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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 13 Issue 9, September 2024

Modelling of a Controller for Effective Flow Monitoring in Process Industry

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Abstract— **Flow in a process industry is characterized with issue of frictional force in the medium the fluid is being transported, the flow condition often become turbulent instead of being laminar which is easier to control, thereby creating pressure loss which leads to loss of time and output products. In this research, Direct Synthesis (DS) method is used, while the tools used include: Proteus version 7.6, MatLab/Simulink software, LabVIEW Control Design and Simulation Module. A Proportional Integral Derivative (PID) and Distributed Control System (DCS) controllers are utilized in order to control the flow rate of the process fluids by controlling the loss in pressure due to frictional forces in the transport medium to ensure that the flow remains in laminar condition. Firstly, the PID was modeled, and the PID controller was designed and configured into the flow system, then it was simulated using MatLab/Simulink software and the performance showed that when the PID was independently controlling the flow system, there was over shoot which was overcome after some wasteful time before achieving stability. Secondly, DCS was used independently in the flow loop and was simulated using Proteus software. The performance was observed in the software environment and it showed that when DCS was used independently, it had a good control efficiency but some percentage of transient and overshoot was noticed from the output result. Thirdly, the DCS and the PID were installed together and simulated using LabVIEW and the results obtained showed that the cascading of the two controllers reduced the over shoot drastically, attained stability faster and the problems of drag and pressure loss were eliminated in a very short time. The research work achieved 99 percent of the results anticipated as all the specific objectives were achieved. The research was validated using Routh- Hurwitz stability criterion.**

Keywords: **Process Flow control, PID controller, DCS controller, Modelling, Direct synthesis method.**

I. INTRODUCTION

The ability to control a flow field to achieve a desired result is of great importance, and to actualize optimum output and stability when fluid is being transported, adequate and reliable flow control becomes necessary. Maintaining proper flow of fluids in a process system, is essential to maintain correct supply of raw materials to reactors, correct supply of water or steam for cooling or heating purpose etc [1].

The factors affecting flow measurement are conductivity, temperature, pressure, and viscosity. It can affect certain types of flow meters. How clean or dirty the fluid may be, it could also impact on the type and style of meter [2]. In choosing a flow meter, one advice is to thoroughly understand the characteristics of the flow to be measured. Types of Flow Meters include Coriolis, DP Meters, Magnetic Meters, Multiphase Meters, Ultrasonic Meters, and Vortex Meters [3].

The dynamic behavior of industrial plants heavily depends on disturbances and in particular on changes in operating point [4]. In many industrial processes, control of liquid flow or temperature control is required. Classic PID approaches as well as controllers are updated and expanded over the years, from the primary controllers on the basis of the relays as well as synchronous electric motors or pneumatic or hydraulic systems to current microprocessors [5].

Currently, many techniques for the tuning as well as design of PI and PID controllers are proposed [6]. The method proposed by [7] is the most widely utilized PID parameter tuning methodology in chemical industry and is considered as a conventional technique. Flow management encompasses a big selection of application in method industries. In 90% of method management, applications have a tendency to manipulate the flow to get desired output. Flow is dynamic parameter and has totally different standardization strategies for standardization [8].

There are three tuning parameters for PID and it is also known as a three-term controller. The three parameters are proportional gain, integral gain and derivative gain. These three parameters affect in different ways the stability of system. So, the controller has to maintain the process variable close to desired set point, [9]. Currently, there is a special linear structure deployed with sensors on pipelines to monitor and regulate flow and pressure. They demonstrated a multilayer communication scheme that ensures the effective routing of data among the sensors but there is no consideration of control valve and proper controllers among the sensor based remote communication networks which involves manual operation to achieve desired performance of pipeline transportation [10].

Summary of review of related works

[11] The authors actually worked on the process flow control but emphasis was on vibration in the pipe which could be harmful or alter the stability of the system. No attention was given to other numerous problems associated with flow of a process system.

[12] From their analysis and conclusion, they worked on using PID to control flow in multiple tank staking. Emphasis on how different errors were articulated was not shown.

[13] The authors attributed that Flow control subsumes all types of technical flow control including laminar flow control, mixing enhancement, separated flow control, vortex control, turbulence

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control, heat transfer control, favorable wave interference, designer fluids and much more. Their work was generic in approach, in process flow control, there are specific errors that need to be eradicated to have robust flow void of losses.

