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***Research Paper***

# Stability analysis of paper machine headbox using a new PI(D) tuning technique

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## Abstract

Paper, today, has made an important place in human’s life. Being an important commodity, paper has different qualities throughout the globe. As the technology is advancing, paper is being used for numerous applications and need of good quality paper is increasing daily. To have papers of desirable quality, paper machines with latest technology are developed. However, the quality of paper principally depends on the prime element of paper machine i.e. Headbox. Headbox is a highly non-linear Multi-input Multi-output (MIMO) component of paper machine and requires a precise control of its major parameters to get good quality papers which eventually responsible for sustained economy of pulp and paper industry. In past few decades, headbox has been a key element for research. Researchers have developed different control algorithms for headbox. This paper presents stability analysis of paper machine headbox using a new technique of Proportional – Integral – Derivative (PID) controller design namely Extended Forced Oscillation method (EFO). Also, the paper presents a comparative analysis of EFO method of PID tuning with the conventional Ziegler - Nichols(ZN) tuning technique based on transient characteristics and performance indices of headbox.

***Keywords***: *Paper Machine Headbox; Level; Pressure; PID/PI Controller; Ultimate Point.*

## 1. Introduction

The first paper was developed around almost 2000 years ago in China [46]. Paper making plays a vital role in adding billions of dollars to the world economy annually [17]. The most important subsystem of the pulp and paper making process is paper machine [13]. The most important element that plays a vital role in paper manufacturing is the paper machine which continuously converts the cellulose fibers and slurry of water in an efficient way [17]. Many modern paper machines are based on the principles of the Fourdrinier Machine. Major components of Fourdrinier paper machine are: Flow spreader, Headbox, Fourdrinier Table, Presses, Dryers, Calendar, and Reel [13], [17] as shown in figure 1. The process of making paper is a highly complex process of heat and mass transfer. Also it is nonlinear process which has the distributed parameters [13]. The need of high quality paper continuously increasing which has resulted in the design and development of paper machines with high speed and better efficiency [23]. The paper machine operation is completely defined by the modeling and control the process. Being a highly complex process and various mandatory requirements (such as quality, low cost, safety and environmental concerns), the paper making process now requires a high performance advanced control for the enhancement of the overall process operation. A paper making process is not a single variable process. It includes several sub processes which are highly inter-related to each other and need to be controlled efficiently through a proper cooperation among each sub-process [23], [47], [48]. One of the most important sub-systems of the paper making process is “Headbox”. Headbox in a paper machine is intended to cause a steady state movement of pulp to wire. Important step in the paper making process is the stock material which is uniformly distributed on the wire through headbox [22]. A headbox is categorized as: open type headbox and pressurized headbox. Further a pressurized headbox is also categorized as: air cushioned and hydraulic type headbox. Since the quality of the final product (i.e. paper) is largely influenced by the operation of headbox, so its precise control and monitoring is highly required. A broad view of Fourdrinier paper machine has been depicted in figure 1 [17].

## 2. Literature review

Since headbox is a multivariable (2x2) system and is highly nonlinear. Due to its complexity and loop interactions, a highly robust control technique is required which can ensure the desirable operation of headbox even if there are disturbances and various uncertainties. In past few decades, headbox has seen a considerable research over its various parameters of concern. A brief survey of research has been presented in this section. Kothari in [1], presents the difficulty in paper formulation of headbox due to effect of its different parameters. Torsten Cegrell et. al. presented adaptive control methodology for paper machine in [2], while a computer-based design of controller and indeterministic state variable model have been proposed in [3] & [4] by Sinha and Rutherford. Ming Rao et. al. have proposed the technique to use Kalman filters for pressurized headbox in [5], bilinear control strategy in [6] and systematic decoupling control in [7], Nonlinear predictive control in [8], An Internal model control with reference model was proposed in [12], Robust control through loop-shaping design in [10], An object oriented control using modeling language OMOLA in [11], MIMO

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digital-linear-quadratic-regulator in [12], The fragility issues related to the controllers and the aspect of robustness that has been neglected in analytical treatments of control system design of paper machine headbox is discussed in [13], Shape optimization and optimal control techniques were developed for numerical control of paper machine headbox flows in [14], Design of CD control of paper machine through multivariable problem, Optimal minimum control effort for a Fourdrinier machine headbox in [16], Spatially-distributed feedback control technique for CD control of paper machines in [17], A non-smooth bi-objective optimization technique for the design of the shape of a slice channel [18], Interactive multi-objective optimization method NIMBUS [19], Advanced control methods and decoupling algorithms [21], A neural network (NN) based decoupling control technique has been developed in [22], Artificial neural network (ANN) based retention control [23], Adaptive fuzzy controller [24], Various controllers and tuning methods have been.

