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Large feedback control design with limited plant information

Robert L. Cloud *,[1], John F. O'Brien [2]

Department of Electrical and Computer Engineering, University of Wyoming, Laramie, WY 82073, USA

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ABSTRACT

A novel method is presented that provides a novel, large feedback design with adequate stability margins without a plant model. First, a PID controller is found using on-line tuning. Next, the closed-loop transient response of the PID system is used to define a bandwidth, and the PID compensator transfer function is used to determine the plant gain and heuristically estimate the plant slope at crossover. Then, these parameters are used to find the compensator. A prefilter is designed to improve transient response, and adjustments are suggested for plants possessing feedback-limiting dynamics. Analytical examples and experimental data illustrate the approach's efficacy.

1. Introduction

Applied control is dominated by the proportional–integral-derivative (PID) compensator (Ang, Chong, & Li, 2005; Astrom & Hagglund, 1995, 1996, 2001; Gerry, 1987; Kaya & Scheib, 1988; O'Dwyer, 2003; Ziegler & Nichols, 1942) because of its familiarity, ease of tuning and intrinsic robustness. There is much literature on PID topics, such as automated tuning methods (Gorez, 1997; Hang & Sin, 1991; Li, Feng, Tan, Zhu, Guan, & Ang, 1998), fuzzy logic tuning methods (Arulmozhiyal, 2012) and adaptive tuning methods (Astrom, Hagglund, Hang, & Ho, 1993; Minter & Fisher, 1988). For control applications where large feedback is required over a prescribed bandwidth (applications on type-0 systems), PID is not the best solution as the compensator is of insufficient order (only two zeros and an integrator) to adequately and accurately shape the loop at frequencies near crossover (O'Brien, 2012). For such systems, high-order compensation (usually between eighth and fifteenth-order) is required to carefully shape the response to maximize the available feedback (O'Brien, 2012).

The *Nyquist-stable controller* (Lurie & Enright, 2000; O'Brien, 2012) uses a greater than second-order roll-off after the functional bandwidth and recovers phase with a sharp lead near crossover, providing more feedback at low frequency. This loop shape has been successfully implemented on several systems (Carruthers & O'Brien, 2011; McInroy, O'Brien, & Allias, 2015; Neat & O'Brien, 1996; O'Brien, 2009). The principal drawback of the Nyquist-stable controller is its inherent sensitivity to changes in the loop response caused by actuator saturations or nonlinearities due to component imperfections that cause oscillation. Recent advances in nonlinear dynamic compensation have been successful in alleviating these negative features (O'Brien & Carruthers, 2013). 'Fractional-order' controllers, often applied to PI systems (Lino & Maione, 2013), have been used to improve feedback at low frequency while retaining sufficient relative stability and are an important feature of 'Bode optimal loop shape', which provides robust, large feedback and sufficient sensor noise suppression (Lurie & Enright, 2000; O'Brien, 2012). The loop shape prescribed in the following, the 'modified Bode optimal' (MBO) loop shape, combines the feedback maximizing roll-off of the Nyquist-stable controller with the features of the Bode optimal loop shape.

On-line tuning algorithms provide an advantage for the PID compensator. High-order compensators often require accurate plant transfer functions, and often the designer does not have these, requiring system identification (SID). Experimental SID methods are iterative procedures and the most time consuming and costly components in high-complexity control design (Astrom & Eykhoff, 1971; Hjalmarsson, 2009; Hussain, 1999; Ljung, 1999; Ljung, Hjalmarsson, & Ohlsson, 2011; Ogunnaike, 1996). SID requires a very carefully chosen model set (i.e. model structure and polynomial orders), which is the most important and difficult choice in a SID problem (Astrom & Eykhoff, 1971; Ljung, 1999). Incorrectly identifying the model set that describes the true system can result in large errors in the estimated model, complicating control design (Astrom & Eykhoff, 1971; Hou & Wang, 2013).

* Corresponding author.
E-mail addresses: rcloud2@uwyo.edu (R.L. Cloud), obrienj@uwyo.edu (J.F. O'Brien).
[1] Student Member, IEEE.
[2] Member, IEEE.

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Inherently unstable systems or those that must be identified under normal operation for safety warrant identification in closed-loop. Closed-loop identification creates additional difficulties because the inputs and disturbances become correlated and feedback automatically resists small perturbations (Forssell & Ljung, 1999; Tangirala, 2015). Like traditional compliance testing techniques and stability augmentation systems for aircraft, arbitrary agitation (i.e. sine sweeps, white noise inputs, etc.) of the closed-loop system for purposes of SID may also not be possible, and only a simple input (i.e. a step or finite impulse) may be all that is available for closed-loop SID (Tischler, 1995).

A three-step algorithm that allows the design of the MBO controller without requiring a model of the plant to be controlled is presented. First, a PID controller is designed using a well-known on-line tuning algorithm. Next, the closed-loop transient response of the PID system is used to define a control bandwidth, and the PID compensator transfer function is used to determine the plant gain and heuristically estimate the plant slope at crossover. Then, these parameters are used to find the MBO compensator poles and zeros, and adjustments are suggested to achieve a stable closed-loop response. A prefilter is designed to improve transient response characteristics. Eleven analytical examples and one experimental example are provided to show the efficacy of the procedure.

