

# TR Optimization in High-Performance Drilling Machine for Various Control Actions & Algorithm

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**Abstract:** Drilling industry has moved into a paradigm shift with the controlled Proportional Integral Derivative (PID) tuning, which provides optimum outcomes in recent decades. Interestingly the outcomes of several aspects of these PIDs are quite important for the industry sector. Many of the large industry or construction firms' project that was seemed impossible at one point of time is now feasible. A significant amount of research has been commenced for tuning of PID controllers from the last six decades. Many tuning methods have also been proposed. Most of the tuning methods are model-based like Ziegler Nichols (ZN) method. It provides initial tuning of PID, which offer consistent result, but there is always suggested to fine-tune the PID controller further for the particular process to get optimum results. This paper represents a comparison for the several control schemes such as PID controller, PI with PD in feedback, PID with PD in feedback, PID-D and PID-PD controller and lead compensator. This relative study based upon rise time, settling time and peak-overshoot. The block diagrams were simulated in MATLAB, and their results are compared.

**Keywords:** Drill machine, Modified ZN method, PID Tuning, ZN method

## I. INTRODUCTION

Tunnels and underground passages are formed for a variety of purposes such as subways, station power plants which require specific measure during drilling and a unique set of closed-loop control system design to create a system. High-speed performance drilling machines are used in turnkey projects, which require a lot of study on numerous factors like feed rate, spindle speed, flute length, etc. which can influence the drilling process. In this paper, the transfer function of the drilling machine is considered, which correlates the parameters such as cutting force and feed-rate from which the effects are studied on vibrations and other factors like rise time, settling time, peak overshoot. The performance of the drilling machine is very sluggish.

It can be improved by the use of a PID controller. The tuning of a PID controller plays a vital role in the performance of the device. A better tuned PID controller gives a better response of the system like a drilling machine. Vibration is observed during the drilling operation. The intensity of vibration depends upon the speed of the drilling machine if speed is high vibration is more and vice versa.

The vibration degrades the performance of the drilling machine. The performance of the drilling machine is improved by optimizing tuning of Proportional Integral Derivative (PID) controller. Since the last six decades, researchers worked on the optimization of the PID controller. Dos Santos Coelho, L.(2009) proposed a Chaotic optimization approach that gave the easy tuning of the PID controller for an automatic regulator voltage (AVR) system based on the Lozi map[1]. S.M. Giriraj Kumar, Deepak Jayaraj and Anoop R.Kishan (2010) gave a systematic design method to increase the response of PID controlled high-performance drilling machines. It was analytically proven and graphically represented by them only that there has to be considerable development in the time domain specification of transient response (TR) in terms of shorter rise time, peak time, settling time as well as a lower overshoot. The performance index for various error criteria for the proposed controller using Particle Swarm Optimization (PSO) algorithm was proved to be less than the controller tuned by Ziegler Nichols (ZN) method [2]. R. Kumar, S.K. Singla & V. Chopra (2015) have proposed two different methods (ZN method and relay auto-tuning (RA)) to tune PID controllers. The result worked in complete tandem with RA method for feed-forward with additional feedback along with cascade control schemes which provide better transient performance while ZN method provided optimum outcomes in cascade with added feedforward control[3]. Fahid S. M. Alkhatfaji, W. Z. Wan Hasan, M.M. Isa and N. Sulaiman (2018) designed a PID controller tuned by frequency domain ZN design approach based on integrating requirements of the transient performance. The projected PID controller design scheme gave a tool that allowed the designer to outline the closed-loop response thoroughly. The verified method has a systematic way which contains the simplicity of the original ZN method [4].

This paper works on stabilization techniques of drilling machines, which will reduce vibrations without compromise in speed and optimum results are worked out for drilling machines. Various control schemes for the tuning of the PID controller are analyzed and compared with ZN and Modified ZN method. The paper is pre-arranged with a proper explanation as follows: Section I describes the critical aspects of a drilling process.

