund and Astrom (1985) realised that for a large class of practical systems, a relay in place of the controller can produce a closed loop stable limit cycle at the ultimate frequency. The use of describing function analysis (Atherton, 1975) leads to the relationship for the ultimate gain as,

$$K_U = 4M / \pi A \tag{1}$$

where M and A are the relay height and the amplitude (half peak-peak) of the process output signal, respectively.

The use of the relay to extract the ultimate frequency point data is essentially a non-parametric experiment to identify one point on the frequency response curve of the process. Ultimate point data is calculated using a describing function analysis. This method relies on the process having a low pass characteristic at the ultimate frequency with only the ultimate frequency being propagated around the closed loop. If this assumption is not true, then other frequencies can exist in the closed loop, giving rise to inaccuracies in the identified data. In efforts to reduce the dependency of the relay method on the low pass assumption, many researchers have published work on ways of improving the relay experiment *per se* (Astrom and Hagglund, 1995; Lee *et al*, 1995; Shen *et al*, 1996a; Shen *et al*, 1996b).

The relay experiment is an elegantly simple method of identifying a single point on the frequency response of a process. It was with this in mind that a method was sought that would retain the ease of use and practicality of the relay experiment but would not require the process to have a low pass characteristic for identification accuracy to be maintained. The result of this research was the Phase-Locked Loop (PLL) identification method (Crowe and Johnson, 1998a).

Layout of the paper
The underlying structure of the PLL method is discussed in Section 2 of the paper. In Section 3, the closed loop identification of single loop control systems is discussed along with its extension to cascade control loops. In section 4, an application example is given for the closed

loop identification of a cascade control loop. Conclusions and references close the paper.

2 The Phase-Locked Loop Identifier

The challenge that was initially addressed by this research was to devise an alternative method to the relay experiment for extracting frequency response information where the assumed target point was the phase reference $\phi^{ref} = -\pi$ (rad), compatible with finding the phase crossover frequency, $\omega_{-\pi}$. An approach based on a phase-locked loop framework emerged and it quickly became apparent that it would be possible to identify any point on the frequency response curve of a process specified either by a phase or a gain reference value.

2.1 The digital identifier module

Figure 1 shows the main components of the digital implementation of the PLL identification module. The functions of the component parts are described as follows (Crowe and Johnson, 1998a):

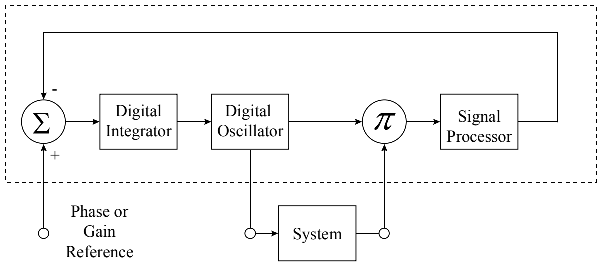

Figure 1 Digital identifier module

(i) A feedback structure using a phase or gain reference at an input comparator.
(ii) A digital model of a Voltage Controlled Oscillator (VCO) which generates a process sinusoidal excitation path and a sinusoidal reference path.
(iii) A digital signal processing unit to extract the actual measured system phase or gain for supply to the comparator.
(iv) A digital integrator unit to ensure the identifier unit converges to the given system phase or gain reference.

The digital process identifier module comprises two processes. The inner process is that of a sine wave experiment. The outer loop process is a digital control loop containing two sub-processes (a) the extraction of phase/gain data from the output of the multiplier and (b) the update process of the overall digital control loop.

The identifier module will accept a gain or a phase reference (Crowe and Johnson, 1998b). This enables it to be used to find either the phase crossover frequency point or the gain crossover frequency point. The reference to the identifier module can even be made to seek a frequency of maximum modulus (Crowe and Johnson, 1999). Closed loop configurations can also be set up (Crowe and Johnson, 2000). It is this extensive flexibility of use along with increased accuracy of estimation which gives the phase locked loop identifier significant advantages over the relay experiment.

3 Closed Loop Identification Theory

From a production operational viewpoint the identification of a process should be carried out in closed loop. This allows a reduction in the production of *off specification* product during the period of the identification. There is also the possibility that a process may be open loop unstable and hence it would not be possible to carry out open loop identification. In this section of the paper the use of the PLL identifier to identify processes connected in single loop control and cascaded loop control are described.

