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Improved Wet End Stability of Paper Machine Using Robust Controller

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Abstract: The objective of this paper is to design a robust controller for the wet end of a paper making machine. The controlled variables are ash content, basis weight and manipulated variable are filler flow rate and thick stock flow rate. This paper includes a mathematical multivariable model and presents a Linear Quadratic Gaussian (LQG) controller design for this system. For LQG, the filler flow rate acting as a disturbance. In this paper, Simulation results conclude that the stability & performance of robust controller is better than that of the PID controller in the presence of uncertainty & disturbances.

Keywords: Wet end of paper machine, Linear Quadratic Gaussian, Kalman filter, state space model.

I. INTRODUCTION

Robust control is used to control the obscure plants with obscure dynamics which subject to unknown disturbances. The key issues with robust control systems is the instability and unsettling influences i.e disturbances in the model of the plant, Also there is noise, which is read on the sensor inputs. The plant loop with uncertainties is as shown in Fig.1

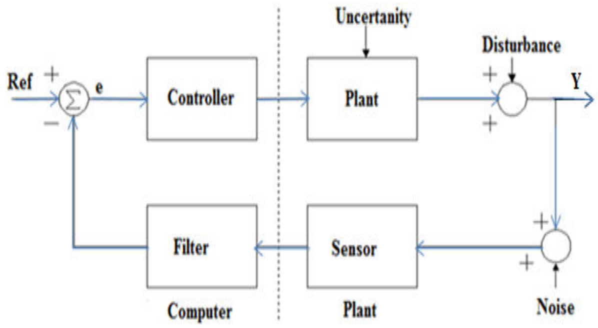

Fig.1 Plant loop control with uncertainty

A system is said to be robust when it has acceptable changes in performance and stability due to model change or in the presence of all noises. The robust control system is useful for nonlinear and complex processes. In paper industry, one of the sub system i.e wet end needs robust controller to control individual parameter in the presence of disturbances. So the system uses advance robust controller i.e linear, quadratic

Gaussian (LQG) to analyze the performance of the wet end of a paper machine

II. WET END OF PAPER MAKING MACHINE

The wet end Process essentially comprises of the approach flow system, fiber recovery. The approach flow includes blending chest, consistency regulators and controllers, flow control devices and constant head tank/stuff box, magnetic flow meter, basis weight valve(stock valve), secondary refiner, mixing box (to mix with white water) and machine chest. The wet end of paper machine as shown in Fig.2. The stock is pumped by primary fan pump to a series of centri-cleaners at a consistency of 0.6-1.0% consistency and then again to vacuum treatment and screening operation [3].Refining usually refers to fiber separation and cutting, the pulp from stock preparation section enters to head box. The function of the head box is to receive cleaned pulp stock at the consistency of 0.2-0.8 % and distribute it uniformly across the width of wire at constant head.

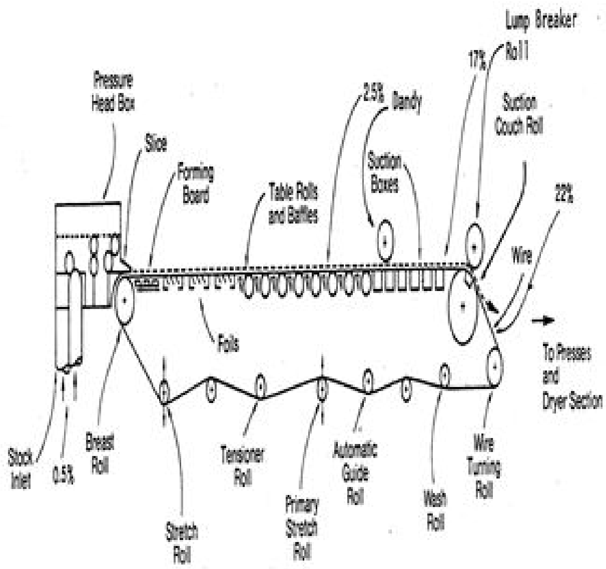

Fig2. Wet end of Paper Making Machine

The wire part consists of endless wire to support the weak web and water. When stock enters on the wire the consistency of stock remains 0.5-0.6 %. About 97 % water is removed on the wire part, 1.5% on the press section and about 1.0 % by the dryer part. Out of 97 % water removal on wire part, 83-85 % is drained in forming zone mainly due to table rolls; 10-12 % is removed by wet & dry suction boxes and 2-3 % by Suction Couch roll. Dandy roll and shake are used to improve the sheet formation. Dandy roll is also used for water marking, it also smoothens the top surface of paper, and it helps in breaking froth bubbles. It also makes a sheet more dense

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and compact. In the wire section of paper machine natural drainage of water takes place by gravity, which is collected in rich wire tank and recirculated back to head box via fan pump.

