

Instrumentation and control

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There was requirement for a control system design capable of controlling a process defined by the assignment brief. The control system was able to bring the process under control within the defined constraints. A mathematical model was implemented to critically analyse the response given, additionally the simulation was excised in MATLAB and Simulink software. Slight deviation is shown on close inspection likely the resultant of rounding errors in mathematical execution. Application of theoretical mathematical models in conjunction with simulated models will allow full critical analysis of a system prior to its physical introduction. A base understanding could be sought to the range of responses of each component of the system to enable solution to be sought to meet a requirement.

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1 INTRODUCTION

1.1 SCOPE

There was Requirement for a control system design capable of controlling a process detailed in 2. Following a simplified construct defined by the assignment brief, the control system was able to bring the process under control within the defined constraints. The constraints were; stability was achieved in under two seconds, an overshoot of less than 5%. Following this a mathematical model was implemented to critically analyse the response given when the simulation was excised in MATLAB and Simulink software.

1.2 P.I.D. APPLICATIONS

First introduced into control systems in 1939 the Proportional-Integral-Derivative (P.I.D.) controller remains the most widely used industrial system control unit. An appropriately and correctly tuned P.I.D. controller will essentially enable plant to maintain a steady state between two process variables such as an upper and lower temperature limit or pressure limit et al. The ideal state is referred to as the set point and is ascertained by the block output adjusting itself to combat the error in the control loop. Incorrect tuning can lead to instability through transient oscillation of the signal. As alluded too, applications for P.I.D. controllers are wide and varied and can be found on most simple plant function be it temperature/humidity control, speed of a motor, pressure or flow. [1, 2, 3,4]

1.3 THEORY

1.3.1 Process control

Process control is defined primarily by two typed of system: open loop systems; a system where only input is put into the feed and no return signal is received to enable the dynamic calculation and corrective action to maintain the desired set point. The remnant and focus of this document is known as a closed loop system.

Closed loop systems exist in a myriad of formats as suggested in 1.2, a closed loop system will retain the ability to monitor system output; this feedback system will allow the controller to assess the system conditions, attain an error signal from varied ratios of input and output depending on the feedback system be it a positive feedback system or a negative feedback system.

Feedback systems enable the controller to assess the action required and its magnitude to enact the systems steady state around the desired set point within the upper and lower parameters of the process variables. A negative feedback system will log the input signal value and will subtract the output signal received through the feedback loop from it to ascertain the remnant control measures to be exacted on the system.

A negative feedback system can be represented by the transfer function:

$$\frac{G}{1 + GH}$$

Negative feedback systems generally will not be as sensitive being gain has diminutive effect to the transfer function.

Positive feedback systems will take a percentage of the output signal and add it to the output signal received through the feedback loop to calculate the required control measures. [3,5, 6, 7]

The positive feedback system was represented by:

$$\frac{G}{1 - GH}$$

1.3.2 Closed loop system control

As focus of this document closed loop systems retain a multitude of methods:

Control method	Description
Discrete Control	The received error signal will cause the controller to turn the plant on or off as appropriate to enact a corrective measure to acquire the desired set point.
Three state controller	As discrete control with the addition of a '50% on' function to its application of corrective measure to achieve the desired set point
Proportional (P)	Gain derived error signal is generated and a proportion of the error signal to control the output for set point acquisition the proportional response will have remnant steady state error of considerable magnitude that will require manual rectification
Proportional–Integral (PI)	As a proportional controller however Proportional – Integral controllers use the integral of the error signal to remove aforementioned proportional steady state error Integral control require a history of application signals before stability is achieved this can be a time-consuming process
Proportional–Derivative (PD)	Proportional– Derivative controllers use the derivative of the error signal to control the amount of overshoot the application is improvement of stability but retains the steady state error of a proportional system. Application of a derivative only system is not possible due to constant deviation resulting in no application of control
Proportional–Integral – Derivative (PID)	"PID controllers use the absolute error value, the integral of the error, and the derivative of the error to control the process value. The proportional control takes account of the current error, the integral control takes account of the accumulation of previous errors, the derivative control takes account of the possible future errors due to overshoot" [3]

Mathematical representation of P.I.D control;

$$V = -(k_p\theta + k_i \int \theta dt + k_d \frac{d\theta}{dt})$$

Alteration in gain of the Proportional, Integral, and Derivative elements (k_p, k_i, k_d) enables control to be applied for different conditions and applications. The controller can be configured to provide stable responsive control to a system or plant application [3, 8, 9, 10]