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The mathematical model of the drilling machine & the basic concept of the PID controller is also discussed. Section II gives a brief prologue of the tuning method and tuning of the PID controller using the ZN method & modified ZN method. In section III response of transfer function and simulation results of a drilling machine in an open loop and closed loop are discussed. In section IV drilling machine with the closed-loop mode is discussed using various controllers. Section V presents simulation results and their discussion.

A. Drilling Machine

A drilling machine comes with several parts (pertaining to the drill bear down on type) such as drill chuck, table, base, hand, column, fixed-head, adjustable-head, and spindle. The motor of the drilling machine is the most significant element that is used for rotating the drill and is installed in the fixed head of the drilling machine. Twist, auger, paddle, gun drill, drill with Bozel Carbide tip and drill with indexable carbide insert are various types of drill which are used in drilling machine[5]. The drill has an elevated length to diameter ratio, which made it easier to drill deeper holes. Drilling machines also competent to do other operations such as tapping, reaming, and small diameter boring other than drilling.

The modelling and finding out to design a high-Performance drilling machine consists of modelling of the feed drive system, the spindle system, and the cutting process. The cutting force and command feed are directly proportional to each other, and corresponding gain varies according to the drill diameter and workpiece material.

The overall system for a drilling machine which was modelled as a third-order system represented by (1) with a given transfer function [2, 6, 8].

$$G(s) = \frac{F(s)}{f(s)} = \frac{1958}{s^3 + 17.89s^2 + 103.3s + 190.8} \quad (1)$$

Where s is the Laplace operator, F is the cutting force, and f is the command feed.

B. PID Controller

Throughout the drilling procedure, the pace of the motor that rotates the cutting tool will tend to be slower from the preliminary pace owing to the friction caused when the cutting tool makes contact with the work piece[5]. The diminution of speed during drilling operation decreases the performance of the drilling operation and makes it with a reduction efficiency. A PID controller is used to resolve this problem to maintain the speed of the motor. The concept is while the speed of the motor becomes diminishing during the drilling operation, the PID will identify the error and will be tried to eliminate it. To eliminate the error the voltage supply or command feed is increased to the motor through the PID controller for sustaining the speed of the motor. When the speed of the motor is retained, the performance of the drilling maneuver is continued and becomes more proficient [7, 8].

A block diagram representation of the PID Controller with the drilling machine is shown in Fig.1.

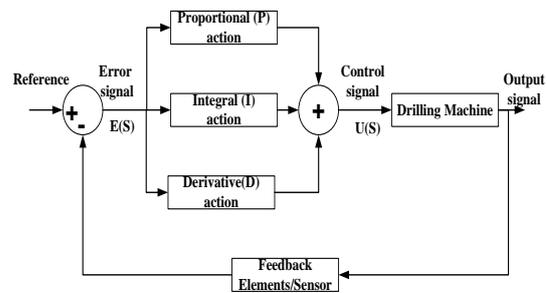


Fig. 1. PID controlled drilling machine in a closed-loop control system

The mathematical model of the PID controller is given by the following dynamics (2)-(3).

$$U(s) = K_P \left( 1 + T_D s + \frac{1}{T_I s} \right) E(s) \quad (2)$$

$$U(s) = \left( K_P + K_D s + \frac{K_I}{s} \right) E(s) \quad (3)$$

Where  $K_P$ -proportional gain,  $T_I$ -integral time constant,  $K_I$ -integral gain,  $T_D$  -derivative time constant,  $K_D$  - derivative gain &  $E(S)$  is the error of the system[9].

Table-I: Effect the increasing of PID controller parameters  $K_P$ ,  $K_I$  and  $K_D$  [11]

Parameters	Rise Time	Overshoot	Settling Time	Steady State Error
$K_P$	Decrease	Increase	Minor Change	Decrease
$K_I$	Decrease	Increase	Increase	Eliminate
$K_D$	Minor Change	Decrease	Decrease	Minor Change

Tuning and designing of a PID controller seem to be abstractly perceptive. Still, it is challenging to put practically, if all parameters such as squat transient and high stability are to be achieved. Initial designs need to be accustomed frequently through computer simulations until the closed-loop system performs optimally [9]. Table-I shows the effect of increasing the different gain values on transient performance parameters.