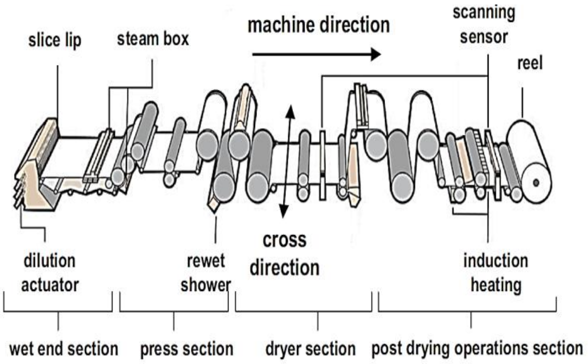

**Fig. 1:** Fourdrinier Paper Machine [17].

Figure 2 illustrate a general working of paper machine headbox.

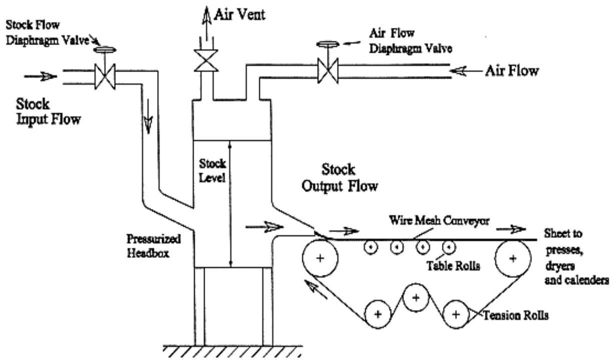

**Fig. 2:** Headbox Arrangement [16].

studied on paper machine headbox in [25]. Neural network decoupler control system [26], Model Predictive Control for consistency and liquid level control [27], GA based Neural PID decoupling control [28], Advanced prediction based control approach [29], A decoupling control system design [30], Non-fragile bilinear state feedback control [31], fuzzy tuned PID control for nonlinear control problem in air cushion headbox in [32] and for the total pressure and stock level control of paper machine headbox [33]. Since, the demand of high quality paper is increasing day by day, so the research on headbox control is continue. This paper also presents a new technique of PID controller design for headbox.

## 3. Headbox mathematical model

In paper industry, the high-speed paper machine is equipped with pressurized flow box with air cushion. Pressurized headbox can be used for complete automation, so it is necessary to know dynamic processes which are associated with the incoming and outgoing stock on the paper machine wire. One type of pressurized headbox is shown in figure 2. Kikiewich et. al. (36) developed partly the dynamics of the same but could not analyze. This problem has been solved in this present study. The paper machine headbox may be divided into three zones in which dynamic may be conceived independently. These three zones are:

i) Portion of box filled with stock
ii) Space above stock surface filled with air cushion
iii) Overflow system

The MIMO transfer function obtained is [13]:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \dfrac{0.528e^{(-0.6s)}}{(2.2s+1)} & \dfrac{(1.2539s+.063)}{(30.051s^2+17.79s+1)} \\ \dfrac{(0.0205s+.0001)e^{(-1.5s)}}{(43.6s^2+s)} & -\dfrac{(0.0007)e^{(-2s)}}{s} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_1(s) \end{bmatrix} \quad (2)$$

The approximated headbox model considering the important dynamics is given as [35]:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \dfrac{0.528e^{-0.6s}}{2.2s+1} & \dfrac{0.081}{1.89s+1} \\ \dfrac{1.49\times10^{-4}e^{-1.5s}}{s} & \dfrac{-7.0\times10^{-4}e^{2s}}{s} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix}$$

$$G_{Headbox}(s) = \begin{bmatrix} \dfrac{0.528e^{-0.6s}}{2.2s+1} & \dfrac{0.081}{1.89s+1} \\ \dfrac{1.49\times10^{-4}e^{-1.5s}}{s} & \dfrac{-7.0\times10^{-4}e^{2s}}{s} \end{bmatrix} \quad (3)$$

Where, $y_1$ and $y_2$ are pressure and stock levelin the headbox respectively. And $u_1$ and $u_2$are the feed pump speed and air valve position respectively.