1.3.3 Root locus

Root locus provides a graphical representation of the poles in a closed loop system, it provides detailed analysis of transient performance and stability enabling the alteration of parameters in a controlled and predicted manner. It details the movement of system poles in a closed system when change is applied. [3, 11]

1.3.4 Stability

Stability in control systems is in reference to its ability to retain operation within the parameters of its process tolerances around the desired set point. The addition of delay propagates lag within the system meaning control measures that may be time sensitive may not be applied at the correct moment further exacerbating the lag causing instability, a way to analyse this is through gain and phase margin. Available tools to predict the stability of a system could be but not limited to: [3,11]

- Pole zero plots
- Nyquist plots
- Nichols chart
- Bode plots

1.3.5 Lag

Lag can be an integral cause of system failure so must be appropriately defined and assessed, system lag can be categorised into three prevalent criteria:

Transfer lag; the lag that occurs from a signals transfer through a component or plant system, the delayed output relative to its input.

Distance velocity lag; essentially a delay in the signal indication from a prior point in the system to a latter position. Its occurrence and magnitude are relative to proliferation of signal over a time period

Measurement Lag; lag caused by the measuring system itself

As alluded to in 1.3.4. propagation of lag within a system can cause low reactivity due to extension of reactive function to correct a non-conformance within the defined parameters around the set point leading to inaccuracy and potential failure should a cumulative oscillation be in process. [3,11, 12, 13, 14]

1.3.6 Transfer Functions

Transfer functions are a mathematically derived model that defines system operation; the transfer function usually represents a plant unit and its definition is usually the ratio of output relative to input otherwise referred to as gain.

$$\text{Transfer Function} = \frac{\text{Output Value}}{\text{Input Value}}$$

Laplace transforms simplify time domain response of a system process investigation. [3, 11,15, 16, 17, 18]

1.4 LIMITATIONS

Defined within the context of this document is the fact that this exercise is a simulation and comparative theoretical exploration. There is no account for the reality of a system such as this as it was an idealised system with no account for loss. A real world non idealised system would likely encounter loss and a varied output to multiple nodules and sympathetic hubs over the timescale of operation and so output and block response may vary somewhat. [1,3,4,11,14]

2 METHODOLOGY

For the purpose of this assignment the industrial process to be simulated is represented by the process transfer function $G(s)$

$$G(s) = \frac{1}{as^2 + bs + c}$$

The variables in the denominator of the process transfer function were defined by the assignment brief [3,19.]:

Student ID	<i>a</i>	<i>b</i>	<i>c</i>
1810310	2	2	5

2.1 TASK 1

2.1.1 Fabrication of the system

In order to run the simulation initially a system was fabricated within the simulation software; MATLAB and Simulink. The control system was comprised initially of a step source, this fed to a math operation; in this case this operation was an 'add' meaning the application of a positive feedback system. Following in linear fashion came the continuous P.I.D. controller and the continuous transfer function, the feedback loop was positioned from the output of the transfer function into the aforementioned math operation 'add' module (negative terminal).

2.1.2 Defining the system

The system components required some modification in that; the maths operation required a positive and negative input port to receive the feedback signal. The P.I.D. controller had its filter coefficient set to 1 prior to tuning and the process transfer function was input into the transfer function module

2.1.3 Monitoring the system

A scope was added with 4 input ports, each with a specific point of interest in the system:

1. Input
2. Error signal
3. P.I.D. controller output/block response
4. Output of the system

2.1.4 System assessment

The completed system as shown in figure 1? Was simulated to run for ten seconds: results for this simulation are detailed in 3.1.1.