II. OVERVIEW OF TUNING METHODS

The task of tuning a PID controller is to determine parameters  $K_P$ ,  $K_I$ ,  $K_D$  such that minimum overshoot along with the minimum settling time ( $T_s$ ) and minimum rise time ( $T_r$ ) are to be obtained [10]. There are numerous methods available for tuning of a PID controller. The most effective methods commonly engross the improvement of some form of the process model. As per the requirement of the dynamic model select the parameters of  $K_P$ ,  $K_I$ , and  $K_D$ . Manual tuning of PID will take more time as compared to other methods, particularly for systems with long loop times. The assortment of the scheme depends typically on whether the loop can be taken offline (passive) for tuning or not and keep a track view on the response time of the system.

Now, keeping the content to be in passive mode, the most optimal tuning strategy has a frequent response that is subjected concerning step change at the input and then checking the output as time function with the suitable response that shows the control parameters [11].

**A. Tuning Methods**

For tuning of the PID controller, so many methods are available [11]. Some of them are -ZN method, modified ZN method, Process reaction curve method, Cohen coon method, Particle swarm optimization method, Ant colony method.

In this paper, the following methods are considered for comparison :

- a) ZN method
- b) Modified ZN method

**a) ZN Method**

One of the heuristic method which is used for tuning of PID controller named as ZN tuning method. This method was proposed by John G. Ziegler and Nathaniel B. Nichols. It is designed by setting the D (derivative), and I(integral) gains to zero and infinity, respectively. The proportional gain ( $K_p$ ) is then increased (from zero) until it attains the Critical gain ( $K_{cr}$ ), at which the response of the control loop has unwavering with sturdy oscillations, and the oscillation period is used to set the value of  $K_I$  and  $K_D$  based on the type of controller used [12,14]. ZN method is a trial and error tuning method based on critical gain ( $K_{cr}$ ) and critical frequency( $W_{cr}$ ). In this method, we use the quarter amplitude damping ratio for the design criterion[12,13]. The drawbacks of the ZN method is that it is an overwhelming time process, and it is not appropriate for those plant whose open-loop system is unstable.

**Table-II: ZN closed-loop tuning method[12]**

Type of controller	$K_p$	$T_I$	$T_D$
P	$(1/2) K_{cr}$	$\infty$	0
PI	$(9/20)K_{cr}$	$(5/6)P_{cr}$	0
PID	$(3/5) K_{cr}$	$(1/2)P_{cr}$	$(1/8) P_{cr}$

$K_{cr}$ -Critical gain

$P_{cr}$  -Critical period

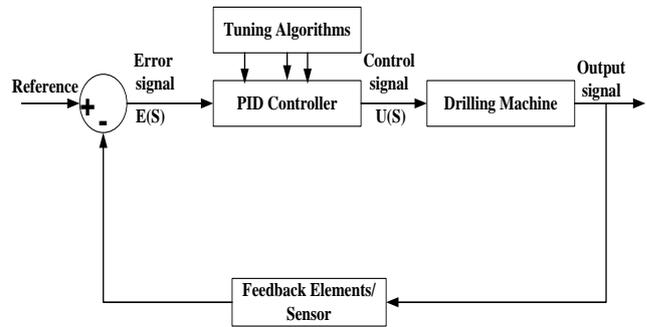
**b) Modified ZN Method**

Modified ZN method based on Chien–Hrones-Reswick (CHR) tuning algorithm which emphasizes on set point regulation[11].

**Table-III: Modified ZN closed-loop tuning method with some overshoot[11]**

Type of controller	$K_p$	$T_I$	$T_D$
PID	$(1/3) K_{cr}$	$(1/2)P_{cr}$	$(1/3)P_{cr}$

A comprehensive diagram for any kind of control system that undergoes tuning mechanism is shown in Fig.2.