The Single Input – Single Output (SISO) model of the headbox can be derived by determining the loop pairing. Since the headbox is a 2x2 MIMO system and it is highly required to check the interactions among the loops and find out the suitable loop pairing. Through relative gain array (RGA) it has been found that 1 – 1 and 2 – 2 loop pairing is recommended for the given plant. The whole process of deriving SISO model is described below:

The loop interaction is tested by calculating the Relative Gain Array (RGA). The RGA is given below:

RGA for 2 × 2 matrix is

$$\Lambda = \begin{bmatrix} \lambda_{11} & \lambda_{12} \\ \lambda_{21} & \lambda_{22} \end{bmatrix} \quad (4)$$

Where,

$$\lambda_{11} = \frac{1}{1 - \dfrac{k_{12}k_{21}}{k_{11}k_{22}}}\ ;\ \lambda_{12} = 1 - \lambda_{11}\ ;\ \lambda_{22} = \lambda_{11}\ ;\ \lambda_{21} = \lambda_{12}$$

The static gains are as:

$$k_{11} = 0.528\ ;\ k_{12} = 0.081\ ;\ k_{21} = 1.49\times10^{-4} I\ ;\ k_{22} = -7.0\times10^{-4} I$$

Where, $I = \dfrac{1}{s}$

The respective RGA values calculated are given as:

$$\lambda_{11} = \lambda_{22} = 0.97$$

$$\lambda_{12} = 1 - \lambda_{11} = \lambda_{21} = 0.03$$

The relative gain array matrix obtained is,

$$\Lambda = \begin{bmatrix} 0.97 & 0.03 \\ 0.03 & 0.97 \end{bmatrix} \tag{5}$$

For a MIMO system, the SISO modeling is followed by the equations given below:

$$y_1 = \left( g_{11} - \frac{g_{12} g_{21}}{g_{22}} \right) v_1 \tag{6}$$

$$y_2 = \left( g_{22} - \frac{g_{12} g_{21}}{g_{11}} \right) v_2 \tag{7}$$

$$y_1 = \left( g_{11} + g_{12} g_{I_2} \right) v_1 \tag{8}$$

$$y_2 = \left( g_{22} + g_{21} g_{I_1} \right) v_2 \tag{9}$$

Where, $g_{I_1} = -\frac{g_{12}}{g_{11}}$ and $g_{I_2} = -\frac{g_{21}}{g_{22}}$

For this work, static decoupling is used to design decoupler. The static decouplers obtained are as given below:

$g_{I_1} = -0.1534$ and $g_{I_2} = 0.2129$

$$G_{11}(s) = \frac{-0.288s^2 + 0.8825s + 0.5452}{1.247s^3 + 5.365s^2 + 4.39s + 1} \tag{10}$$

$$G_{22}(s) = \frac{5.421s^2 + 1.693s - 7.229}{7500s^3 + 17500s^2 + 10000s} \tag{11}$$

Where, $G_{11}(s)$ and $G_{22}(s)$ are the SISO loops of the plant given by equation (10 & 11). $G_{11}(s)$ is obtained by 1 – 1 loop pairing and $G_{22}(s)$ is obtained by 2 – 2 loop pairing.$G_{11}(s)$, represents the pressure and $G_{22}(s)$ represents the liquid level of the headbox. Out of the two SISO models, $G_{22}(s)$ is an integral process with negative gain values. And that is why it is hard to control this process. The given SISO models have been used to design the PI and PID controllers. The controller design for the current work has been discussed in section 4.

## 4. Controller design

PID controllers are majorly used in many process industries because of their simple structure and can be easily implemented in the industries [37]. PID controllers are simple, robust, efficient, applicable to wide range, fast response, and can eliminate steady state error in time. Due to these features, PID controllers are favorite choice for industries [38 - 44]. The standard forms of PID/PI controller are given by the following equations:

Proportional – Integral – Derivative (PID) Controller

$$C_{PID}(s) = \kappa_c \left( 1 + \frac{1}{\tau_i s} + \tau_d s \right) \tag{18}$$

Proportional – Integral (PI) Controller

$$C_{PI}(s) = \kappa_c \left( 1 + \frac{1}{\tau_i s} \right) \tag{19}$$

Where, $\tau_i$ and $\tau_d$ are the respective time constants of integral and derivative control.