[14] Their work basically depicts using DCS AND MATLAB to actualize the set objective. Even when DCS is used in the control system, agitations are bound to be there as a result of errors emanating due to disturbance from the system flow

[15] Their work was not streamlined to a particular area of process. Process flow has so many dimensions either flow in pipes, tunnels, tanks, bottles, cylinders etc. There was no particular emphasis to know where the mitigation approach is channeled to.

II. METHODS

The results obtained is crucial to process industries and as a result, validation of stability is required. Routh Hurwitz stability criterion shall be used to validate the design.

Modeling of Flow Measuring Device

In considering measuring device, the average velocity of the medium has to be known. The value of the average velocity V_{avg} at some stream wise cross-section is determined from the requirements of the conservation of mass principle. Equation (1) shows the expression for the mass flow rate, according to [16]

$$\dot{m} = \rho V_{avg} A_C = \int_{A_C} \rho U(r) d\, A_C \quad (1)$$

Where: $\dot{m}$ = Mass flow rate, ρ = Density of the fluid, A_C = Cross Sectional Area, $U(r)$ = Velocity Profile.

The average velocity for flow in a circular pipe of radius R according to [16] can be expressed as:

$$V_{avg} = \frac{\int_{A_C} \rho U(r) dA_C}{\rho A_c} = \frac{\int_0^R \rho U(r) 2\pi r dr}{\rho \pi R^2} = \frac{2}{R^2}\int_0^R U(r) r dr \quad (2)$$

Therefore, when we know the flow rate or the velocity profile, the average velocity can be determined easily.

Orifice Meter

For this research, Orifice meter was considered. This flow measuring device is created by inserting an obstructing plate, usually with a round hole in the middle, into the pipe and measuring the pressure on each side of the orifice. Pressure taps on each flange allow you to easily measure the pressure differential across the plate. This pressure differential, along with the dimensions of the plates are combined with certain fluid properties to determine the flow through the pipe.

Figure 1 shows samples of the several types of orifice plate used for flow measurement.

Fig. 1: Samples of several types of orifice plate [3]

To obtain the flow rate, equation (3) is applied

$$Q = C_d \sqrt{\frac{2(P_1 - P_2)}{\rho} \times \frac{A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}}} \quad (3)$$

Where: Q = Flow rate, P_1 = Upstream pressure, P_2 = Downstream pressure, C_d = Discharge coefficient (This is the point at which the flow turns turbulent in the medium), A_1 = Area of the orifice at upstream, A_2 = Area of the orifice at downstream

Determination of flow profile in the downstream is cumbersome, therefore substitution of C_d and the area with C_f becomes necessary. Thus

$$Q = C_f A_0 \sqrt{\frac{2\Delta P}{\rho}} \quad (4)$$

To account for the outlet loss, equation (5) is applied

$$Q = CDVA \quad (5)$$

where: Q = flow rate, V = average velocity, A = cross-sectional area of the pipe and CD is the discharge coefficient that is dependent on the shape and size of the orifice.

Frictional losses. They are losses from liquid flow in a pipe due to friction between the flowing liquid and the restraining walls of the container. These frictional losses are given by:

$$h_L = \frac{fLV^2}{2Dg} \quad (6)$$

Where: hL = head loss, f = friction factor, L = length of pipe, D = diameter of pipe, V = average fluid velocity, g = gravitation constant.

Form drag is the impact force exerted on devices protruding into a pipe due to fluid flow. The force depends on the shape of the insert and can be calculated from

$$F = C_D \gamma \frac{AV^2}{2g} \quad (7)$$

Where: F = force on the object, C_D = drag coefficient, g = specific weight, g = acceleration due to gravity, A = cross-sectional area of obstruction, V = average fluid velocity

Modelling of Flow Controllers

The methodology of internal mode principle is utilized in order to extract the gains of PID and PI controllers. Exhaustive investigation from literatures revealed that the outcomes of P control are very sensitive to the sensing location as well as the quantity of phase shift. By suitable selections of these variables, the P control can be completely efficient in annihilating the vortex shedding or minimizing its strength.

In order to implement the control law, the primary step is to determine a desired output response of a particular system to an arbitrary input over a time interval that can be carried out by system identification. Generally, it is feasible to generate a model on the basis of a complete physical illustration of the system.