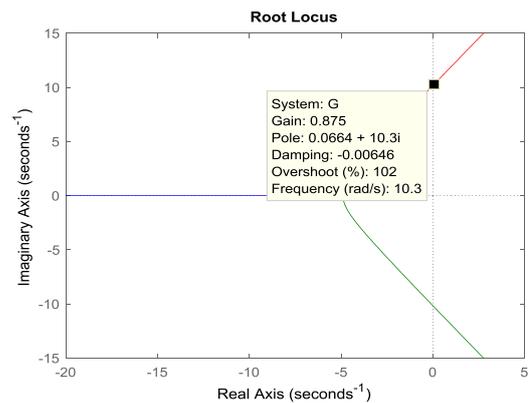


**Fig.2. Block diagram representation of a tuned PID controlled drilling machine**

As per the discussion approach to get optimum output, the present paper is subjected to compute and find out the best promising rise time, settling time and peak overshoot for drilling machine under standard conditions through all possible mentioned tuning methods. Table-II & Table-III are observing the comprehensive values of  $K_p$ ,  $T_I$  &  $T_D$  for the PID controller using ZN & Modified ZN tuning method.

**III. SIMULATION RESULTS**

In this paper, the tuning of the drilling machine is done with different control schemes using the different combinations in loop feedback. And analyze the result with the ZN method and modified ZN tuning mechanism to find out which one of the used six combinations provides the best optimum result for the drilling machine. Root locus for the given transfer function described by (1) of the drilling machine is shown in Fig.3.



**Fig.3. Root locus of drilling machine**

The root locus of the drilling machine in Fig.3 is showing the critical gain ( $K_{cr}$ ) = 0.875, critical frequency ( $W_{cr}$ ) = 10.3 rad/sec and critical time period ( $P_{cr}$ ) =  $2 * 3.14 / 10.3$  = 0.6097 sec. That can be used for calculating the value of  $K_p$ ,  $K_I$  &  $K_D$  for both tuning methods as shown in Table-IV & Table-V, respectively.

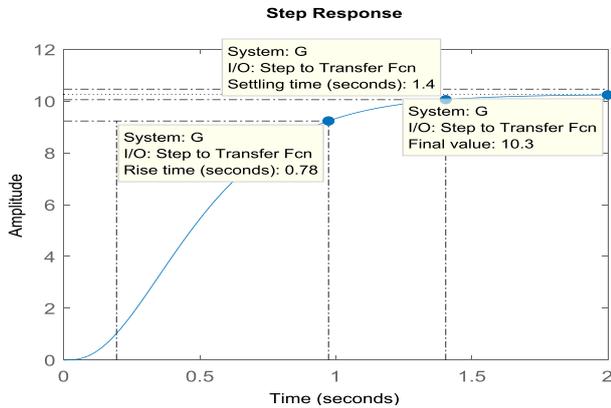
**Table-IV: Values of controller parameters for the ZN method**

Controller	$K_p$	$K_I$	$K_D$
PID	0.525	1.722	0.040

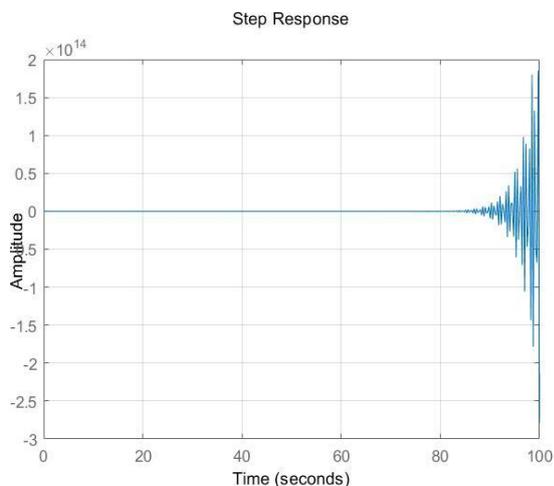
**Table-V: Values of controller parameters for the modified ZN method**

Controller	$K_P$	$K_I$	$K_D$
PID	0.289	0.947	0.0587

The transfer function of the open-loop drilling machine is described by (1), and step response of this transfer function (drilling machine) in open-loop mode and closed-loop mode with unity feedback is shown in Fig.4 and Fig.5 respectively.