The controller design techniques presented in this study are based on the conventional tuning techniques along with the new tuning techniques as discussed in [34]. The EFO method as proposed in [34], discusses the methodology of determining the ultimate frequency and ultimate gain of an integral process. The integral processes do not possess the ultimate point in their Nyquist plot. The ultimate point is basically the point where the Nyquist plot crosses the negative real axis. In EFO method, a new methodology has been proposed for such systems which do not possess ultimate point. The basic theme of the proposed methodology is based on the relay feedback experiment as proposed by Astrom & Hagglung [45]. Astrom & Hagglung in their experiment suggest that the ultimate point can be obtained from the Nyquist plot of a system. However, if the ultimate point is not available then it can also be determined by introducing a Integrator in the closed loop along with relay. The result of introducing integrator in the loop is that the ultimate point is obtained where the phase of the given system is equal to -180° for integral processes. The desired phase margin is specified and accordingly the value of ultimate frequency and gain are obtained through the relay feedback experiment with an integrator in the loop [45]. The same approach has been used by Alexandre S. B. et. al. in [34]. The proposed phase margin is 60° and the controller's contribution in the phase is considered -10°. In this technique, instead of an integrator, a fractional order integrator (FOI) has been used in the closed loop along with a relay in relay feedback experiment. The FOI transfer function is known. A brief of the EFO methodology is given below:

1) Consider a system with transfer function G(s), (where G(s) is an integral process).
2) Replace s with jω and Obtain the magnitude, $\left| G(j\omega) \right|$ and phase, $\angle G(j\omega)$ of the given system
3) Introduce an FOI of transfer function F(s) in the given closed loop of relay feedback. The F(s) is given by $F(s) = \frac{1}{s^{\Psi}}$ ; where $\Psi$ is a fractional number.
4) Obtained the open loop transfer function $F(s) * G(s)$ .
5) Obtain its Nyquist plot and find the ultimate point (i. e the point where Nyquist curve crosses negative real axis)
6) The ultimate frequency can also be obtained using following equation:

$$\angle G(j\omega) = \frac{-2\pi}{3} \tag{20}$$

Though, the method is purely proposed for the systems without ultimate point, but still it is claimed that the proposed technique [34] is also suitable for systems with ultimate point with reasonable results. The figure 3 depicts the block diagram of relay feedback experiment using an FOI to determine the ultimate point.

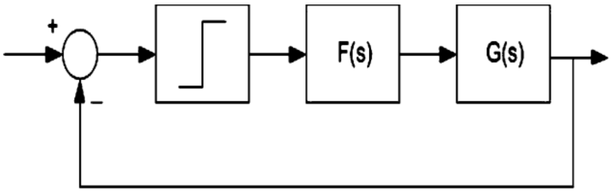

**Fig. 3:** Relay Feedback Experiment Using an Integrator of Known Transfer Function to Determine the Ultimate Point [34].

For the present work, the considered headbox system [13, 35] is a 2x2 MIMO system. The given system is converted into the two SISO loops by using the equations 4 – 9. The obtained SISO loops are given in equations 10 & 11. $G_{11}(s)$ and $G_{22}(s)$are the headbox pressure loop and headbox level loop and are used as P_Headbox and L_Headbox in the result figures as shown in section 5. Following the same methodology of determining the ultimate point as discussed in [34], [45], the following values of ultimate points are obtained.

a) System: P_Headbox

Method: EFO [34]
Ultimate frequency ($\Omega_{120}$): 1.5 rad/sec
Ultimate gain, (ƙ$_{120}$): 6.6667
Ultimate time, (Ʈ$_{120}$): 4.2 sec

Method: ZN
Ultimate frequency ($\Omega_{180}$): 3.88 rad/sec
Ultimate gain, (ƙ$_{180}$): 16.45
Ultimate time, (Ʈ$_{180}$): 1.62 sec

b) System: L_Headbox

Method: EFO [34]
Ultimate frequency ($\Omega_{120}$): 0.271 rad/sec
Ultimate gain, (ƙ$_{120}$): -370.37
Ultimate time, (Ʈ$_{120}$): 23.18 sec
Method: ZN
Ultimate frequency ($\Omega_{180}$): 1.01 rad/sec
Ultimate gain, (ƙ$_{180}$): -1397.8
Ultimate time, (Ʈ$_{180}$): 6.23 sec

The controller tuning values for the two systems (viz. P_Headbox and L_Headbox) using EFO and ZN method are given in tables 1 & 2 respectively. These values have been used to tune controller for headbox and the stability analysis is performed. The result analysis has been discussed in section 5.