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International Journal of Engineering Research & Technology (IJERT)
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PID electronic controller

In any electronic setup, there are two basic blocks which are analogue and digital. Digital systems are built on the basis and foundation of analogue blocks. So first we consider the analogue. Figure 2 shows the block diagram of an analogue PID controller. The measured variable from the sensor is compared to the set point in the first unity gain comparator; its output is the difference between the two signals or the error signal. This signal is fed to the integrator via an inverting unity gain buffer and to the proportional amplifier and differentiator via a second inverting unity gain comparator, which compares the error signal to the integrator output. Initially, with no error signal the output of the integrator is zero so that the zero-error signal is also present at the output of the second comparator.

When there is a change in the measured variable, the error signal is passed through the second comparator to the proportional amplifier and the differentiator where it is amplified in the proportional amplifier, added to the differential signal in a summing circuit, and fed to the actuator to change the input variable. Although the integrator sees the error signal, it is slow to react and so its output does not change immediately, but starts to integrate the error signal. If the error signal is present for an extended period of time, the integrator will supply the correction signal via the summing circuit to the actuator and input the correction signal to the second comparator. This will reduce the effective error signal to the proportional amplifier to zero, when the integrator is supplying the full correction signal to the actuator. Any new change in the error signal will still be passed through the second comparator as the integrator is only supplying an offset to correct for the first long-term error signal. The proportional and differential amplifiers can then correct for any new changes in the error signal.

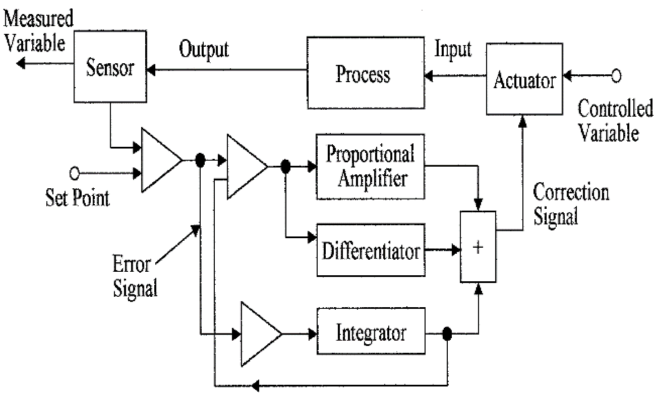

Fig. 2: Block diagram of a PID analogue electronic controller.

The circuit implementation of the PID controller is shown in figure 3. This is a complex circuit because all the amplifier blocks are shown doing a single function to give a direct comparison to the block diagram. In practice there are a large number of circuit component combinations that can be used to produce PID action.

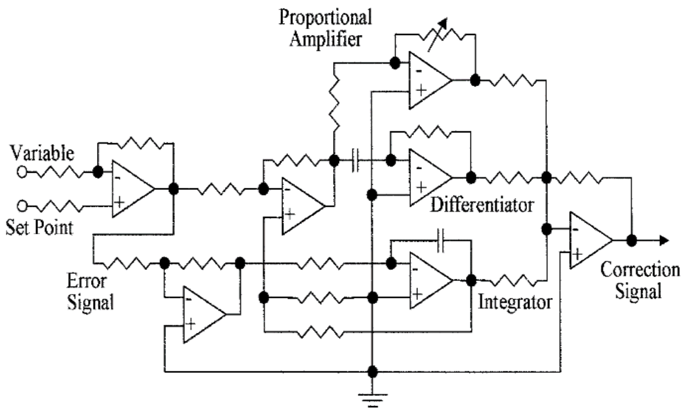

Fig. 3: Circuit of a PID action electronic controller

A single amplifier can also be used to perform several functions which would greatly reduce the circuit complexity. Such a circuit is shown in Figure. 4 where feedback from the actuator position is used as the proportional band adjustment.