**Fig.4. Open-loop step response of the drilling machine**



**Fig.5. Closed-loop step response of the drilling machine**

Transient performance parameter using MATLAB (R2018a) are calculated from Fig.4 and Fig.5 are shown in Table-VI.

**Table-VI: Transient performance parameters**

Method	Rise Time(sec)	SettlingTime (sec)	Overshoot (%)	Peak Time (sec)
Open Loop	0.7796	1.4040	0	1.1865
Closed Loop	Nan	Nan	Nan	Nan

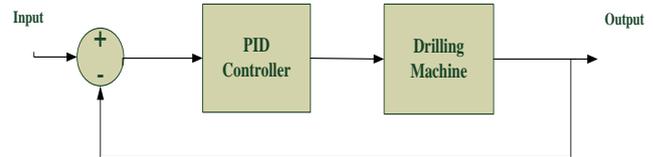
The step response of the closed-loop system is unstable, which is shown in Fig.5. Transient performance parameters cannot be intended for this unstable system. A compensator or PID controller has to be designed to make system stable and look up the system transient response (TR) parameters like rise time, settling time, peak overshoot and steady-state error. For this unstable closed-loop control system, the PID controller will be tuned by ZN & modified ZN method.

**IV. VARIOUS CONTROLLER**

Different MATLAB simulation combination has been created, and results have been discussed for the various controller to find out the most optimum controller for ZN and modified ZN method that will be best suited for drilling machine system.

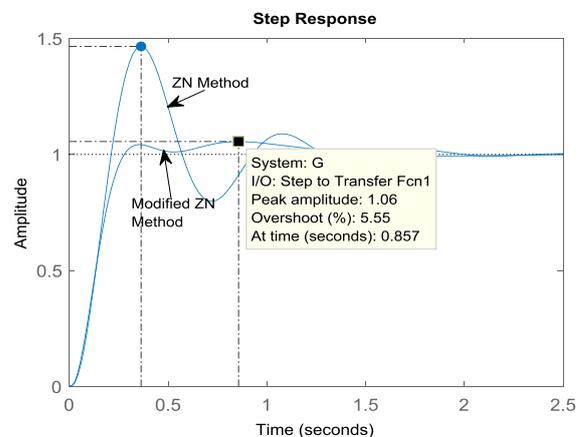
**A. PID Controlled Drilling Machine In Closed Loop System**

A block diagram of the PID controlled drilling machine with unity feedback is shown in Fig.6. In this, the controller parameter is tuned using the ZN & modified ZN method.



**Fig.6. Block diagram of PID controlled drilling machine**

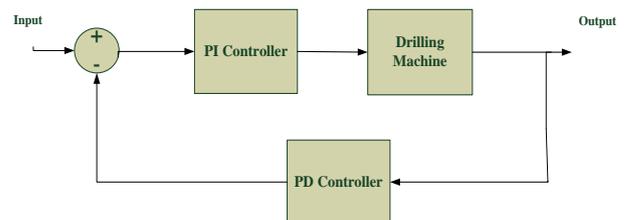
The transient response of PID controlled drilling machine for a step input is shown in Fig.7.



**Fig.7. Step response of PID controlled drilling machine**

**B. Proportional Integral (PI) Controlled Drilling Machine With Proportional Derivative (PD) in Feedback**

The block diagram of a PI controlled drilling machine with PD in feedback is shown in Fig.8. Using this type of PI-PD configuration, we reside absent from the setpoint boot phenomenon, i.e. differentiation obtain merely on the feedback signal, not for the reference signal which shrinks the overshoot by a great amount, which is shown in Fig.9.