**Table 1:** Controller Tuning Values for Headbox Pressure Transfer Function

| System | Method | Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|---|---|
| P_Headbox | EFO | PI | 6.53 | 3.72 | --- |
| | | PID | 6.47 | 3.72 | 0.12 |
| | ZN | PI | 7.40 | 1.35 | --- |
| | | PID | 9.87 | 0.81 | 0.21 |

**Table 2:** Controller Tuning Values for Headbox Level Transfer Function

| System | Method | Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|---|---|
| L_Headbox | EFO | PI | -362.96 | 20.86 | --- |
| | | PID | -359.26 | 20.86 | 0.65 |
| | ZN | PI | -629.01 | 5.19 | --- |
| | | PID | -838.68 | 3.12 | 0.78 |

## 5. Result analysis

This section discusses the results obtained for the considered paper machine headbox. Starting with, figure 4 and 5 represent the open loop step responses of systems P_Headbox and L_Headbox respectively. From the open loop step responses, the headbox pressure SISO loop (i.e. P_Headbox) is open loop stable system. While, the open loop step response of headbox level SISO loop (i.e. L_Headbox) is not a stable system. Also, it is an integral process and does not posses the ultimate point normally. So it is interesting to test the EFO technique [34] for its credibility. The pressure SISO loop is not an integral process and hence posses an ultimate point without inserting the integrator in the loop. However, as claimed, EFO method can be used on this system also and it has given considerably good results. The ultimate points are obtained on the Nyquist plot of the two loops. Figure 6 and 7, depict the Nyquist plots of pressure and level loops of the given headbox. From the figures, it can be notices that inserting an integrator (especially an FOI) in the closed loop of relay feedback experiment can bring an ultimate point. In figure 6, a comparison of the Nyquist plot of the normal pressure loop transfer function and the transfer function with FOI is shown. The ultimate frequency of normal P_Headbox is 3.88 rad/sec and P_Headbox with FOI is 1.5 rad/sec. Similarly, a comparison of Nyquist plots of L_Headbox system is shown in figure 7. The red line indicates the Nyquist curve of normal level transfer function of headbox. While, dashed blue line indicates the Nyquist curve of L_Headbox with an integrator of order 2. The green dashed line in same figure indicates the Nyquist curve of L_Headbox with an FOI of order 2/3. Figure 8 and 9 represent the open loop Nyquist plots of P_Headbox with PI and PID controller respectively, which clearly indicate that the controllers designed are keeping the system stable. Similarly, figure 10 and 11 indicate the Nyquist plots of L_Headbox with PI and PID controller respectively. The controller designed are stable and keeping the systems stable.