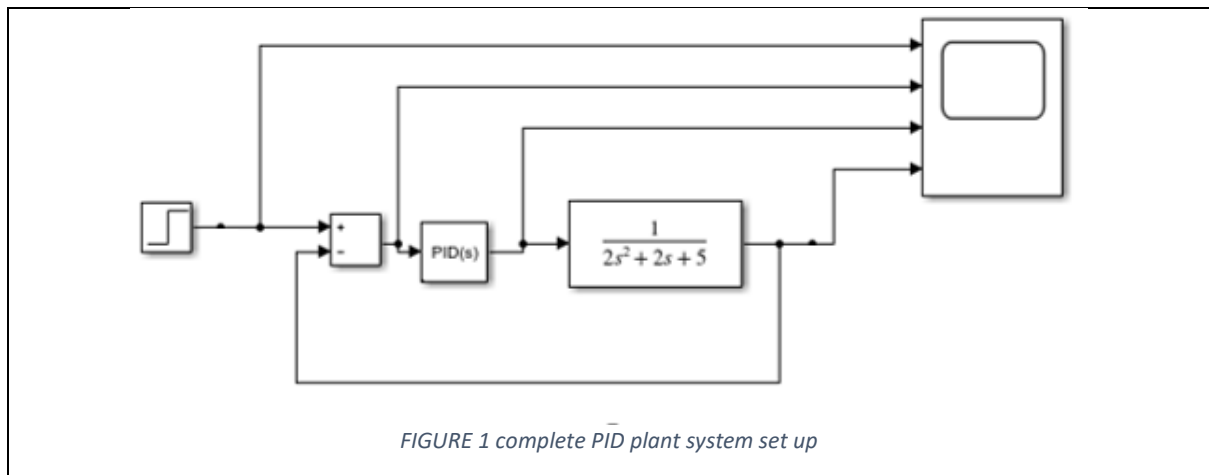


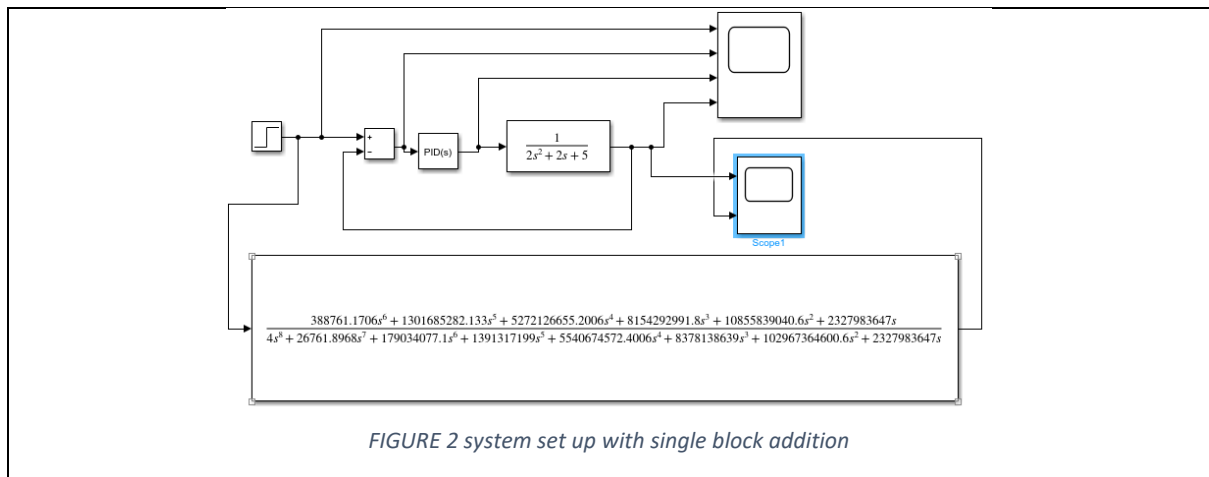
FIGURE 1 complete PID plant system set up

2.1.5 Tuning and post modification assessment

Following definition of the system tuning was required to enable the simulation to meet the requirements defined in the assignment brief. This was completed by a transfer function based automatic P.I.D. tuner application within MATLAB, sliders were used to dynamically assess the controller parameters until through trial and error adjustment of speed of reaction and stability; requirement was met. Once these parameters had been applied to the P.I.D. controller the system was simulated to operate for 10 seconds. The results for this simulation are retained in 3.1.3.

2.2 TASK 2

Validation of the system referred to in task 1 was required; this envisaged the operation of a simulant mathematical model in the form of a theoretical exploration. Parameters were acquired from defined points of task 1 and transformed into a singular transfer function for assessment through the simulation process. To enable the simulant validation of the system it would need to retain only the input, continuous transfer function and scope. For completeness a feed was taken from step input from task 1 to a single continuous transfer function through to a new scope and a feed to the output from task 1 to allow overlay and direct comparison; the set up can be seen in figure 2 below



3 RESULTS

3.1 TASK 1

Task 1 was completed as detailed in 2.1. using MATLAB and Simulink to achieve stable state from transient within two seconds and to achieve no more than a 5% overshoot in terms of amplitude.