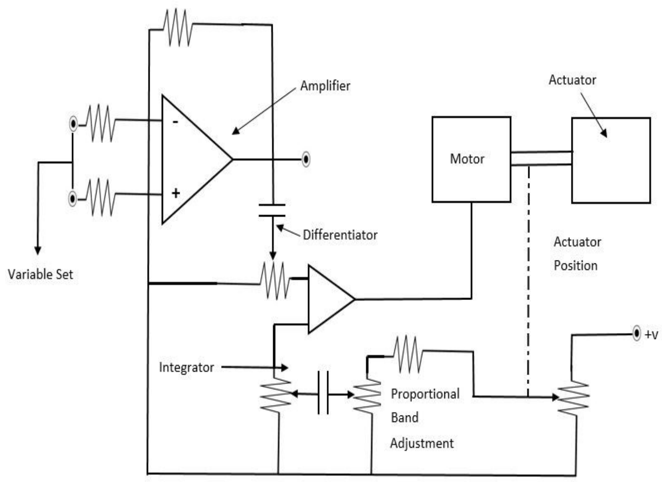

Fig. 4: Circuit of a PID electronic controller with feedback from the actuator position

The major key component of the proposed process is the proportional-integral-derivative controller (PID controller) control loop mechanism, which is widely used in industrial control systems, to mitigate faults by adjusting the process control inputs. Examples of such systems are the ones where the temperature, pressure, or the flow rate, need to be controlled. In such scenarios, the PID controller aims at detecting the possibility of a fault far enough in advance so that an action can be performed to prevent it from happening.

Figure 5 shows the general PID control system loop. The set point is the desired or command value for the process variable. The control system algorithm uses the difference between the output (process variable) and the setpoint to determine the desired actuator input to drive the system.

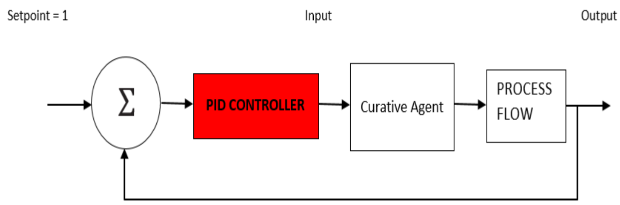

Fig. 5: PID control system loop

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International Journal of Engineering Research & Technology (IJERT)
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Inter Phase Friction Coefficient:

In modeling the PID, certain variables need to be considered. The first is the interface fiction coefficient. The two phases, gas and liquid, slip with respect to each other resulting in the inter phase-friction force, as stated in equation (8)

$$F = D_C \rho B_P V_{slip} \qquad (8)$$

Where: ρ = Density of the gas phase, D_C = Drag coefficient, V_{slip} = The resultant slip velocity, B_P = The total projected droplet area in the cell given by

$$B_P = \left(1.5\frac{V}{d}\right) R_e \qquad (9)$$

Where: d is the droplet diameter, V is the volume of the cell, and R_e is the particle Reynolds number given by

$$R_e = d\frac{V_{SLIP}}{\beta_i} \qquad (10)$$

Where: β_i is the laminar viscosity of the gas, the drag coefficient D_c is evaluated as follows;

$$D_c = max\left[0.42\frac{24}{R_e}(1 + 0.15R_e^{0.68}) + \frac{0.42}{1+(4.25\times10^4)R_e^{-1.16}}\right] \qquad (11)$$

Mass Transfer Coefficient for Fluid Inter Phase:

As cooling of heated areas deals with evaporating fluids due to friction, the loss of mass of the fluid droplets which is the second variable needs to be calculated, see equation (12).

$$\dot{M} = \frac{A\sigma}{C_p D} ln\left(1 + C_p\frac{T_g - T_s}{L}\right) \qquad (12)$$

Where: C_p= The specific heat, which is assumed to be constant for both phases, D = The initial droplet diameter, σ = The thermal conductivity of the fluid droplets, L = The latent heat of evaporation, T_g = The temperature of the gas, T_s = The temperature at the surface of the droplet, A = The interface surface area per cell given by

$$A = \frac{6R_2V}{d} \qquad (13)$$

where R_2 is the liquid volume fraction, V is the cell volume, and d is the droplet diameter.

PID Models

The control signal $u(t)$ (output) is defined as follows:

$$u(t) = K_p e(t) + K_i \int_0^i e(t)\, dt + K_d \frac{de(t)}{dt} \qquad (14)$$

Where K_p is the proportional gain constant, K_i is the integral gain constant, K_d is the derivative gain constant, and *e* is the error defined as the difference between the *setpoint* and the process variable value. For a process fluid, consider the loop in figure 7, where each variable is the Laplace transform of a deviation variable. To simplify the notation, the primes and s dependence have been omitted; thus, *Y* is used rather than Y'(s). Because the final control element is often a control valve, its transfer function is denoted by G_v. *T*he process transfer function G_p indicates the effect of the manipulated variable on the controlled variable. The disturbance transfer function G_a represents the effect of the disturbance variable on the controlled variable for the flow channel.