III. DYNAMICE MODEL FOR WET END PROCESS

The dynamic model can be an essential tool in the design of new system and in modification of existing system. For a multivariable 2×2 processes, with ash content (Y_1), basis weight (Y_2) as outputs and filler flow rate (U_1), thick stock flow rate (U_2) as inputs, is modeled as [1]

$$Y_1 = \frac{0.214e^{-68s}}{125s+1}U_1 + \frac{-0.192e^{-68s}}{17s+1}U_2 \qquad (1)$$

$$Y_2 = \frac{0.153e^{-68s}}{125s+1}U_1 + \frac{0.93e^{-68s}}{17s+1}U_2 \qquad (2)$$

Firstly, identify the interaction between multiple input and multiple output variables. The interaction exists between outputs Y_1, Y_2 & inputs U_1, U_2 [2].
As each transfer function of model is a first order plus dead time so the exponential term is linearize by first order Pade's approximations is given as:

$$e^{-t_d s} = \frac{1-\frac{t_d}{2}s}{1+\frac{t_d}{2}s} \qquad (3)$$

By using MATLAB, the linearized new model is given by:

$$Y_1 = \frac{-0.214s+0.006294}{125s^2+4{,}676s+0.02941}U_1 + \frac{0.192s-0.005647}{17s^2+1.5s+0.02941}U_2 \qquad (4)$$

$$Y_2 = \frac{-0.53s+0.01559}{125s^2+4.676s+0.02941}U_1 + \frac{-0.93s+0.02735}{17s^2+1.5s+0.02941}U_2 \qquad (5)$$

IV. DESIGN OF ROBUST CONTROL

A few methods are there to design the robust controller. But, LQG technique is more suitable because LQG identified with the uncertainty of the linear system, which is disturbed by additive white Gaussian noise. LQG is the mixture of linear, quadratic controller (LQR) & Kalman filter or linear,quadratic estimator. In this present work a linear, quadratic Gaussian (LQG) has been designed for the wet end of the paper machine. For designing LQG, the filler flow rate is acting as a disturbance and the following steps have to be followed:
Wet end system is described to the continuous-time state equation as presented by Gopal [5]

$$\dot{x} = Ax+Bu \qquad (6)$$

A cost functional or performance index, J is also defined for system dynamics

$$J = \int_0^{\infty} (x^T Q x + u^T R u)dt \qquad (7)$$

The cost function is quadratic in state and quadratic in control and final time is infinity, the control law that minimizes the value of the cost function i.e.

$$u = -K_c x \qquad (8)$$

$$K_c = R^{-1}B^T P \qquad (9)$$

Where, x, State vector, n×1
A, time-varying real matrix=n×n
B, time-varying real matrix=n×p
u, Input vector = p×1
Q, positive semi definite n×n matrix
R, positive definite p×p matrix
x^T, State error
K_c, LQR gain

By solving the continuous time algebraic Riccati Eq. (10), where $P=P^T \geq 0$ is the unique +ve semi definite solution of algebraic Riccati equation

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \qquad (10)$$

The LQR is a state feedback controller, but sometimes there may be difficulty in obtaining the states in the stochastic environment. So another function is needed, called an observer or estimator.
The kalman filter is used to estimate the state of a process, in a way that minimizes the mean of the squared error.Kalman filter is characterized by the state equation and the measurement equation, shown in equation. (11) & (12) respectively & in Fig 3.

$$\dot{X} = Ax+Bu+W \qquad (11)$$

$$Y = Cx+V \qquad (12)$$

Where, x=n×1, state vector
u=p×1, control vector
A= n×n, characterizing matrix
B=n×p, control matrix
Y=q×1, measurement vector
C=q×n, measurement matrix
W=n×1, state excitation noise vector
V=q×1, sensor noise vector