**Fig.8. Block diagram of PI-PD controlled drilling machine**

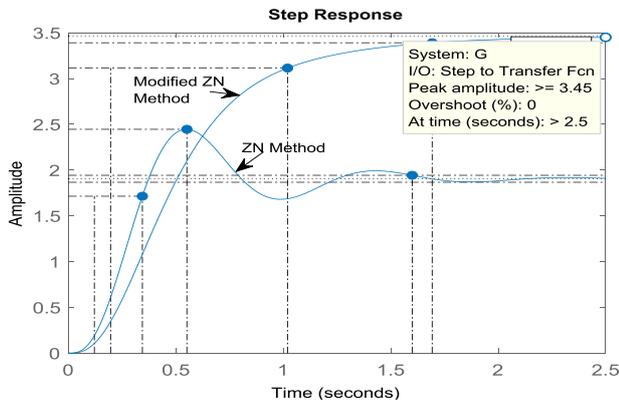


Fig.9. Step response of PI-PD controlled drilling machine

C. PID Controlled Drilling Machine With PD in Feedback

A block diagram of the PID controlled drilling machine with PD in feedback is shown in Fig.10. Fig.11 is showing the step response of the drilling machine using PID in the forwarding path with PD feedback controller.

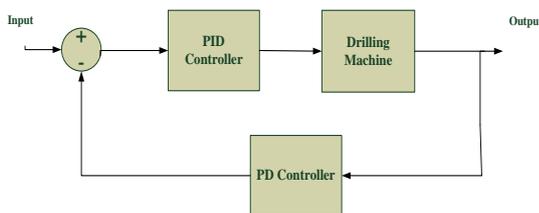


Fig.10. Block diagram of PID-PD controlled drilling machine

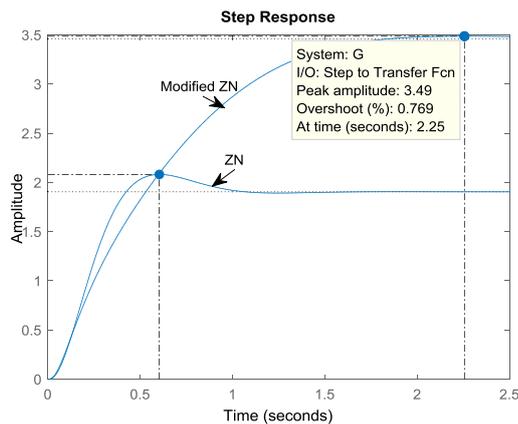


Fig.11. Step response of PID-PD controlled drilling machine

D. PID With Derivative Controller Using Two Degrees Of Freedom Control

Two degrees of freedom control method includes generating one signal for feed-forward control and generating another signal for feedback control is shown in Fig.12 and Fig.14. Step response for PID-D and PID-PD controlled drilling machines are shown in Fig.13 and Fig.15, respectively.

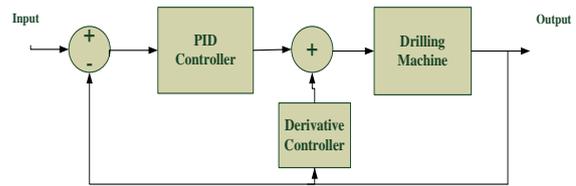


Fig.12. Block diagram of (PID-D) controlled drilling machine using two degrees of freedom control

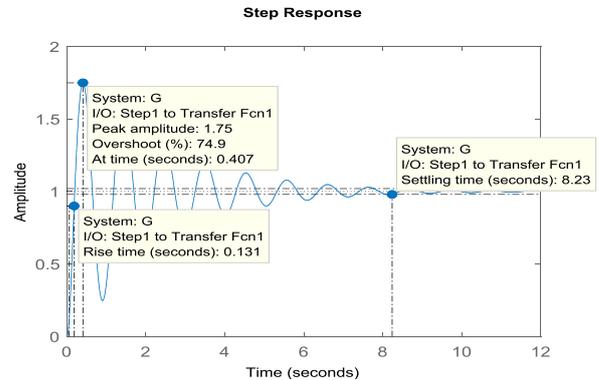


Fig.13. Step response of (PID-D) controlled drilling machine using two degrees of freedom control

