Nat. Volatiles & Essent. Oils, 2021; 8(5): 3303-3313

NVEO
Natural Volatiles &
Essential Oils

Composite Active Disturbance Rejection Controller For Magnetic Levitation System

[1]Arun Kumar Pinagapani , [2]Vipin Kumar P E

[1]I&CE Department,
PSG College of Technology,
Coimbatore, Tamil Nadu, IndIa
arunkumarakshai@gmail.com
https://orcid.org/0000-0003-4602-9944

[2]EEE Department,
LBS College of Engineering,
Kasargod, Kerala, Inida
vpnkumarpe@gmail.com

Abstract

A composite Active Disturbance Rejection Controller (ADRC) and Proportional Integral Derivative (PID) controller are designed and implemented for the stabilization of steel ball in a magnetic levitation (MAGLEV) system. The performance of the two controllers are analysed under two scenarios namely with and without disturbance. Simulation results prove the competence of composite ADRC and it outperforms conventional PID controller. Simulations were carried out in MATLAB.

Keywords*— ADRC, PID, MAGLEV, Composite controller, Disturbance rejection*

I. Introduction

Magnetic levitation is a technique for suspending an item in the air using magnetic force. The goal here is to levitate the steel ball into a specific ball position. The control concern is to give a regulated current to the coil such that the magnetic force on the levitated body is exactly equal to the gravity force operating on it. As a result, without any control action, the magnetic levitation system is inherently unstable. It is desirable to not only lift the object, but also to keep it in a specific position or to follow a specific path.

A steel ball, photo emitters, photo receivers, and a ball post make up the magnetic levitation system. An electromagnetic force is created when electricity is delivered to the electromagnet, which causes the steel ball to hover in the air. There are three sections to the maglev system. An electromagnet composed of a solenoid coil with a steel core is located in upper part. The ball will be suspended in the central portion of the track[1]. The signal conditioning unit for the light intensity position sensor is the other portion. These photo emitters and photo receivers can be used to determine the ball's location.

There are several controllers created for magnetic levitation systems[6],[8],[16],[17] and one that provides the best results in the face of disturbances is particularly intriguing. An observer, specifically a disturbance observer, can assist with this. Disturbance accomodation control (DAC), Extended high gain state observer (EHGSO), Active disturbance rejection control (ADRC), and other disturbance-observer-based regulating strategies exist. As a result, it's clear that the rejection of disturbances and uncertainty is a crucial goal for control system design[2].

The usage of disturbance as a prolonged state of the system that is subsequently cancelled by an observer's activity is a useful way to get better outcomes. Using a reduced order state observer rather than a full order observer will give you a solid notion of how to cancel out the influence of disturbances that affect the performance of the system[3].

The controller design begins by focusing on settling time and peak overshoot as main issues. The design of PID-ADRC and the design of Reduced Extended State Observer are the primary components included in the controller design (RESO). The main principle is to model the system with an input disturbance that reflects any difference between the model and the actual system, including external disturbances; this input is then lumped into the term f, and it is assumed to be one of the system's states. An ESO's estimate of this condition can be employed in a control signal to adjust for actual plant disruption. The ADRC tuning process was first suggested in a nonlinear version. The structure was reduced to its simplest form, the tuning is basically a pole placement approach, and the required performance is accomplished indirectly through the placement of the closed loop poles. However, the ultimate selection of these poles becomes a trial-and-error technique that practising engineers may find challenging to completely comprehend and successfully apply to real-world systems[5], [7].[9],[10],[11],[12],[13],[15]. In current optimal control theory, the linear quadratic regulator is a well-known design method that has been widely applied in a variety of applications. Unlike the pole-positioning method, the desired performance objectives are directly addressed by reducing the quadratic function of the state and control input. [4]. The key contribution is to use the LQR methodology and decreased tuning parameters to achieve an optimal tuning of the ADRC method that guarantees some closed loop specifications

II. SYSTEM MODELLING

The mechanical system, which controls the location of the ball by altering the coil current, and the electrical system, which controls the coil current by adjusting the coil voltage are the two subsystems. As a result, the coil voltage may regulate the ball's location. Fig. 1 illustrates a typical MAGLEV.

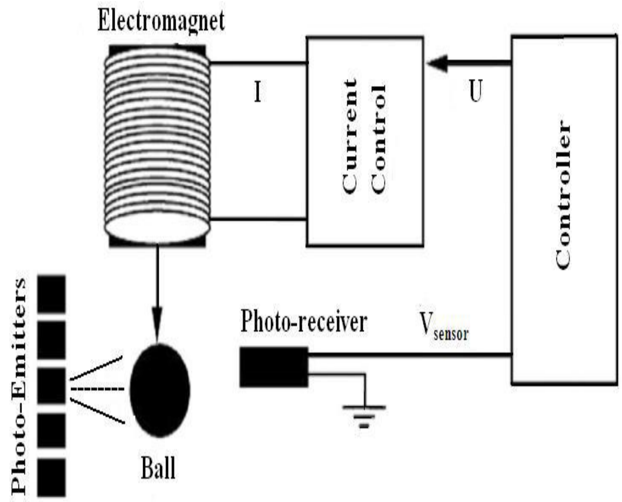

Fig 1 MAGLEV system

The model of the MAGLEV is shown in Fig 2, L_c is the inductance of the electromagnetic coil, M_b is the mass of the steel ball, R_c is the resistance of the electromagnetic coil, X_b is the ball position and F_g is the gravitational force.