3.1.1 Initial state

For the initial state the set up was detailed as per 2.1.1 – 2.1.4. where definition of the system was required through system assessment, the resultant graphical output is shown in figure 3.

The graphs are shown in order listed below.

1. Input
2. Error signal
3. P.I.D. controller output/block response
4. Output of the system

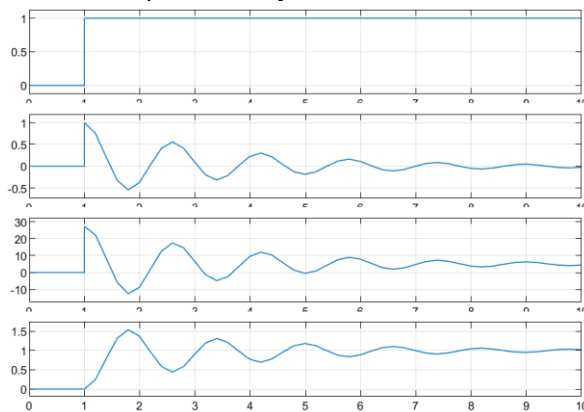


FIGURE 3 initial state graphical output

The top graph denotes step input wherein the signal is input it shows the application of signal that is sustained throughout the full simulation.

The following graph shows the error signal received and its degrading oscillation that begins to attain stability by the end of the simulation.

The next shows the output of the P.I.D. controller wherein it tries to combat the oscillation.

The final shows the plant output as a culmination of the input modified by the error signal and P.I.D. controller again this follows the second and third graphical representation.

3.1.2 Tuning

As mentioned in 2.1.5 methodology defined the application of tuning the P.I.D. note should be given to the Tuning Compensator formula.

$$P + I \frac{1}{s} + D \frac{N}{1+N \frac{1}{s}}$$

Explored and assessed in 3.2.1. theoretically; expectation to get and enable accurate delivery of results slight error was expected due to application of clerical rounding errors during function however, resultant graphical representation should be somewhat similar in appearance in 3.1.3.

Controller Parameters		
	Tuned	Block
P	177.4557	20.646
I	41.6309	15.0337
D	58.071	6.5481
N	3344.2371	1
Performance and Robustness		
	Tuned	Block
Rise time	0.0639 seconds	0.313 seconds
Settling time	0.33 seconds	10.4 seconds
Overshoot	3.92 %	54.1 %
Peak	1.04	1.54
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	85.5 deg @ 29.3 rad/s	12.1 deg @ 3.92 rad/s
Closed-loop stability	Stable	Stable

FIGURE 4 controller parameters

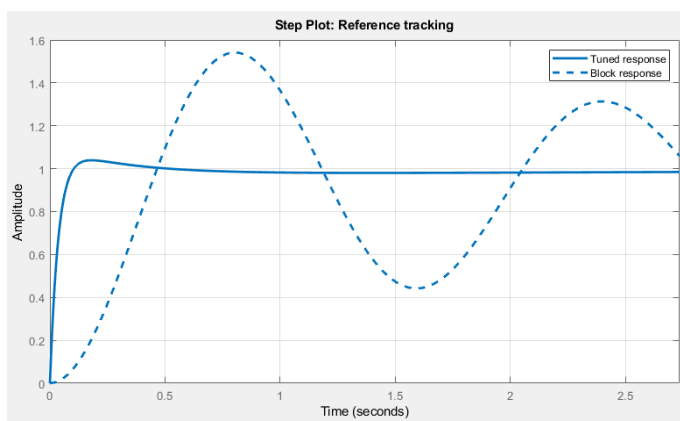


FIGURE 5 block v tuned system response

Controller parameters (figure 4) defined the necessary tuning required to enable the simulant P.I.D. to bring the plant into its operational constraints demonstrated in figure 5 where the untuned oscillation can be seen to be shown against the post tuning constrained and controlled output.

3.1.3 Tuned

Following the application of methodology detailed in 2.1.5. the resultant graphical output is shown in figures 6 and 7 the signatures detailed in 7 are arranged as previously referred to in 3.1.1.