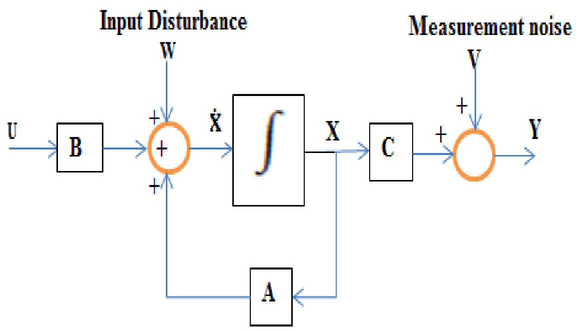

Fig.3 System representation including i/p disturbance and measurement noise

Under these conditions, knowing the input and output of the system, the Kalman filter provides an optimal estimate of the state of the process 'x', by minimizing the variance of the estimation error and constraining the average of the estimated outputs.
The LQG controller is the combination of a Kalman filter i.e LQE & LQR is based on separation principle which guarantees that these can be designed and computed independently. Using LQG, the state space model for the ash content, thick stock flow rate is expressed as

$$\dot{X} = Ax+Bu \qquad (13)$$

$$Y = Cx+Du \qquad (14)$$

$$\text{Where, } A = \begin{pmatrix} -0.0882 & -0.0554 \\ 0.0313 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} 0.1250 \\ 0 \end{pmatrix}$$

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C = 0.0904 0.0850
D = 0

Similarly, from Eq. (13) and (14) are the state space model for the basis weight (Y_2) and thick stock flow rate (U_2) is expressed as

Where, $A = \begin{pmatrix} -0.0882 & -0.0554 \\ 0.0313 & 0 \end{pmatrix}$

$B = \begin{pmatrix} 0.2500 \\ 0 \end{pmatrix}$

C = -0.2188 0.2059
D = 0

V. RESULT & ANALYSIS

In case of PID controller, the Fig.4 shows the step response of MIMO system. The step response between ash content and filler flow rate reveals that it takes 563 Sec. to settle. For the basis weight and filler flow rate the settling time is 690 Sec, Also the step response between ash content and thick stock reveals that it takes 1010 Sec. to settle. The settling time for basis weight and thick stock flow rate is 494 Sec.

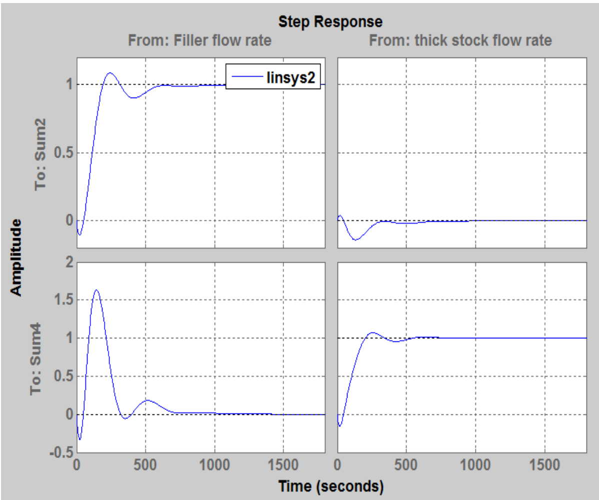

Fig.4 Step response for MIMO system using PID controller

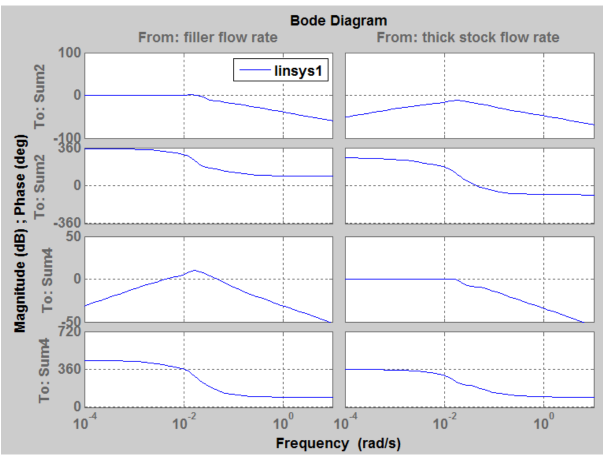

Fig.5 Bode plot for MIMO system using PID controller

The Fig.5 shows the bode response for MIMO system using PID controller. The phase margin is 47degree and gain margin is infinite for ash content and filler flow rate. The phase cross-over frequency is 0.0182 rad/sec and bandwidth is 0.0225 rad/sec.

For the basis weight and filler flow the phase margin is 19 degree and gain margin is infinite. The phase cross-over frequency is 0.0454 rad/sec and bandwidth is equal to 0.0592 rad/sec, also bode plot response between ash content and thick stock flow rate reveals that it has infinite gain and phase margin. For basis weight and thick stock flow rate gain margin is infinite and phase margin is 90 degree. The phase cross-over frequency is 0.0139 rad/sec and bandwidth is equal to 0.0204 rad/sec.