1.1. Terminology and background theory

Rational function $T(s)$ of the Laplace variable, s, is the *loop transmission* (alternatively *return ratio*) of a feedback loop (O'Brien, 2012). Frequency ω_b, where $|T(j\omega_b)| = 1$, is the *control bandwidth* (alternatively the 0 dB *crossover frequency*) (O'Brien, 2012). Frequency ω_0 is the *functional bandwidth* where the modulus breaks from a flat response at low frequency (O'Brien, 2012). $|F(s)| = |1 + T(s)|$ is the *feedback* (O'Brien, 2012). $|F(s)| > 1$, $|F(s)| < 1$ and $|T(s)| \ll 1$ define *negative*, *positive* and *negligible* feedback, respectively (O'Brien, 2012). $|F(s)| \gg 1$ defines *large* feedback (O'Brien, 2012). These definitions indicate the effect of feedback on the logarithmic response of the closed-loop system to disturbances. *Non-minimum phase*, $B_n(\omega)$, is the phase lag not found using the Bode phase/gain relationship (Bode, 1940). When comparing two systems, the system with larger feedback in a frequency band will be superior in the rejection of disturbance in that band. A feedback system is *Nyquist-stable* if $T(s)$ is stable, satisfies the Nyquist Criterion and has a steeper than −12 dB/oct roll-off over an interval of frequencies less than ω_b (Lurie & Enright, 2000).

1.2. Problem statement and assumptions

A high-performance/large feedback controller is sought to control an unknown, resonant system with high modal density without the benefit of a mathematical model of the plant. The following assumptions are made (Astrom & Eykhoff, 1971; Forssell & Ljung, 1999; Hjalmarsson, 2009; Hou & Wang, 2013; Hussain, 1999; Ljung, 1999; Ljung et al., 2011; O'Brien, 2012; Ogunnaike, 1996; Tangirala, 2015; Tischler, 1995).

(1) The plant is linear, time-invariant and is either single-input, single-output (SISO) or a diagonally-dominant multivariable system.
(2) The system is high-performance, thus requiring large feedback.
(3) The plant, actuator and/or sensor possess unknown bandwidth-limiting features.
(4) A first-principles model of the plant is not available.
(5) The system possesses dynamics which limit open-loop SID.
(6) Feasible closed-loop SID methods are limited; a simple input is all that is available for closed-loop SID.

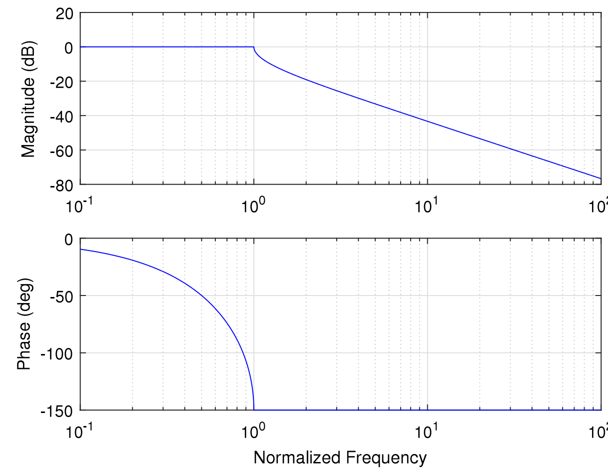

Fig. 1. Optimal loop transmission shape at frequencies near crossover.

2. Modified bode optimal loop shape

The Bode optimal loop shape is a design method that provides a loop shape for robust, large feedback with steep roll-off at high frequency for sufficient sensor noise suppression (Lurie & Enright, 2000). A lead provides just enough phase advance to compensate for a steep roll-off at high frequency and non-minimum phase delay near crossover. Between the functional bandwidth and crossover, this shape implements a fractional-order slope. Mimicking the Nyquist-stable controller, this shape is modified to a more aggressive shape at low frequency when sufficient control bandwidth is available, thus providing larger feedback over the functional bandwidth and defining the MBO loop shape.

2.1. Shaping the response between crossover and the functional bandwidth: slope between first and second-order

A network pole reduces the loop shape slope −6 dB/oct, two poles by −12 dB/oct and so on. A −6 dB/oct roll-off at crossover provides 90° of phase margin, an excess of 60° over the Bode minimum of 30° (O'Brien, 2012). A −12 dB/oct roll-off at crossover provides more feedback at low frequency but 0° of phase margin and positive feedback is excessive. Consider the complex frequency response in Fig. 1. The magnitude is flat to the functional bandwidth and then transitions to a roll-off of −10 dB/oct. This slope provides a phase of −150° at all frequencies higher than the functional bandwidth, thus 30° of phase margin at any crossover frequency beyond the functional bandwidth. This is a desirable loop shape for a linear controller, as the system is robust to variations in the crossover frequency. This allows the designer the ability to reduce the loop gain to gain-stabilize unknown high frequency modes without destabilizing the system at low frequency, which is an important feature of designing for resonant systems as is discussed in the following.

The synthesis of this shape is of concern as it cannot be provided by a rational function. However, recursive pole-zero distributions to achieve a desired roll-off over a given frequency interval are widely studied in fractional control. Deriving a relationship like frequency-band complex noninteger differentiation, a constant slope function is decomposed into a product of rational and irrational functions, $s^{-p} = s^{-r}s^{-q}$, where r is an integer and $0 < q < 1$ (O'Brien, 2012; Oustaloup, Levron, Mathieu, & Nanot, 2000). The modulus slope of s^{-q} can be approximated by a network function of appropriately placed poles and zeros separated by the following.

$$q = \frac{b}{a+b} \tag{1}$$

Real numbers a and b are the logarithmic octave spacings from zero to pole and pole to zero, respectively (O'Brien, 2012).