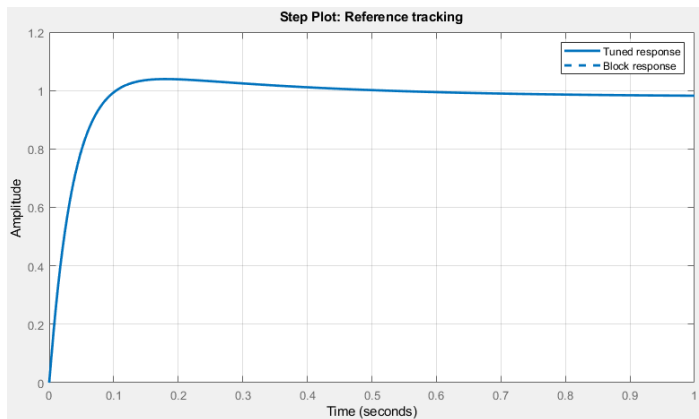


FIGURE 6 tuned system output

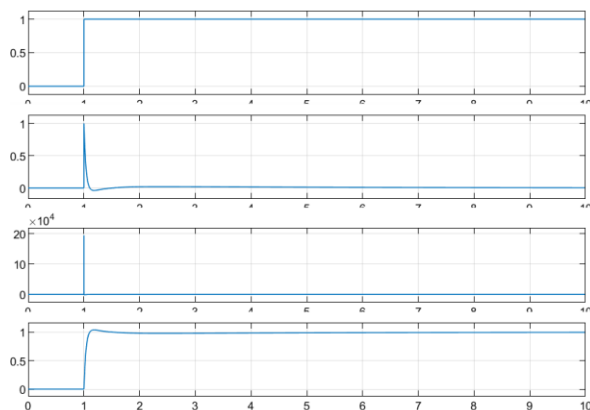


FIGURE 7 tuned output graph

The top graph denotes step input wherein the signal is input it shows the application of signal that is sustained throughout the full simulation.

The following graph shows the error signal received this time as a spike before the error has been quashed by the output of the P.I.D. controller returning the error signal to zero following a minor undershoot.

The next shows the output of the P.I.D. controller enacting a control spike to actively combat any error demonstrated from the plant output.

The final shows the plant output as a culmination of the input modified by the error signal and P.I.D. controller this time showing a likeness to the input signal from the step source denoting minimal error.

3.2 TASK 2

Validation of the system referred to in task 1 was required; this envisaged the operation detailed in 2.2 for assessment through the simulation process. 3.2.1. details the steps taken to the mathematical model exploration and 3.2.2 details the simulant validation process results.

3.2.1 Theoretical exploration

$$\text{process transfer function} = G(s) = \frac{1}{as^2 + bs + c}$$

Taking $a = 2$, $b = 2$, $c = 5$

$$\text{process transfer function} = G(s) = \frac{1}{2s^2 + 2s + 5}$$

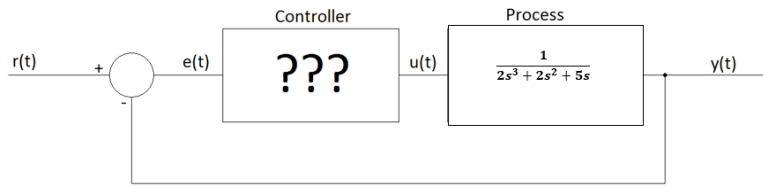


FIGURE 8 block diagram modified [3]

Using the PID tuner in MATLAB, the following values were obtained:

Kp:	177.455665234007
Ki:	41.6309207688729
Kd:	58.0710337097158
N:	3344.23710894482

Controller transfer function (PID):

$$K_p + K_i \frac{1}{s} + K_d \frac{s}{\frac{1}{N}s + 1}$$

$$177.4557 + \frac{41.6309}{s} + 58.0710 \frac{s}{\frac{1}{3344.2371}s + 1}$$

forward path transfer function = controller transfer function x process transfer function

$$\left(177.4557 + \frac{41.6309}{s} + 58.0710 \frac{s}{\frac{s}{3344.2371} + 1} \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\left(177.4557 + \frac{41.6309}{s} + 58.0710 \frac{s}{\frac{s + 3344.2371}{3344.2371}} \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\left(177.4557 + \frac{41.6309}{s} + 58.0710 \left(s \div \frac{3344.2371}{3344.2371} \right) \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\left(177.4557 + \frac{41.6309}{s} + 58.0710 \left(s \left(\frac{3344.2371}{s + 3344.2371} \right) \right) \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\left(177.4557 + \frac{41.6309}{s} + 58.0710 \left(\left(\frac{3344.2371s}{s + 3344.2371} \right) \right) \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\left(177.4557 + \frac{41.6309}{s} + \left(\frac{194203.1926s}{s + 3344.2371} \right) \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\left(\frac{((s(s + 3344.2371) \times 177.4557) + (s + 3344.2371)41.6309 + s(194203.1926s))}{s(s + 3344.2371)} \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\left(\frac{177.4557s^2 + 593453.9355s + 41.6309s + 139223.6003 + 194203.1926s^2}{s^2 + 3344.2371s} \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\left(\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{s^2 + 3344.2371s} \right) \times \left(\frac{1}{2s^2 + 2s + 5} \right)$$

