

Instrumentation & Control (QQ), Assignment 1, 2017

by Kenny Johnston

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Instrumentation and Control
Technical Report

Module M5X00940

Building a Single Transfer function
from a multi-element Control System

For Dr Stephen Mosey

By

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Building a Single Transfer function from a multi-element Control System

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A control system was designed for a given transfer function with the intention to operate within a set period and performance envelope. The initial design was constructed in Simulink from discrete elements and MATLAB was used to analyse the stability and operational tolerances. The discrete elements were combined and analysed at each stage until the control system was contained within one single element. Each stage of amalgamation was analysed and compared with the previous results. It was found that while the each stage of control system design performed as expected and to the specified performance characteristics, with no modification to the external input or internal characteristics, two distinct anomalies were observed.



1. Introduction

Controller systems are used to automate functions of plant machinery or other electro-mechanical systems in order to reduce or negate the requirement of human interaction or interference.

Closed loop systems using feedback come in several configurations, including On/Off, Three-State, Proportional (P), Proportional Integral (PI) and Proportional Integral Derivative (PID) control configurations.

An On/Off controller is the simplest configuration but also produces the most rudimentary of output behaviour. If the control criteria are too stringent, it is possible to induce chatter due to high frequency switching. Due to these

processes, this type of controller is rarely used. ^[1]

A Three-State controller uses an If, Then, Else methodology to produce a three-stage control designed to lessen the impact on the control and actuator equipment. ^[2]

P controllers are designed so that "the output of the controller is proportional to the input signal". ^[3] A simple example is that of a cistern where the valve slowly reduces the water flow as the float nears the top until the desired level has been reached, whereupon the valve is fully closed.

A PI controller sums a P controller output with that of an integral of the system error input over a defined period. "Due to the proportional component, the manipulated variable immediately reacts to any error signal, while the integral component starts gaining influence only after some time." ^[4]

A PID controller includes a derivative function of the control system error. This generates an output as a function of the rate of change of the control system error. "Derivative controllers generate - by anticipation, so to speak - large control amplitudes as soon as a change in amplitude occurs." ^[4]

2. Method

An industrial process was described as having the transfer function G(s) below. (1)

$$G(s) = \frac{1}{5s^2 + 1s + 5} \dots\dots\dots \text{(Eqn. 1)}$$

MATLAB and Simulink were used to design a control system using a PID controller capable of controlling this process. A

unit step input was used and our control system was tasked with bringing the process under control within two seconds, with an overshoot of less than 5%.

2.1 Initial Design

G(s) was defined in MATLAB as a continuous-time transfer function.

```
>> G=tf([1], [5 1 5])

G =

      1
-----
5 s^2 + s + 5

Continuous-time transfer function.
```

Figure 1: Defining G (Eqn. 2)

A PID controlled system was built using Simulink and the transfer function defined as G.

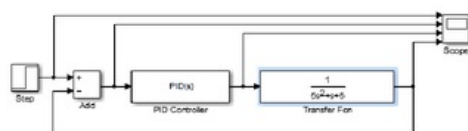


Figure 2: Initial design

The PID was then tuned to comply with the control parameters previously stated as a two second limit with a less than five percent overshoot.

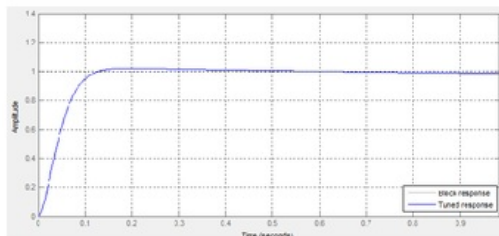


Figure 3: Tuned PID response curve

Performance and robustness		
	Tuned	Block
Rise time	0.0736 seconds	0.0736 seconds
Settling time	0.223 seconds	0.223 seconds
Overshoot	2.09 %	2.09 %
Peak	1.02	1.02
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	73 deg @ 20.3 rad/s	73 deg @ 20.3 rad/s
Closed-loop stability	Stable	Stable

Figure 4: Tuned PID performance characteristics

2.2 Two element design

The tuned PID parameters, defined as C were exported to MATLAB and used to calculate the combined transfer function below.

$$H = G * C \dots\dots\dots(\text{Eqn. 3})$$

The Simulink Transfer Function was then updated with the new values, (Fig. 4) The PID was then removed from the simulation and the function was analysed.

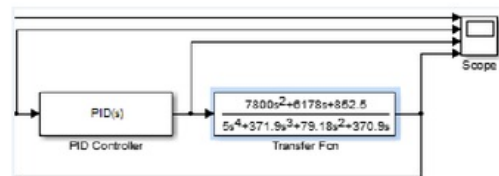


Figure 5: Combined Transfer Function, H = G x C.