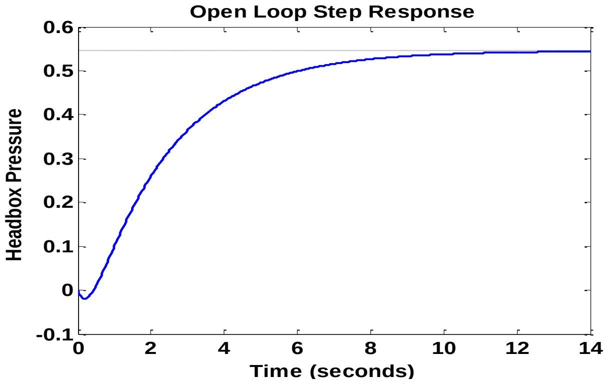

**Fig. 4:** Open Loop Step Response of P_Headbox.

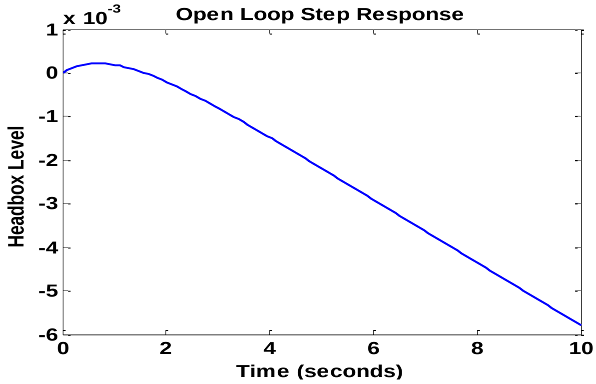

**Fig. 5:** Open Loop Step Response of L_Headbox.

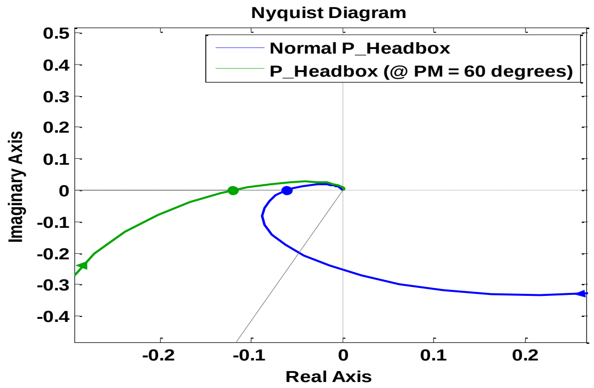

**Fig. 6:** Nyquist Plots of P_Headbox (Green Line: Using FOI With Ψ = 2/3).

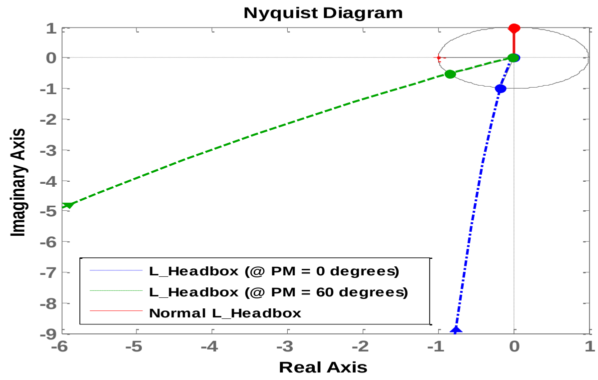

**Fig. 7:** Nyquist Plot of L_Headbox (Blue Dashed Line: Using Integrator with Ψ = 2; Green Dashed Line: Using FOI With Ψ = 2/3)