E. PID with PD Controller Using Two Degrees Of Freedom Control

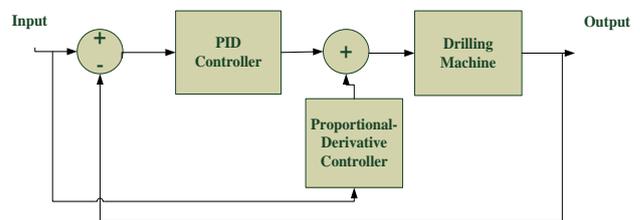


Fig.14. Block diagram of (PID-PD) controlled drilling machine using two degrees of freedom control

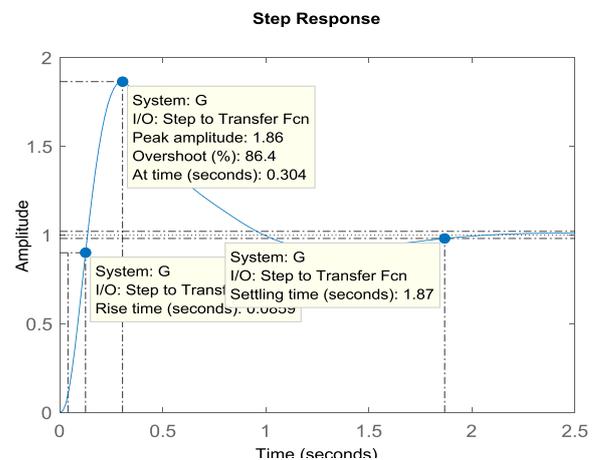


Fig.15. Step response of (PID-PD)controlled drilling machine using two degrees of freedom control

F. Lead Compensator Design For Drilling Machine

The lead compensator, which is used for optimizing the performance of the drilling machine, is shown in Fig.16 and described by (4)-(5).

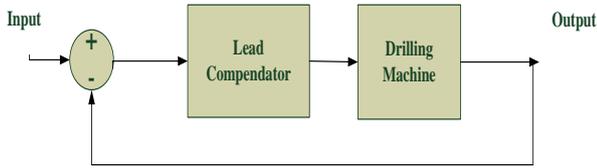


Fig.16. Block diagram of lead compensated drilling machine

Transfer function[15] of lead compensator-I and II are as follows:

$$C1 = 0.47791 \left( \frac{1 + 0.21s}{1 + 0.035s} \right) \quad (4)$$

$$C2 = 0.35068 \left( \frac{1 + 0.26s}{1 + 0.032s} \right) \quad (5)$$

The transient performance of lead compensated drilling machine for a step input is shown in Fig.17.

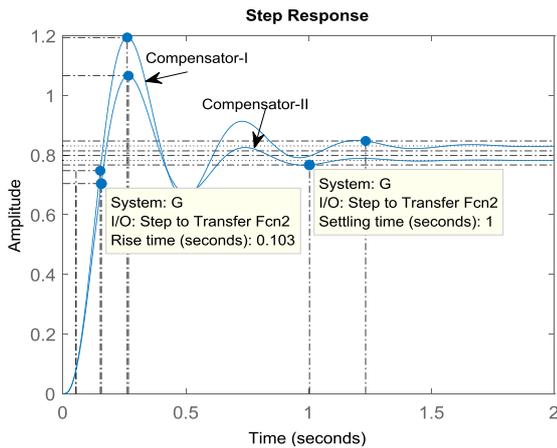


Fig.17. Step response of lead compensated drilling machine

V. RESULTS & DISCUSSION

In this paper for performance optimization of the drilling machine, the PID controller is tuned by ZN & modified ZN method and also proposed the design of lead compensator for the same. The step response of PID controlled drilling machine with unity feedback, PI controlled drilling machine with PD in feedback and PID controlled drilling machine with PD in feedback is shown in Fig.7, Fig.9 and Fig.11 using ZN and modified ZN method in MATLAB(R2018a).Table-VII shows that modified ZN tuned PID schemes give the fastest response system for adequate overshoot. But if the overshoot of the system response is more significant than the system speed, then modified ZN tuned PI with feedback PD controller is best in comparison to other as shown inTable-VII.