$$\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{(s^2 + 3344.2371s)(2s^2 + 2s + 5)}$$

$$\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 2s^3 + 5s^2 + 6688.4742s^3 + 6688.4742s^2 + 16721.1855s}$$

$$\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}$$

The block diagram can be demonstrated as per figure 8:

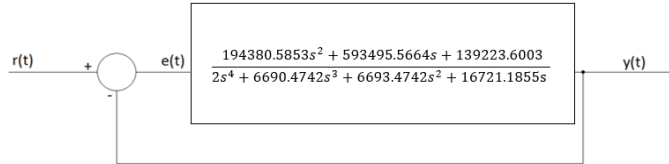


FIGURE 9 block diagram with feedback loop

Removal of the feedback loop and calculation of the transfer function of the entirety of the system.

$$TF = \frac{G}{1 + GH}$$

TF = transfer function of the system whole,

G = forward path transfer function

H = transfer function of the feedback loop = 1

$$TF = \frac{\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}}{1 + \left(\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{(2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s)} \right) \times 1}$$

$$TF = \frac{\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}}{1 + \left(\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{(2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s)} \right) \times 1}$$

$$TF = \frac{\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}}{\frac{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s} + \frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}}$$

$$TF = \frac{\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}}{\frac{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s} + \frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}}$$

$$TF = \frac{\frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}}{\frac{2s^4 + 6690.4742s^3 + 201074.0595s^2 + 610216.7519s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}}$$

$$TF = \frac{194380.5853s^2 + 593495.5664s + 139223.6003}{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s} \times \frac{2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s}{2s^4 + 6690.4742s^3 + 201074.0595s^2 + 610216.7519s + 139223.6003}$$

$$TF = \frac{(194380.5853s^2 + 593495.5664s + 139223.6003)(2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s)}{(2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s)(2s^4 + 6690.4742s^3 + 201074.0595s^2 + 610216.7519s + 139223.6003)}$$

$$TF = \frac{388761.1706s^6 + 1300498291s^5 + 1301081433s^4 + 3250273824s^3 + 1186991.133s^2 + 3970766775s^4 + 133869484s^6 + 44782516.44s^5 + 1345884030s^4 + 4084470085s^3 + 931889576.6s^2 + 33442.371s^5 + 111872660.2s^4 + 3362196648s^3 + 102035475000s^2 + 2327983647s}{(2s^4 + 6690.4742s^3 + 6693.4742s^2 + 16721.1855s)(2s^4 + 6690.4742s^3 + 201074.0595s^2 + 610216.7519s + 139223.6003)}$$

Collecting like terms

TF

$$= \frac{388761.1706s^6 + 1301685282.133s^5 + 5272126655.2006s^4 + 8154292991.8s^3 + 10855839040.6s^2 + 2327983647s}{4s^8 + 26761.8968s^7 + 179034077.1s^6 + 1391317199s^5 + 5540674572.4006s^4 + 8378138639s^3 + 102967364600.6s^2 + 2327983647s}$$

The block diagram representation as a single block.