3.1 Known Controller Unknown Process

From Figure 2, the closed loop responses give,

$$G_{cl}(j\omega) = \frac{y(j\omega)}{u(j\omega)} = \frac{G_p(j\omega)G_c(j\omega)}{1+G_p(j\omega)G_c(j\omega)} \tag{2}$$

Thus if the closed loop transfer function is identified and the transfer function of the controller is known then it will be possible to identify the process from,

$$\left|G_p(j\omega)\right| = \frac{\left|G_{cl}(j\omega)\right|}{\left|1-G_{cl}(j\omega)\right|\left|G_c(j\omega)\right|} \tag{3}$$

$$\arg\left(G_p(j\omega)\right) = \arg\left(G_{cl}(j\omega)\right) - \arg\left(1-G_{cl}(j\omega)\right) - \arg\left(G_c(j\omega)\right) \tag{4}$$

3.2 Unknown Controller and Unknown Process

The unity feedback connection of an unknown process $G_p(s)$ with an unknown controller $G_c(s)$ is shown in Figure 3. It is easily shown that the process identification uses,

$$\arg\left(G_p(j\omega)\right) = \arg\left(\frac{y(j\omega)}{u(j\omega)}\right) - \arg\left(\frac{x(j\omega)}{u(j\omega)}\right) \tag{5}$$

$$\left|G_p(j\omega)\right| = \left|\frac{y(j\omega)}{u(j\omega)}\right| \div \left|\frac{x(j\omega)}{u(j\omega)}\right| \tag{6}$$