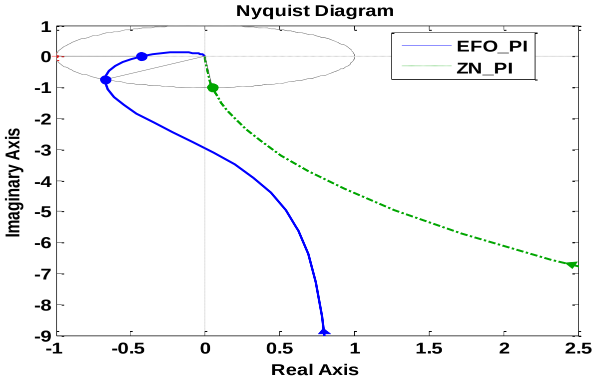

**Fig. 8:** Nyquist Plot of P_Headbox with PI Controller.

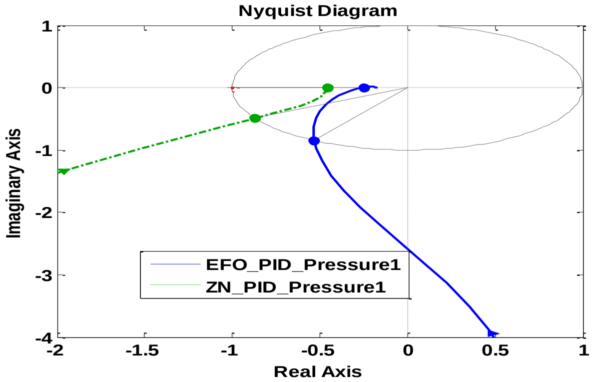

**Fig. 9:** Nyquist Plot of P_Headbox with PID Controller.

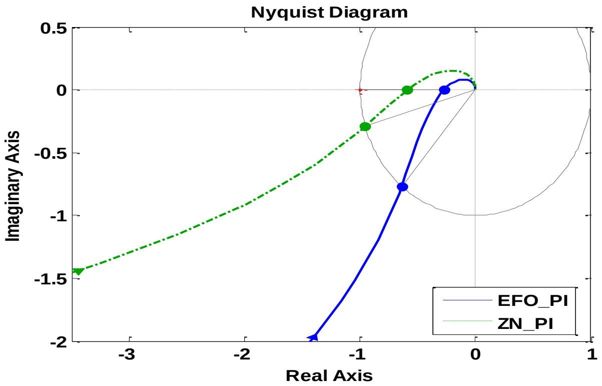

**Fig. 10:** Nyquist Plot of L_Headbox with PI Controller.

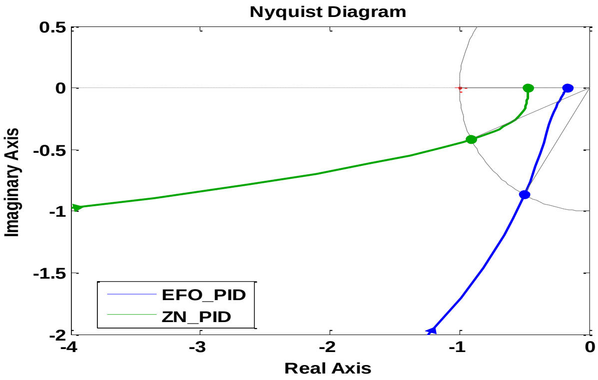

**Fig. 11:** Nyquist Plot of L_Headbox with PI Controller.

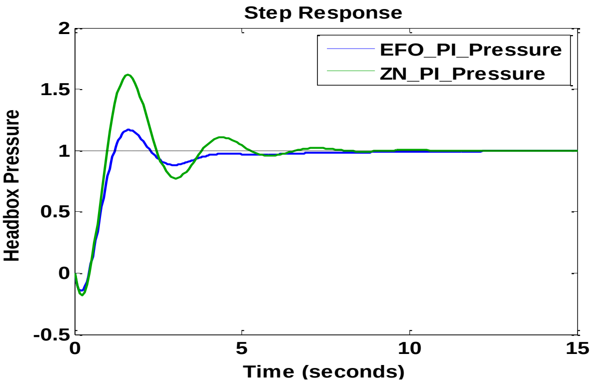

**Fig. 12:** Step Responses of P_Headbox Using PI Controller.

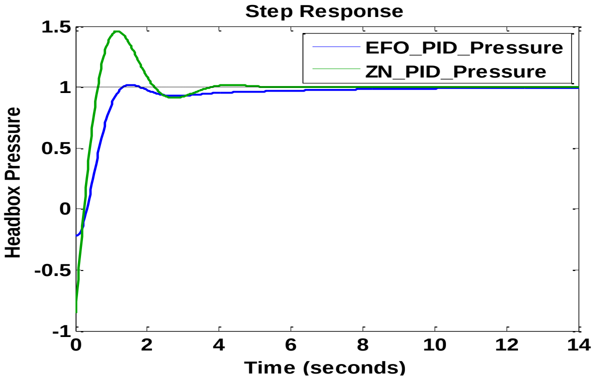

**Fig. 13:** Step Responses of P_Headbox Using PID Controller.

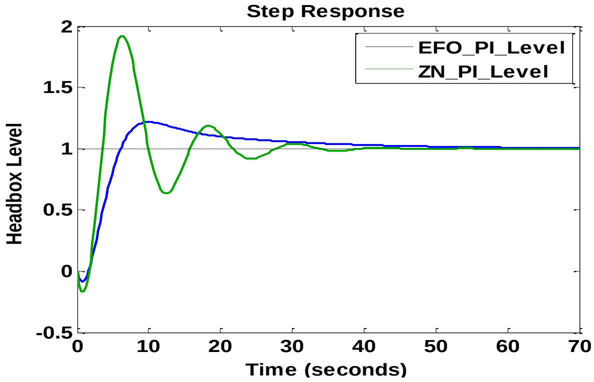

**Fig. 14:** Step Responses of L_Headbox Using PI Controller.

A comparison of step responses of the two SISO loops for EFO and ZN tuning techniques have been depicted in figure 12 to 15. Similarly, the time response values of the systems with designed controllers have been given in table 3 to 6. The rise time and settling time of P_Headbox for the PI controller designed using EFO and ZN techniques are same.