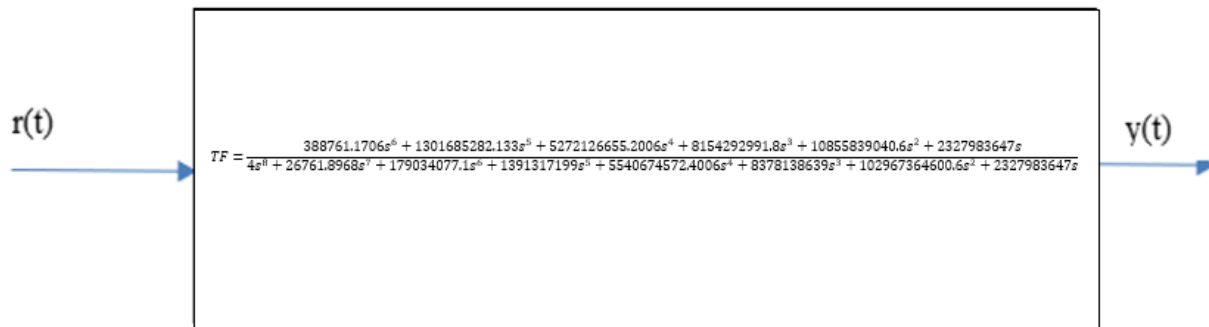


FIGURE 10 block diagram with feedback loop removed

3.2.2 Simulink

The application of methodology in 2.2 demonstrated the delivery of a similar graphical output from both the theoretical mathematical model and Simulink computer model (Fig 10, 11, 12) negligible deviation was noted at close proximity inspection however as indicated in 3.1.2. this was suggested to be clerical rounding error.

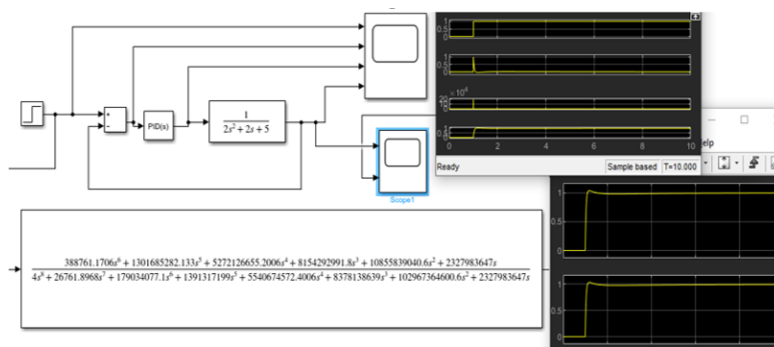


FIGURE 11 Simulink result

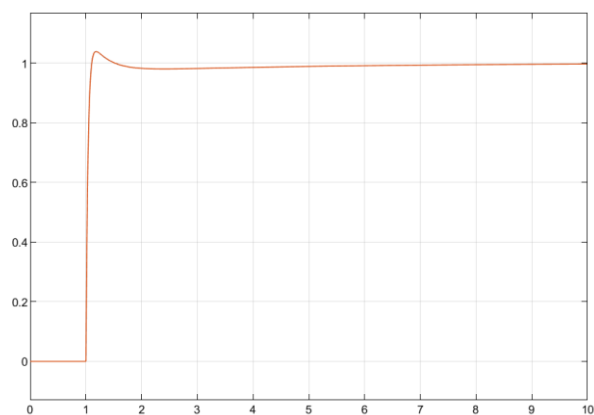


FIGURE 12 dual output overlay

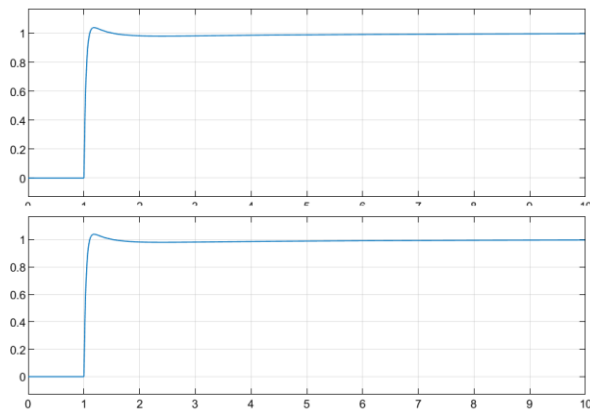


FIGURE 13 dual output separate

4 DISCUSSION

The maths was the same results were mirrored from tuned state in 3.1.3 and when results from 3.2.1 were entered into Simulink 3.2.2 slight deviation is shown on close inspection this is likely the resultant of rounding errors in mathematical execution. Application of theoretical mathematical models in conjunction with simulated models is an apparent methodology for conceptual testing of control systems operation. Different operational constraints and challenges can be modelled and assessment made as to the reaction of the system as to relevance of a closed loop system.

5 CONCLUSION

Application of theoretical mathematical models in conjunction with simulated models will allow full critical analysis of a system prior to its physical introduction. A base understanding could be sought to the range of responses of each component of the system to enable solution to be sought to meet a requirement The application of a honed transfer function will enable the application of a high functioning open loop system at a lower physical cost than a fixed closed loop system.

6 REFERENCES

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