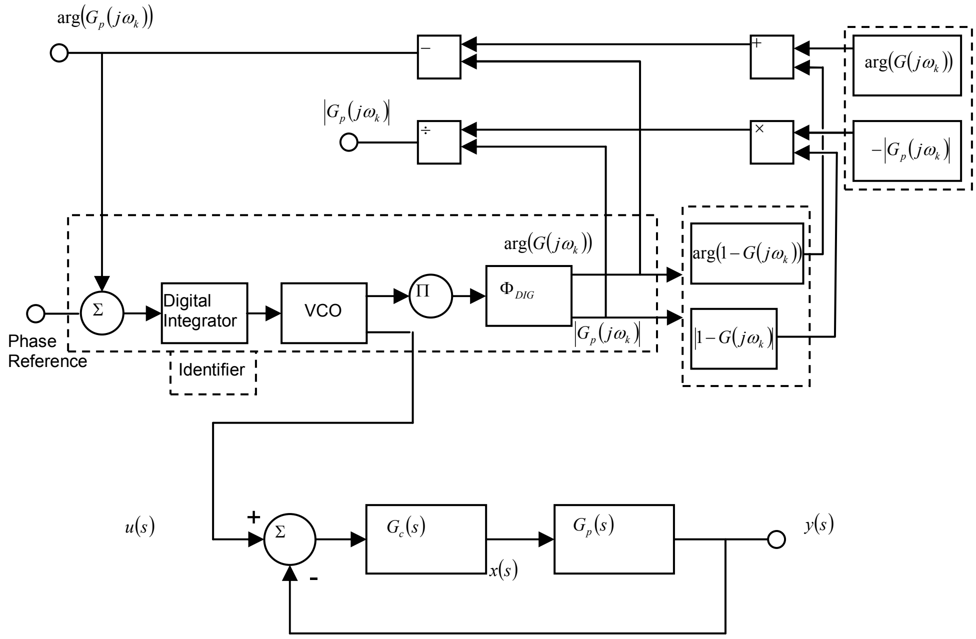

Figure 2 Closed Loop Identification, Known Controller and Unknown Process

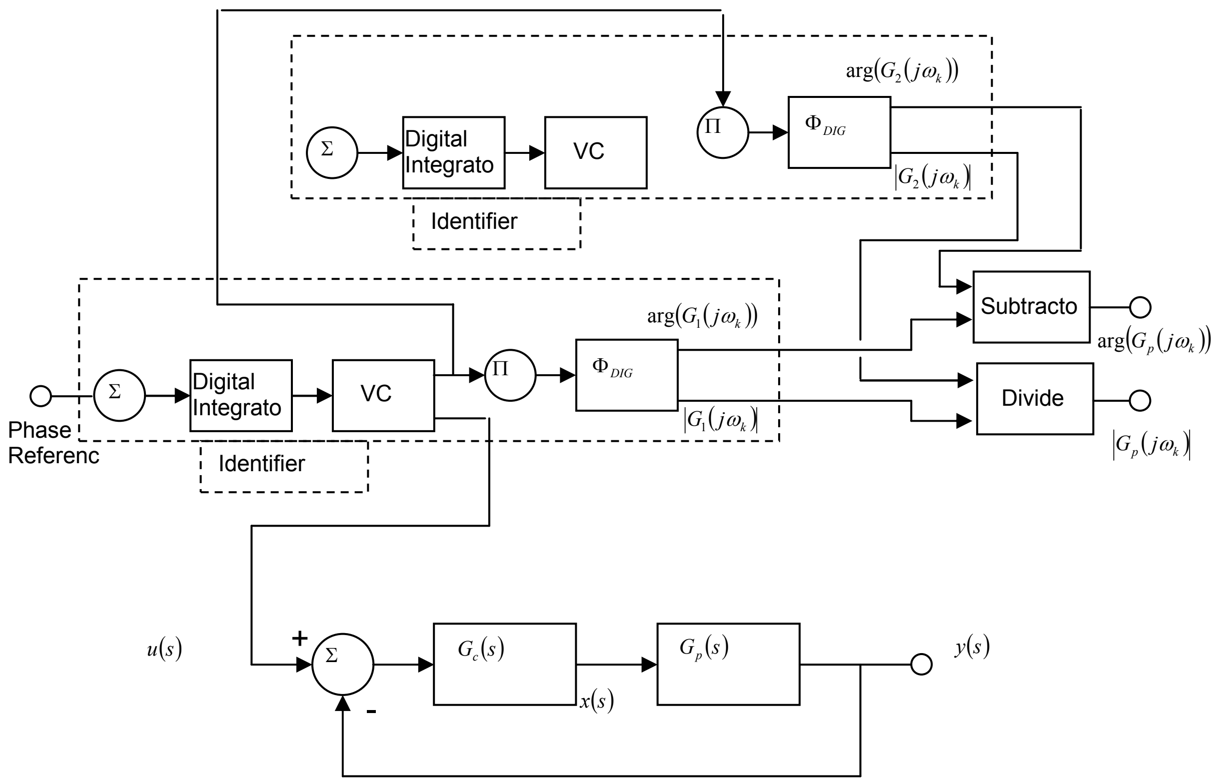

Figure 3 Closed Loop Identification, Unknown Controller and Unknown Process

Thus by simultaneously performing an identification between the reference input and the controller output and between the reference input and the closed loop output, it is possible to identify the process while it is connected in closed loop.

3.3 Cascaded Loop with Unknown Controllers and Unknown Processes

In section 3.1 it was shown how knowledge of the controller structure and tuning parameters could be used to allow an identification of a process in closed loop with a single PLL identifier. In the case of a cascade control loop having knowledge of the structure of the controllers cannot be used and two PLL identifiers are required to carry out the identification.

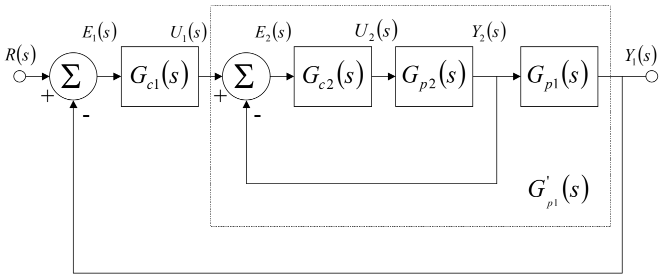

Figure 4 Cascade Loop Set-up

In the cascade loop of Figure 4, the process $G_{p2}(s)$ is identified with both the inner and outer control loops closed. The next stage is to identify the inner closed loop or combined process, $G'_{p1}(j\omega)$. The main motivation for these identification steps is to allow the inner loop controller $G_{c2}(s)$ to be selected to give a desired inner control performance followed by the selection of the controller $G_{c1}(s)$ to give a desired outer loop control performance (Crowe, 2003). From Figure 4, with closed loop responses,

$$Y_2 = G_{p2}U_2 \tag{7}$$

$$G_{p2} = \left(\frac{Y_2}{U_2}\right) = \left(\frac{Y_2}{R}\right) / \left(\frac{U_2}{R}\right) \tag{8}$$

From equation (8) it can be seen that,

$$\arg\left(G_{p2}(j\omega)\right) = \arg\left(\frac{Y_2(j\omega)}{R(j\omega)}\right) - \arg\left(\frac{U_2(j\omega)}{R(j\omega)}\right) \tag{9}$$

$$\left|G_{p2}(j\omega)\right| = \left|\frac{Y_2(j\omega)}{R(j\omega)}\right| / \left|\frac{U_2(j\omega)}{R(j\omega)}\right| \tag{10}$$