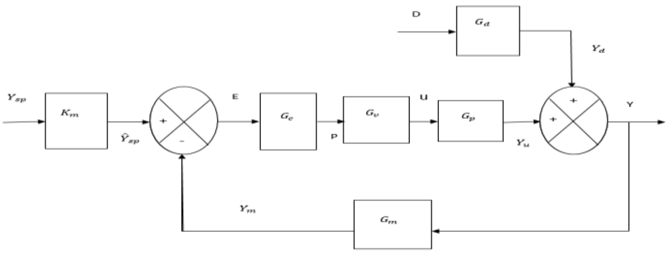

Fig. 6: Block diagram for a process fluid feedback control system. Based on Direct Synthesis (DS) method

The block diagrams considered so far have been specifically developed for the fluid storage system in a process plant.

Where: *Y* =controlled variable, *U* = manipulated variable, *D* = disturbance variable (also referred to as the *load variable), P* = controller output, *E* = error signal, Y_m = measured value of *Y* , Y_{sp} = set point *p,* $\hat{Y}_{sp}$ = internal set point (used by the controller), Y_u = change in *Y* due to *U,* Y_d = change in *Y* due to *D,* G_c = controller transfer function, G_v = transfer function for the final control element, G_P = process transfer function, G_d = disturbance transfer function, G_m = transfer function for sensor add transmitter, *Km* = steady-state gain for *Gm.*

From figure 6, assuming that no disturbance change occurred, it can now be said that D = 0, this follows that:

$$Y = Y_d + Y_u \qquad (15)$$

$$Y_d = G_d D = 0\ (because\ D = 0) \qquad (16)$$

$$Y_u = G_p U \qquad (17)$$

Combining gives

$$Y = G_p U \qquad (18)$$

$$U = G_v P \qquad (19)$$

$$P = G_c E \qquad (20)$$

$$E = \hat{Y}_{SP} - Y_m \qquad (21)$$

$$\hat{Y}_{sp} = K_m Y_{sp} \qquad (22)$$

$$Y_m = G_m Y \qquad (23)$$

Combining the above equations gives

$$Y = G_p G_v P = G_p G_v G_c E = G_p G_v G_c(\hat{Y}_{sp} - Y_m) = G_p G_v G_c(K_m Y_{sp} - G_m Y) \qquad (24)$$

Rearranging gives the desired closed-loop transfer function,

$$\frac{Y}{Y_{sp}} = \frac{K_m G_c G_v G_p}{1 + G_c G_v G_p G_m} \qquad (25)$$

In both the numerator and denominator of Equation. (25) the transfer functions have been rearranged to follow the order in which they are encountered in the feedback control loop. This convention makes it easy to determine which transfer functions are present or missing in analyzing subsequent problems.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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Design of the Flow Controller PID

Direct Synthesis Method: In the Direct Synthesis (DS) method, the controller design is based on a process model and a desired closed loop transfer function.The DS approach provides valuable insight into the relationship between the process model and the resulting controller.

As a starting point for the analysis, consider the block diagram of a feedback control system in Figure. 6 The closed-loop transfer function for set-point changes was derived in equation (25).

Let $G \triangleq G_v G_p G_m$ and assume that $G_m = k_m$ (26)

Then equation (25) becomes:

$$\frac{Y}{Y_{sp}} = \frac{G_c G}{1+G_v G} \quad (27)$$

Rearranging and solving for G_c gives an expression for the ideal feedback controller:

$$G_c = \frac{1}{G}\left(\frac{\frac{y}{Y_{sp}}}{1-\frac{Y}{Y_{sp}}}\right) \quad (28)$$

Desired Closed-Loop Transfer Function

The performance of the controller in Equation (29) strongly depends on the specification of the desired closed-loop transfer function, A practical design equation can be derived by replacing the unknown G by G, and Y/Y_{sp} by a desired closed-loop transfer function, $(Y/Y_{sp})_d$: $(Y/Y_{sp})_d$. Ideally, $(Y/Y_{sp})_d = 1$ so that the controlled variable tracks set-point changes instantaneously without any error

$$G_c = \frac{1}{\tilde{G}}\left(\frac{\left(\frac{Y}{Y_{sp}}\right)_d}{1-\left(\frac{Y}{Y_{sp}}\right)_d}\right) \quad (29)$$

$$\left(\frac{Y}{Y_{sp}}\right)_d = \frac{1}{\tau_c s+1} \quad (30)$$

Where τ_c is the desired closed-loop time constant.