When white noise (disturbance) is introduced in PID MIMO system. The output response is affected by the disturbance and is shown in Fig's 6 & 7. So, we check the statistical data for ash content and basis weight. The standard deviation for ash content is 1.037 and standard deviation for basis weight is 1.051.

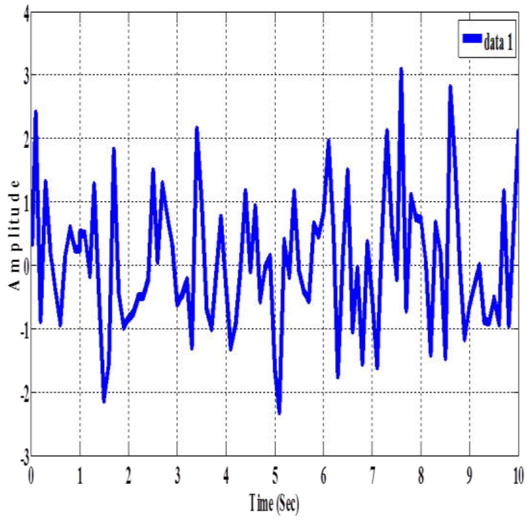

Fig.6 Output response for ash content using PID controller in presence of disturbance

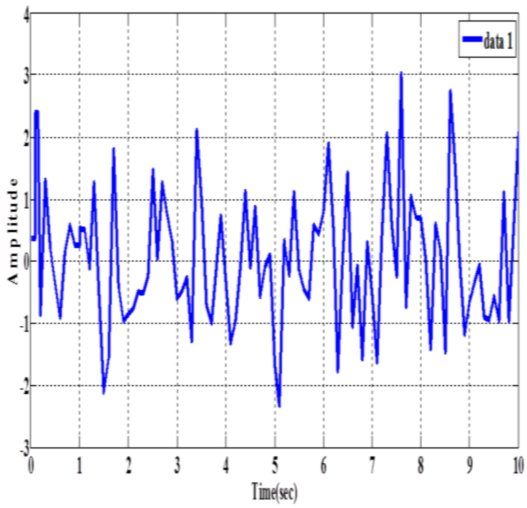

Fig.7 Output response for basis weight using PID controller in presence of disturbance

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PID controller doesn't give good results in presence of disturbances. So, we design a robust controller. Robust controller is designed to analyze the response of the ash content and basis weight of wet end system. To show the effectiveness of this approach, the output response for the same system is shown in Fig.8 & Fig.9 respectively. Here filler flow rate acts as a disturbance. The step response for ash content w.r.t thick stock flow rate is shown in Fig.8 it settles after 66.5 Seconds and for the basis weight w.r.t thick stock flow rate is shown in Fig.9 it settles after 170 Seconds.