Again, using Figure 4, define,

$$G'_{p1} = \frac{G_{p1}G_{p2}G_{c2}}{1+G_{p2}G_{c2}} \tag{11}$$

then

$$Y_1 = G'_{p1}U_1 \tag{12}$$

$$G'_{p1} = \left(\frac{Y_1}{U_1}\right) = \left(\frac{Y_1}{R}\right) / \left(\frac{U_1}{R}\right) \tag{13}$$

From equation (13) it can be seen that,

$$\arg\left(G'_{p1}(j\omega)\right) = \arg\left(\frac{Y_1(j\omega)}{R(j\omega)}\right) - \arg\left(\frac{U_1(j\omega)}{R(j\omega)}\right) \tag{14}$$

$$\left|G'_{p1}(j\omega)\right| = \left|\frac{Y_1(j\omega)}{R(j\omega)}\right| / \left|\frac{U_1(j\omega)}{R(j\omega)}\right| \tag{15}$$

Thus it can be seen from (9) and (10) that by carrying out two simultaneous identifications between Y_2 and R, and U_2 and R that it is possible to identify the inner process $G_{p2}(s)$. Similarly if the identifications are carried out between Y_1 and R and U_1 and R then as shown by (14) and (15) it will be possible to identify the combined process, $G'_{p1}(j\omega)$.

4 Application Example

The PLL method of non-parametric system identification is now applied to a cascade control system as shown in Figure 4 of section 3.3. The transfer functions of the inner and outer processes are given by,

$$G_{p2}(s) = \frac{2.0e^{-0.7s}}{(s+2)(s+4)} \tag{16}$$

$$G_{p1}(s) = \frac{0.1e^{-0.1s}}{(s+0.1)^2(s+0.5)} \tag{17}$$

The outer and inner or master and slave controllers have been tuned using a relay experiment and the application of Ziegler and Nichols' tuning rules. The controllers are of PI type and are given by

$$G_{c1}(s) = 0.1323 + \frac{0.0054}{s} \tag{18}$$

$$G_{c2}(s) = 2.818 + \frac{1.401}{s} \tag{19}$$

The identification performed first is that of the inner process, G_{p2}. The point on the frequency response curve that is to be identified is the $-\pi$ point, viz. the point where the phase angle of the process is $-\pi$ (rad). The frequency at which this phase angle occurs is denoted, $\omega_{-\pi}^{p2}$. The PLL identifiers were set up such that the integrator gain was set at 0.2 and the initial identification frequency was set as 0.5 (rad.s^{-1}) the update tolerance value for the identifier was set as 0.001 as was the stopping tolerance value. The theoretical values derived from the process model for the $-\pi$ point are,

$$\omega_{-\pi}^{p2} = 2.441(\text{rad.s}^{-1}) \text{ and } \left|G_{p2}\left(j\omega_{-\pi}^{p2}\right)\right| = 0.1352.$$

The following graphs show the evolution of the identification process. The time taken to identify the process was 780(sec) with the identified $-\pi$ point frequency being 2.4406(rad.s^{-1}), the identified magnitude being 0.1352 and the identified phase angle as –3.1422 (rad). The percentage identification errors for the frequency, magnitude and phase angle are 0%, 0.0164% and 0.191% respectively. Thus it can be seen that the identification was carried out to a high degree of accuracy. It should be borne in mind that all of the identified points on the graphs can be used to construct the frequency response of the inner process between the frequencies of 0.5(rad.s^{-1}) and 2.4406(rad.s^{-1}). Thus although the identified point was selected as the $-\pi$ point, any point can be chosen and either phase angle or magnitude reference values can be selected for the identifier.

The second identification that is to be carried out is for the process denoted as $G_{p1}^{'}(s)$, as shown in Figure 4 above. The PLL identifiers were initiated at an identification frequency of 0.1(rad.s^{-1}) and the integrator gain was set at 0.2. The tolerance values were once again set at 0.001 for the update tolerance and 0.001 for the stopping tolerance for the identification. As above the $-\pi$ point was chosen as the reference value for the identification. The theoretical values derived from the process model for the $-\pi$ point are,

$$\omega_{-\pi}^{p1'} = 0.2081 \ (\text{rad.s}^{-1}) \text{ and } \left|G_{p1}^{'}\left(j\omega_{-\pi}^{p1'}\right)\right| = 2.9193.$$

The evolution of the identification is shown in the Figures 5-11. The time required to carry out the identification was 2206(sec). The identified data for the $-\pi$ point was $\omega_{-\pi}^{p1'}$ = 0.2080(rad s^{-1}) and $\left|G_{p1}^{'}\left(j\omega_{-\pi}^{p1'}\right)\right|$ = 2.9194. From this, the percentage identification errors for the frequency, magnitude and phase angle are –0.0481%, 0.0292% and 0.0284% respectively.