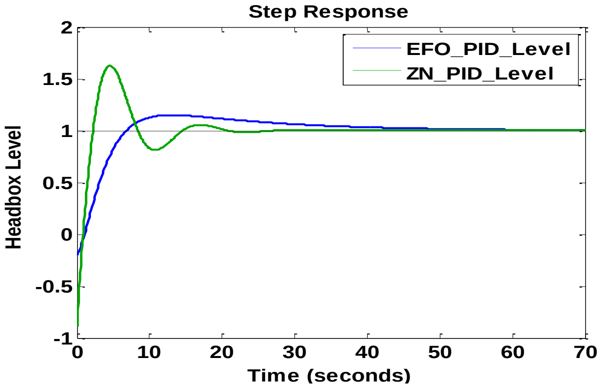

**Fig. 15:** Step Responses of L_Headbox Using PID Controller.

However, EFO_PI technique gives considerably reduced overshoot which is within acceptable limits. Similarly, from all other tables, it is seen that EFO technique of controller design is giving less overshoot as compared to ZN technique. Table 8 and 9 depict the performance indices of the two loops which clearly show that the performance index of controllers designed through EFO technique is better than ZN technique for both systems. Only ITAE (Integral of Time-weighted Absolute Error) is more in case of L_Headbox for both controllers. This is due to the large difference in rise time and settling time of L_Headbox for both tuning techniques.

**Table 3:** Time Response Values of P_Headbox for PI Controller

| Controller | Rise Time $t_r$(sec) | Overshoot $M_P$(%) | Settling Time $t_s$(sec) |
|---|---|---|---|
| EFO_PI | 0.6 | 16.7 | 6.7 |
| ZN_ PI | 0.4 | 61.8 | 6.3 |

**Table 4:** Time Response Values of P_Headbox for PID Controller

| Controller | Rise Time $t_r$(sec) | Overshoot $M_P$(%) | Settling Time $t_s$(sec) |
|---|---|---|---|
| EFO_PID | 0.78 | 1.9 | 6.7 |
| ZN_PID | 0.48 | 45.9 | 3.4 |

**Table 5:** Time Response Values of L_Headbox for PI Controller

| Controller | Rise Time $t_r$(sec) | Overshoot $M_P$(%) | Settling Time $t_s$(sec) |
|---|---|---|---|
| EFO_PI | 3.4 | 21.7 | 45.2 |
| ZN_ PI | 1.4 | 91.9 | 32.1 |

**Table 6:** Time Response Values of L_Headbox for PID Controller

| Controller | Rise Time $t_r$(sec) | Overshoot $M_P$(%) | Settling Time $t_s$(sec) |
|---|---|---|---|
| EFO_PID | 4.8 | 14.9 | 44.6 |
| ZN_ PID | 1.7 | 62.7 | 18.7 |

**Table 7:** Performance Indices of P_Headbox

| Tuning Methods | PI Controller | | | | PID Controller | | | |
|---|---|---|---|---|---|---|---|---|
| | ISE | IAE | ITSE | ITAE | ISE | IAE | ITSE | ITAE |
| EFO | 0.97 | 1.8 | 1.6 | 12.8 | 0.66 | 1.14 | 0.93 | 6.2 |
| ZN | 2.4 | 7.2 | 13.8 | 103.2 | 1.13 | 3.64 | 3.53 | 41.6 |

**Table 8:** Performance Indices of L_Headbox

| Tuning Methods | PI Controller | | | | PID Controller | | | |
|---|---|---|---|---|---|---|---|---|
| | ISE | IAE | ITSE | ITAE | ISE | IAE | ITSE | ITAE |
| EFO | 5.92 | 12.5 | 37.6 | 181.1 | 3.69 | 7.65 | 16.31 | 150.4 |
| ZN | 8.18 | 12.9 | 66.6 | 162.4 | 5.17 | 8.81 | 27.86 | 86.8 |

## 6. Conclusion

Since, there must be a reasonable trade-off between the various time response characteristics and steady state values of a system. Though, the rise time and settling time are better for ZN technique but the overshoot is very high through ZN which generally is not desirable in processes. This paper presented a design and stability analysis of paper machine headbox using a new PI(D) technique which is based on the extended forced oscillation theory and a comparative analysis with ZN tuning technique is also provided through time response and performance indices. To conclude, EFO technique gives smooth results and fewer oscillations. Also, it is better in terms of peak overshoot. Further, the EFO technique can be tested for assuming different values of phase lags contributed by the controller. Also, stability analysis using some different values of phase margins can be done and a new value of phase can be proposed.

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