Table-VII: Comparison of transient specification parameters for PID controller

Control Schemes	Tuning Method	Rise Time (sec)	Settling Time (sec)	Over shoot (%)	Peak Time (sec)
PID Controller	ZN	0.136	1.56	46.6	0.363
	Modified ZN	0.174	1.28	5.55	0.857
PI with PD Controller in Feedback	ZN	0.224	1.6	28.4	0.551
	Modified ZN	0.824	1.69	0	2.5
PID with PD Controller in Feedback	ZN	0.278	0.929	9.27	0.603
	Modified ZN	1.08	1.59	0.769	2.25

Along with that, the step response of PID-D and PID-PD controlled drilling machine using two degrees of freedom control is shown in Fig.13 and Fig.15 using the modified ZN method.

Table-VIII: Comparison of transient specification parameters for PID controller using two degrees of freedom control

Control Schemes	Tuning Method	Rise Time (sec)	Settling Time (sec)	Over shoot (%)	Peak Time (sec)
PID-D	Modified ZN	0.131	8.23	74.9	0.407
PID-PD	Modified ZN	0.0858	1.87	86.6	0.305

Table-VIII shows that the PID-PD system is the fastest response system on the outlay of peak overshoot among all the control schemes discussed in this paper. Table-IX provides a comparison of the transient specification parameter using lead compensator for the drilling machine.

Table-IX: Transient specification parameters comparison for different control schemes

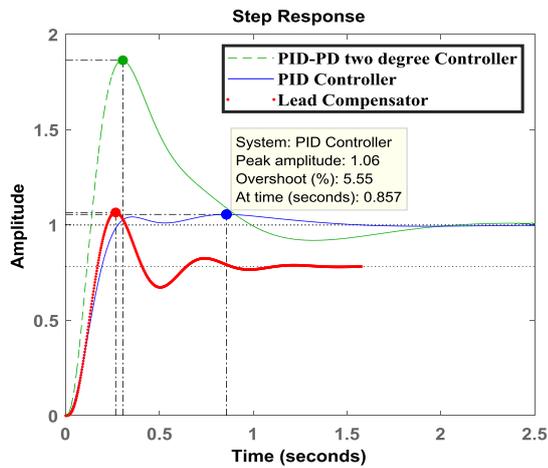
Control Schemes	Rise Time (sec)	Settling Time (sec)	Over shoot (%)	Peak Time (sec)
Lead Compensator Design-1	0.0989	1.24	44	0.263
Lead Compensator Design-2	0.103	1	36.2	0.266

VI. CONCLUSION

In this study of the analytical comparison method, it is best to work on different articulates to achieve the optimum output when the system is performing. We have deduced some of the critical methods that work to provide better key results concerning rise time, overshoot, and settling time. There are three important outline points are as follows:

- In case of minimum rise time & settling time with adequate overshoot PID controller using a modified ZN method provides the best result.
- In the case of the fastest response system on the outlay of peak overshoot, the PID-PD system using two-degree freedom control provides the best result.
- Lead compensator provides optimum result in consideration of minimum rise time and settling time on the cost of sky-scraping overshoot.





**Fig.18. The Response of PID-PD two degree freedom control, PID and lead compensator controlled drilling machine**

In view of the preceding results which is shown in Fig.18, it is finally concluded that PID controlled drilling machine using the modified ZN method provides the optimum value of rise time, overshoot, and settling time.

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