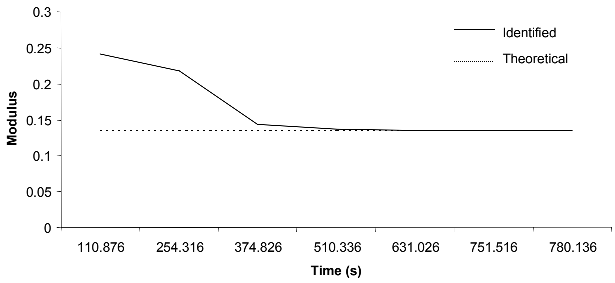

Figure 5 Identified Inner Process Modulus vs. Time

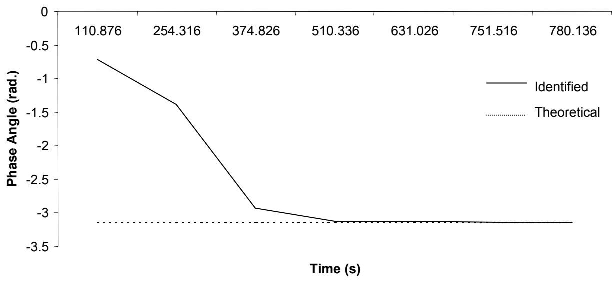

Figure 6 Identified Inner Process Phase Angle vs. Time

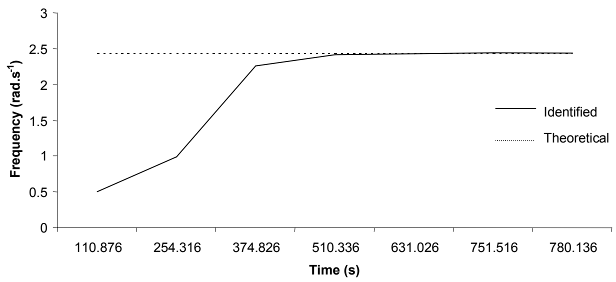

Figure 7 Identification Frequency vs. Time

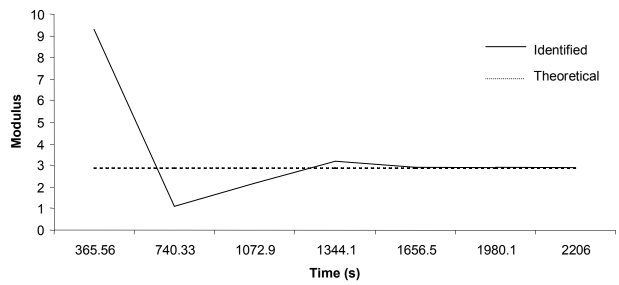

Figure 8 Identified Composite Process Modulus vs. Time

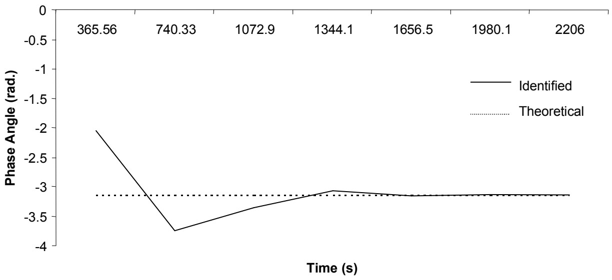

Figure 9 Identified Composite Process Phase Angle vs. Time

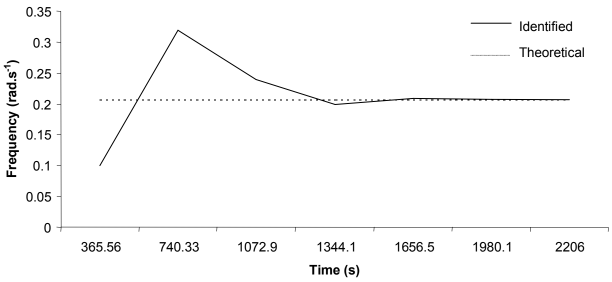

Figure 10 Identification Frequency vs. Time

5 Conclusions

The Phase-Locked Loop method of non-parametric system identification has been described briefly, along with the methods used to carry out single and cascade closed loop identification. Its application to the identification of a cascade control system in closed loop has been presented. The results of the identification show that a high degree of accuracy in the identification can be obtained and that all of the points identified as the PLL converges to the required (setpoint) value can be used to model the process under investigation. It is also clear from the application example that the PLL method of system identification has retained the simplicity of use of the relay experiment but has none of the low pass system requirements.

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