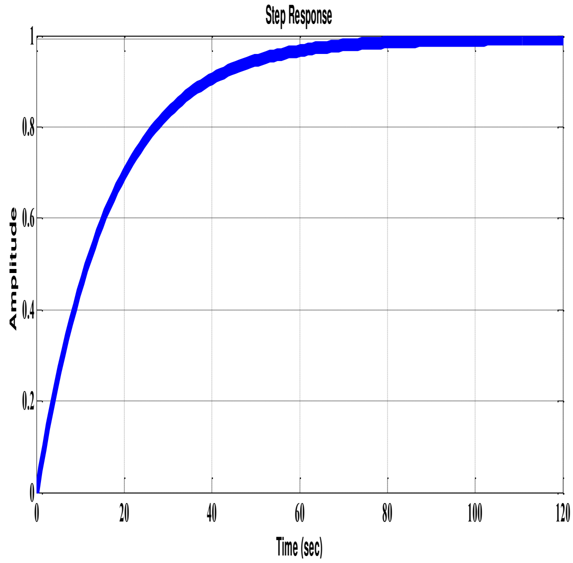

Fig.8 Step response for ash content using LQG

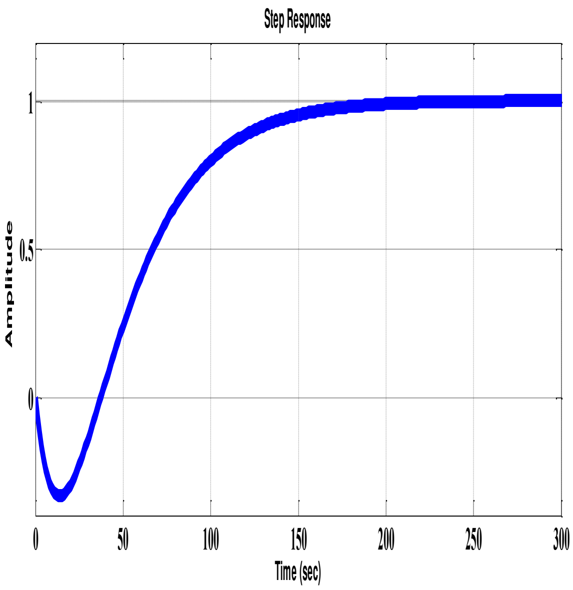

Fig.9 Step response for Basis weight using LQG

Using LQG, the bode response for ash content w.r.t thick stock flow rate is shown in Fig.10 it has infinite gain and phase margin. Fig.11 shows the bode response for the basis weight w.r.t thick stock flow rate.The figure reveals that it has 3.48 db gain margin and 155 degree phase margin. The gain and phase cross-over frequencies are 0.0658 rad/sec and 0.0053 rad/sec.

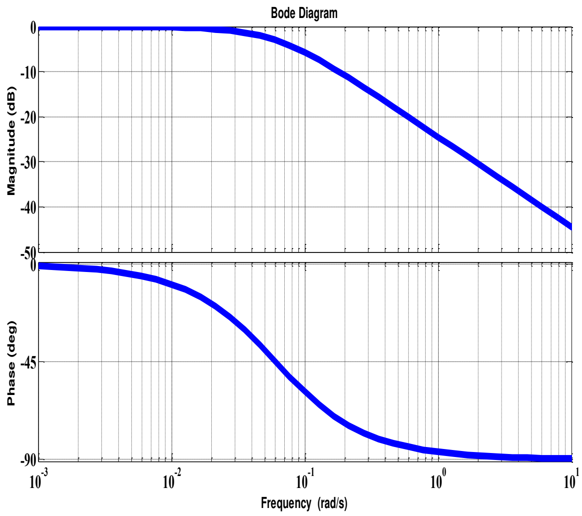

Fig.10 Bode plot for ash content using LQG

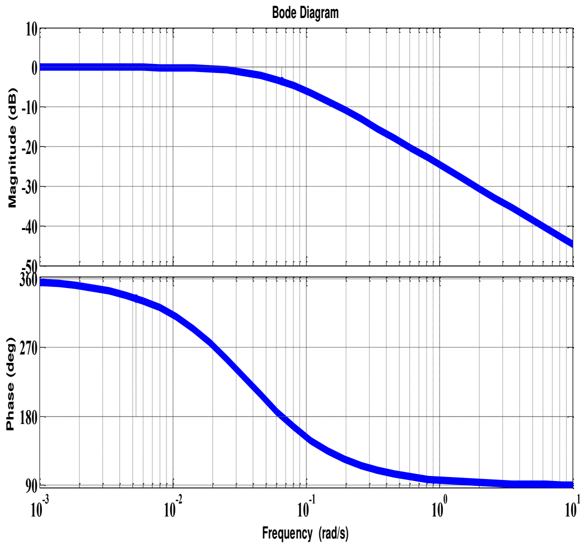

Fig.11 Bode plot for basis weight using LQG

Using PID & LQG controller,the comparision of dynamic performance parameters like rise time, settling time, peak time, overshoot, gain & phase margin of the wet end system as shown in Table I.

Table I. Comparison of PID & LQG controller performance parameters

TECHNIQUES →	PID CONTROLLER		LQG CONTROLLER	
PERFORMANCE PARAMETERS ↓	***Ash content***	***Basis weight***	***Ash content***	***Basis weight***
Rise Time (sec)	104	117	37.3	82.2
Settling Time (sec)	563	494	66.5	170
Peak Time (sec)	242	258	132.8	353.3
Overshoot (%)	8.5	7.05	0	0
Gain Margin (dB)	infinite	infinite	infinite	3.48
Phase Margin (degree)	infinite	90	infinite	155
Stability	Stable		Stable	

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VI. CONCLUSION

The Simulation results conclude that the stability & performance of robust controller is better than that of the PID controller in the presence of uncertainty & disturbances. Robust controller has also been shown to be more powerful tool that can reduce time domain performance parameters & effort involved in designing wet end system for which no systematic design procedure exists.

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