Nyquist and Pole-Zero diagrams were then created using MATLAB. See Figures 7 to 10.

2.3 Single element design

The feedback loop was then added to the combined transfer function, H, to produce a single transfer function for the control system. This was achieved in MATLAB by redefining H, below.

$$H = \frac{GC}{1+GC} \dots\dots\dots(\text{Eqn. 4})$$

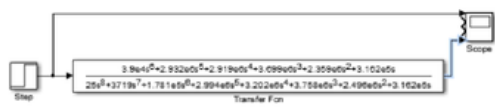


Figure 6: Combined Transfer Function, $H = Gx C / (1 + (Gx C))$

During each stage of analysis, the scope outputs were viewed and recorded for analysis.

3. Results

3.1 Initial Design

The initial design, as shown in Figure 2, produced the scope output shown in Figure 7.

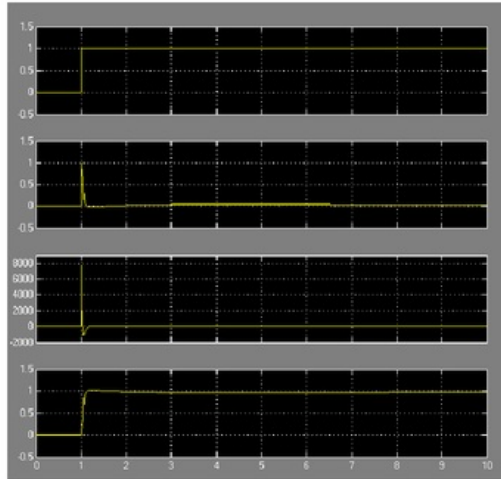


Figure 7: Initial design scope outputs

For the initial design, Simulink shows a PID settling time of

0.223 seconds with a maximum overshoot of 2.09 seconds.

See Figure 4.

3.2 Two element design

Using MATLAB, the PID and TF were combined using equation 3, Figure 4. With this equation available it was possible to plot a Nyquist diagram and a Pole-Zero plot.

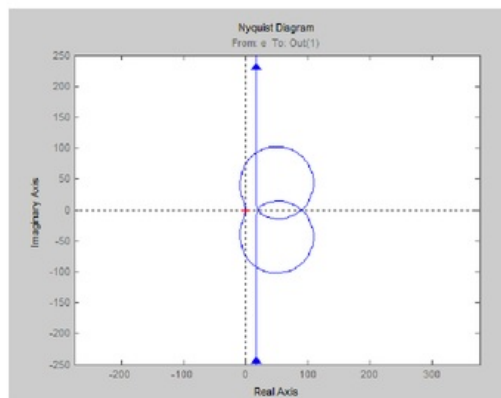


Figure 8: Nyquist diagram, full.

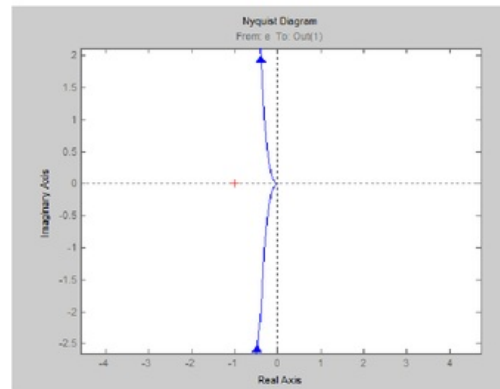


Figure 9: Nyquist diagram, detail on (-1,0) point.

It can be seen in Figures 8 and 9 that the area under the curve does not encompass the (-1,0) point.

The Poles and zeroes were then plotted, again using MATLAB.

The results are shown in Figures 10 & 11 below.

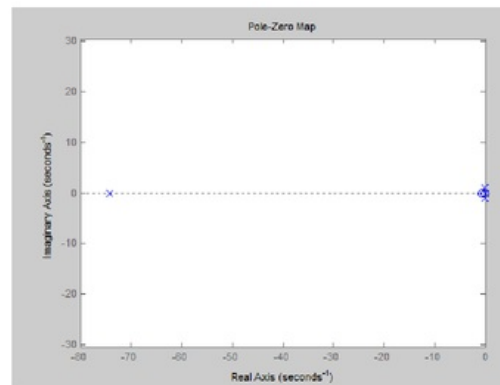


Figure 10: Pole-Zero plot, full

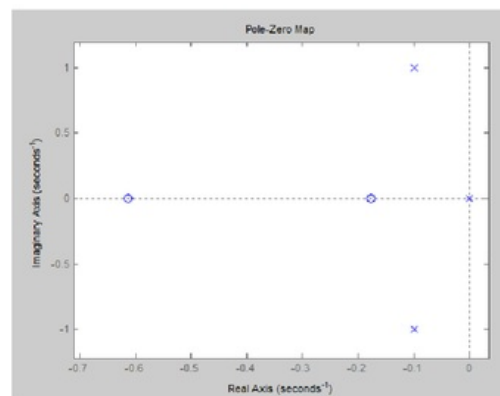


Figure 11: Pole-Zero plot, detail

A Complex pole pair can be seen at $(-0.1, \pm j1)$ and a zero pair at $(-0.15, 0)$ and $(-0.6, 0)$. Two unexpected poles can also be seen at $(0, 0)$ and $(-74, 0)$.