By substituting equation (30) into equation (29), and solving for G_c, the controller design equation becomes

$$G_c = \frac{1}{\tilde{G}}\frac{1}{\tau_c s} \quad (31)$$

PID Hybridized with Distributed Control System (DCS) Controller

Figure 7 illustrates the flow control action when PID is used as a controller while Figure 8 shows the flow control action when PID is cascaded with DCS as a controller.

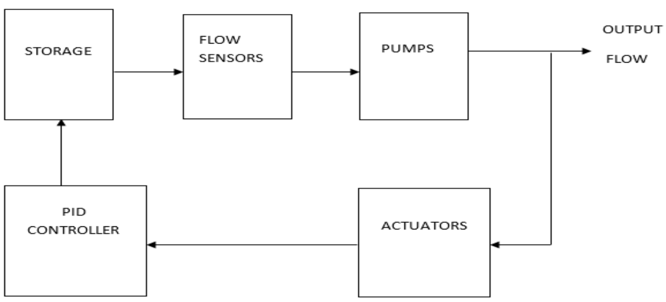

Fig. 7: Flow control action when PID is used as a controller

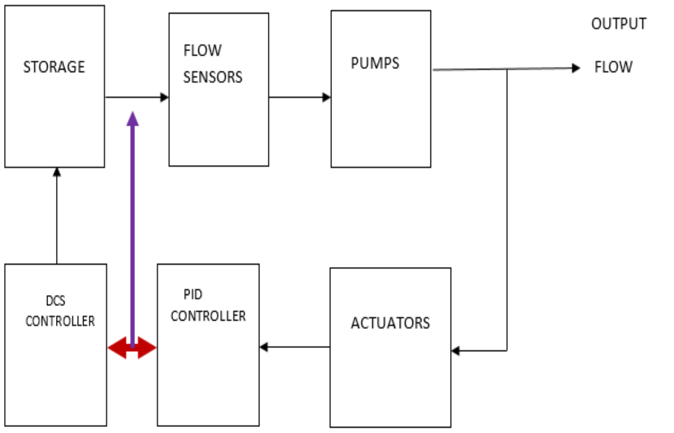

Fig. 8: Flow control action when PID is cascaded with DCS as a controller

For simulation and comparison, the flow system, actuator, valve, flow sensors are mathematically modeled and another experimental data is added. The experimental process data are as follows:

a. Process response to the fluid flow gain -40^{0}C/Kg/Sec
b. Time constants -25 sec
c. Actuator response to variation of process fluid flow gain -2.5^{0}C/Kg/Sec
d. Sensors response to variation of process pressure Control valve capacity for fluid flow -1.8 Kg/Sec
e. Time constant of control valve - 3 Sec
f. Time constant of flow sensor -25 Sec

From the experimental data, the characteristic equation and the gains are obtained as shown in equation (32):

$$G(S) = S^3 + 20S^2 + 30S + 50k \quad (32)$$

III. RESULTS AND DISCUSSION

Test for Stability of the Control System for Validation

Applying Routh- Hurwitz criterion to equation (32), the characteristic equation was obtained as:

$$S^3 + 20S^2 + 30S + 50k = 0 \quad (33)$$

From equation (32), we form the Routh Hurwitz array as

$$\begin{array}{lll} s^3 & 1 & 30 \\ s^2 & 20 & 50K \\ s^1 & \frac{(20)(30)-50K}{20} & 0 \\ s^0 & 50K & \end{array}$$

For the system to be stable, all the coefficient in the first column of the Routh–Hurwitz tabulation must have the same sign. This leads to the following conditions:

$$\frac{(20)(30)-50K}{20} = \frac{600-50k}{20} > 0\ , \qquad \text{and} \qquad 50k > 0$$

Solving for value of K,

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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let $\frac{600-50k}{20} = 0$, Therefore, $600 - 50K = 0$, $K = \frac{600}{50} = 12$

$But\ K > 0$, If we let K = 12,

We will have to find the roots from the auxiliary equation taken from s^2 row of Routh- Hurwitz tabulation

Thus,

$A(s) = 20s^2 + 50k = 0$

$20s^2 + 50x12 = 0$

$20s^2 + 600 = 0$

$20s^2 = - 600$

$s^2 = \frac{-600}{20}$, $\quad s = -(\pm\sqrt{30}) = \pm 5.5$

$s = \pm j5.5$

The corresponding value of K at the points of s above is the critical value for stability.