When the combined TF $H = C \times G$ was inserted into the Simulink circuit, the simulation was run and the scope output shown in Figure 12 (below) was observed.

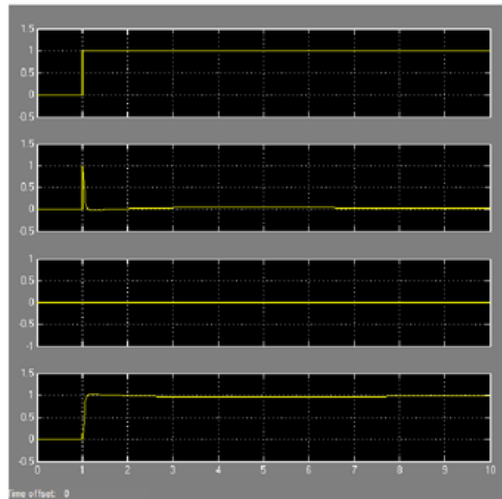


Figure 12: $H = C \times G$ scope output

3.3 Single element design

The single element design, as shown in Figure 5 was modelled and the scope output recorded. However, due to the volume

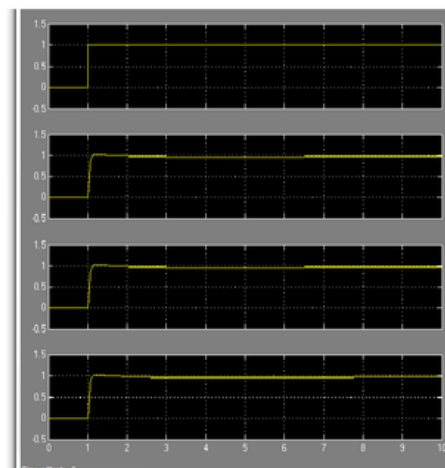
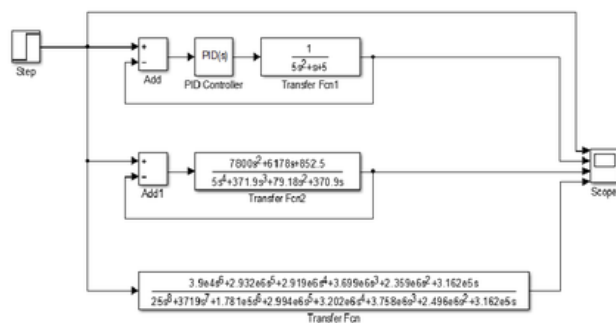


Figure 13: Combined Three, Two and single stage TF controllers and scope outputs

of the results generated between each of the three designs, all were combined into one single Simulink simulation to run in parallel and display the outputs side by side for ease of comparison and analysis. The combined design, shown below in Figure 13, also shows the complimentary outputs of each design, with the common step input.

Close examination of the three TF output waveforms show a near identical output on the three and two-stage design with a very slight difference in the final, single-element design.

4. Discussion

4.1 Initial and Two element designs

The output of the Initial and the Two Element design 'Add' function shows the difference between the Step input function and the TF output. These are shown in the second trace of Figures 7 & 12. This is the error signal driving the PID and TF. They both show an almost vertical rise on the application of the step function followed by an almost as rapid decrease to, and though, zero in an almost mirror of the TF output. These error signals, and the attempted recovery applied by the PID and TF to normalise the output with respect to the step change is as expected.

While these results fall within the assigned criteria of two

second normalisation with an overshoot of less than 5%, both TF outputs (Trace 4) in Figures 7 & 12 drop slightly below the desired Step input level of 1.0 after approximately 1 second. Close examination of both traces show a very slow decline and consequent recovery toward the desired value but 8 seconds after the output dropped below 1.0, the TF output has still not completed the first cycle through the desired output value. While the cliff-like curve and initial overshoot of the TF output signals were expected, the long, slow ripple after the main change in output was not expected.

4.2 Nyquist and PZ Plot diagrams

The scope results shown in the TF output of the Initial design (Figure 7, Trace 4) imply the system will be stable. Therefore, the Nyquist plot should show the $(-1,0)$ point above the curve, verifying the stability.

However, as the TF function (Eqn. 2) does not contain an 's' term, there can be no Zero plots. Combining the PID and TF

functions in Eqn. 3 provide an s term in the numerator, providing both Poles and Zeros in the corresponding PZ Plot for the two element design. (Figs. 10 & 11)

Examination of the Nyquist Plot for the Two element design TF (Figs. 8 & 9) does show the $(-1, 0)$ point well above the curve, confirming system stability.

Examination of the PZ Plot (Figs. 10 & 11) shows a complex pole pair at $(-0.1, \pm j1)$ and a zero pair at $(-0.15, 0)$ and $(-0.6, 0)$. As the pole pair is only -0.1 from origin, the damping effect should be quite muted and with the amplitude of $\pm j1$, the subsequent oscillations should be relatively small in amplitude.

Prior examination of the Simulink Two element design output trace corroborates the mathematical expectations. Upon detailed examination of the PZ plots, two unexpected poles

were found at $(0, 0)$ and $(-74, 0)$. The nature of this data has not yet been identified and requires further investigation.

4.3 Single element design

Careful examination of the TF output waveforms for each of the three designs (Fig. 13) shows a small and unexpected difference between Traces 2 & 3 and Trace 4. It can be seen that the Single element output trace drops below the desired step value of 1.0 almost 0.2 seconds before the Initial and Two element designs and does not begin recovery from its lowest point until almost 1.2 seconds after the Initial and Two element designs have begun recovery to the desired step value.

This difference in results displayed by what should be exactly the same control systems was not expected. Additional investigation of the PID tuning may be required.

5. Conclusion

All three control system transfer functions performed within the desired parameters. The stability of the system was proven using the Nyquist plot and the performance verified by the pole locations on the PZ plot.

The minor aberrations noted in the Single-element output waveform, while within tolerances, are worthy of further investigation.

The cause and effect of the unexpected poles displayed at $(0, 0)$ and $(-74, 0)$ has been identified. An initial search for information regarding this occurrence did not bring forth any pertinent explanation. However, it has since been discovered that a fourth order polynomial denominator will produce additional poles. In this instance, the denominator polynomial in question is $5s^4 + 371.9s^3 + 79.18s^2 + 370.9s = 0$. (Eqn. 4) With this information it was possible to refine search parameters and a Massachusetts Institute of Technology

(M.I.T.) Department of Mechanical Engineering presentation paper entitled "Understanding Poles and Zeros"^[5] was found.

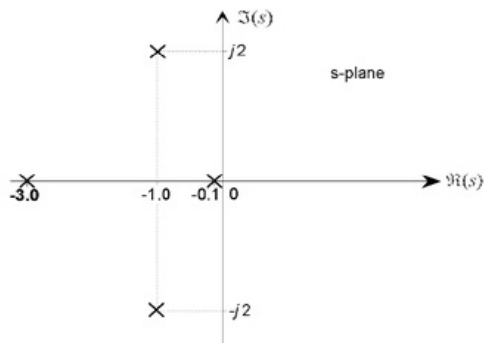


Figure 14: PZ plot of a fourth-order system with two real and two complex conjugate poles

Careful analysis of Figures 10, 11 and 14 show similar characteristics and so explain the appearance of additional poles in the PZ plot. The unexpected nature of these additional poles can be traced to the practical application of the complex nature of solving a fourth order polynomial.

However, it must be emphasised that the control system has performed almost entirely as expected and completely within specified limits.

6. References

1. Dr. Bruce Postlethwaite. "On-Off Control" Internet: http://www.online-courses.vissim.us/Strathclyde/onoff_control.htm [05/06/17].
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Good abstract

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Do you mean %?

PAGE 6

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...in the numerator

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RESEARCH-INFORMED LITERATURE

-  Inclusion of a range of research-informed literature, including sources retrieved independently. Referencing conventions mostly consistently applied. **2.75**

KNOWLEDGE AND UNDERSTANDING

-  Knowledge is extensive. Exhibits understanding of the breadth and depth of established views. **20.4**

ANALYSIS

-  Sound, logical, analytical thinking; synthesis and evaluation. Ability to devise and sustain persuasive arguments, and to review the reliability, validity & significance of evidence. Ability to communicate ideas and evidence accurately and convincingly. Sound, convincing conclusions / recommendations. **20.1**

PRACTICAL APPLICATION AND DEP.

-  A very good application of a range of methods, materials, tools and/or techniques. Very good consideration of the context of the application, with perceptive use of examples, where relevant. Evidence of some innovation and creativity. **16.75**

SKILLS FOR PROFESSIONAL PRAC.

-  Can communicate professionally and, confidently in a suitable format. Work is coherent, very fluent and **7.5**

is presented professionally.