Thus, the system is said to be stable.

Simulation of the Designed Controllers

Simulation of the PID controller was done using MATLAB/SIMULINK software. This was done using the designed control variables and the models shown in sections 3.1, 3.2 and 3.3. Lab-view software and Proteus software were used when the PID and DCS were cascaded for better performance in the Internal Model control method used for the flow control. From figure 9, it could be seen that the overshoot was very high and there was no controller in the system in as much as there were sensors and actuators. There were issues of transients after the overshoot and steady state was achieved after several times were wasted.

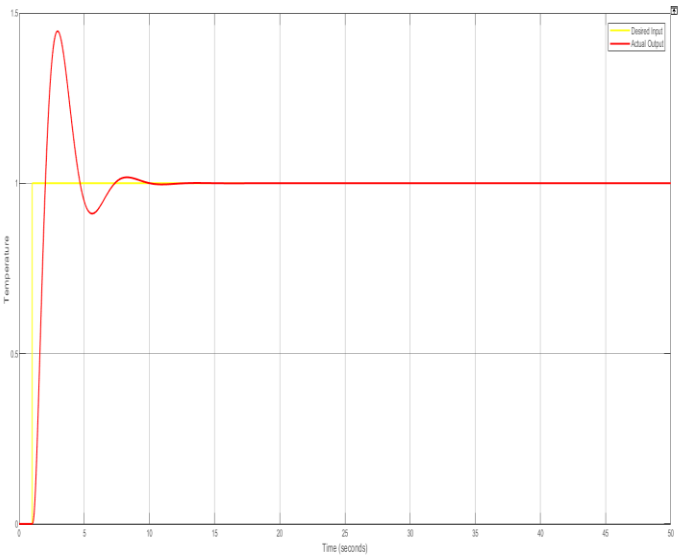

Fig. 9: Simulation results of flow when there was no controller

Figure 10 illustrates a SIMULINK representation of a closed loop control system when the PID controller was configured into the system.

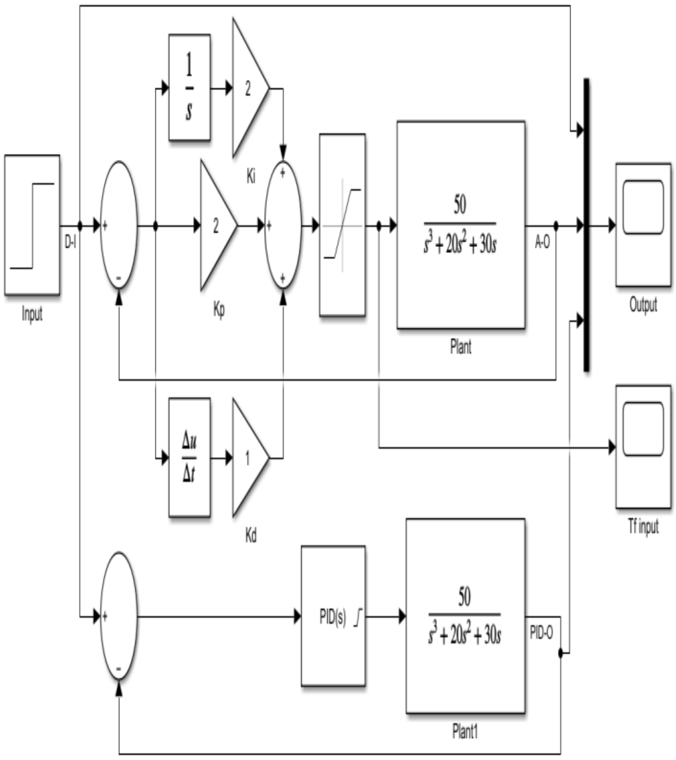

Fig. 10: Closed loop control system with PID controller.

To achieve better stability, PID controller was integrated into the system and the result displayed in figure 11. This brought significant improvement but it could be seen that there were still some overshoots and drag from the beginning of the simulation.

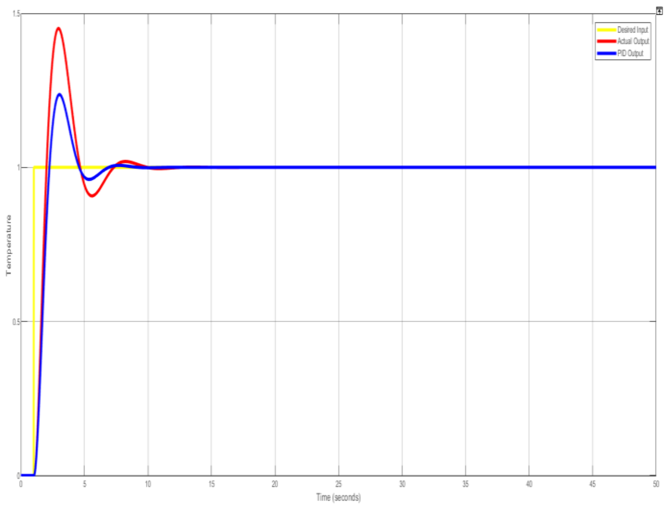

Fig. 11: System response when PID controller was integrated.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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In figure 12, the simulation study shows the performance of two controllers which are used for virtual buildup of control activity of flow. The controllers (DCS and PID) were used independently to see their performance in terms of control activity. When they are used independently, the PID controller had a high over shoot and rise time before overcoming the disturbance to attain stability. Also, the DCS also had some overshoot when used alone to control the flow before attaining stability.

When the two controllers were incorporated in the loop, the result became fantastic as the overshoot was reduced to minimum level and stability was achieved within a very short time. It also gave faster disturbance rejection with the time duration of few seconds and smaller overshoot. This improvement brought a new window that errors of drag under laminar and turbulence could be overcome using cascaded brand of controllers.

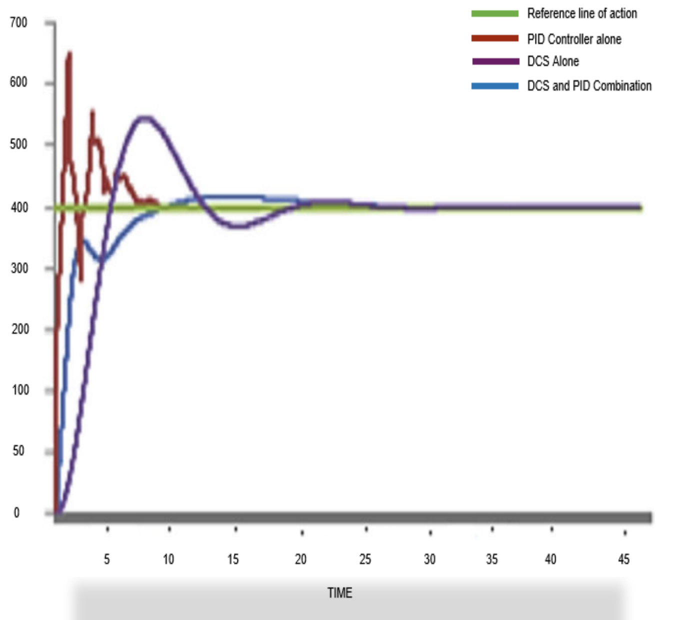

Fig. 12: Performance analysis of the two controllers in different scenarios.

IV. CONCLUSION

In this research work, maintenance of constant flow rate of fluids was achieved through the use of combination of controllers. The research work reviewed how the adverse effect of friction could cause devastating effect on flow of fluids.

Orifice plate was specifically considered and modeled for use as the flow measuring device. PID flow controller was modelled for use in the control of the flow, the performance was monitored and simulated and it was found that in as much as it tried to mitigate the problems associated with flow, there were still issues of disturbance but not as much as when there were only sensors, actuators and pumps. Direct Synthesis (DS) methodology was applied in all the processes. In these, mass transfer coefficient was considered. Design of the flow controller was done to see how the modeled PID could effectively communicate with other devices in the control loop.

Cascading of the PID with DCS controller was done to see if a better result could be achieved. It was discovered that the combination yielded fantastic result as the over shoot was drastically reduced to a level that it became inconsequential in the output result obtained comparing it with the reference point already set out.

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