The mathematical model of a magnetic levitation system is given as follows. The mathematical model of this electro-magnetic system is used to determine the transfer function of the system from which the performance of the system can be analysed. Applying Kirchhoff's voltage law to the electrical circuit shown in Fig 2.

$$V_c = (R_c + R_s)I_s + L_c\frac{d}{dt}I_c \quad (1)$$

Applying Laplace transformation to obtain transfer function

$$G_c(s) = \frac{I_c(s)}{V_c(s)} = \frac{1}{(R_c+R_s)+L_c} \quad (2)$$

So,

$$G_c(s) = \frac{K_c}{\tau_c s+1} \quad (3)$$

Where

$K_c = \frac{1}{(R_c+R_s)}$ and $\tau_c = \frac{L_c}{(R_c+R_s)}$

A. M*otion of ball*

The gravitational force on the ball is

$$F_g = M_b g \quad (4)$$

The force generated by electromagnet is

$$F_c = -\frac{1}{2}K_m\frac{{I_c}^2}{{X_b}^2} \quad (5)$$

So the total force experienced by the ball can be expressed as $F_g + F_c == M_b g - \frac{1}{2}K_m\frac{{I_c}^2}{{X_b}^2}$ (6)

Finally, the nonlinear motion of the ball is expressed by applying Newton's second law

$$\frac{d^2X_b}{dt^2} = -\frac{1}{2}\frac{K_m{I_c}^2}{{X_b}^2} + g \quad (7)$$

Setting all time derivative terms to zero at equilibrium point.

$$-\frac{1}{2}\frac{K_m{I_c}^2}{{X_b}^2} + g = 0 \quad (8)$$

At equilibrium, coil current I_{c0} can be expressed as (8) as a function of X_{b0} and K_m

$$I_{c0} = \sqrt{\frac{2M_b g}{K_m}}X_{b0} \quad (9)$$

The electromagnet force constant K_m , can be obtained using equation (8) as

$$K_m = \frac{2M_b g{X_{b0}}^2}{{I_{c0}}^2} \quad (10)$$

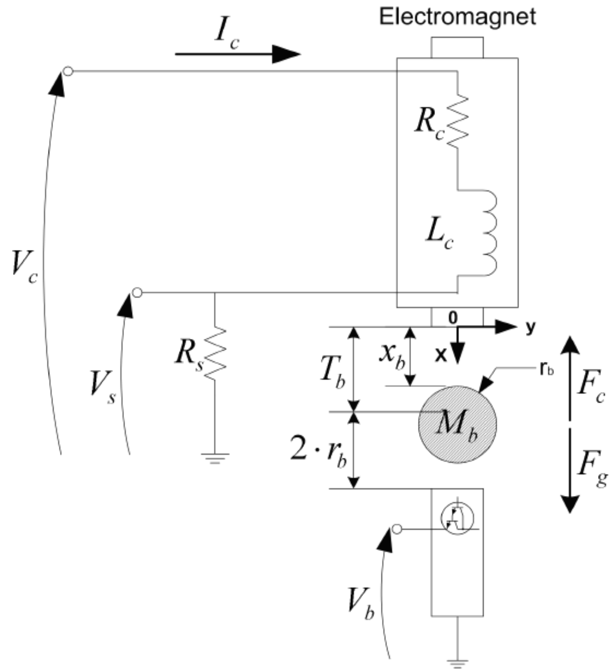

Fig 2. Schematic representation of the MAGLEV plant

The nominal coil current I_{c0} can be obtained at the static equilibrium point.

B. Linearization of motion

The system must be linearized around the equilibrium point where the ball suspension occurs in order to construct a linear controller. Taylor's series is used to linearize the nonlinear system equations around the operational point. Applying Taylor's series approximation to equation (8) to obtain

$$\frac{d^2 X_{b1}}{dt^2} = -\frac{1}{2}\frac{K_m I_{c0}{}^2}{M_b X_{b0}{}^2} + g + \frac{K_m I_{c0}{}^2 X_{b1}}{M_b X_{b0}{}^3} - \frac{K_m I_{c0} I_{c1}}{M_b X_{b0}{}^2} \tag{11}$$

Substitute equation (10) in (11)

$$\frac{d^2 X_{b1}}{dt^2} = \frac{2g X_{b1}}{X_{b0}} - \frac{2g I_{c1}}{I_{c0}} \tag{12}$$

Applying Laplace transform to (12)

$$G_b(s) = -\frac{K_b \omega_b{}^2}{s^2 - \omega_b{}^2} \tag{13}$$

where $K_b = \frac{X_{b0}}{I_{c0}}$ and $\omega_b = \sqrt{\frac{2g}{X_{b0}}}$

Therefore, the open loop transfer function of a maglev system is a type zero, second order system. The two open loop poles of the system are located at $s = \pm\omega_b$.

In this work, a ADRC is designed not only to levitate the ball but also to follow the desired trajectory even when disturbances are applied.

Table 1. PARAMETERS OF THE MAGNETIC LEVITATION SYSTEM[14]

Symbol	**Description**	**Value**	**Unit**
L_c	Coil inductance	412.5	mH
R_c	Coil resistance	10	Ω
N_c	Number of turns in the coil wire	2450	
l_c	Coil length	0.0825	M
r_c	Coil steel core radius	0.008	M
R_s	Current sense resistance	1	Ω
K_m	Electromagnet force constant	6.5308E-005	$N.m^2/A^2$
R_b	Steel ball radius	1.27E-002	M
M_b	Steel ball mass	0.068	Kg
K_b	Ball position sensor sensitivity	2.83E-003	m/V
G	Gravitational constant	9.81	m/s^2
I_{c_max}	Maximum continuous coil current	3	A

III. COMPOSITE ADRC DESIGN

The composite ADRC general block diagram is as shown in Fig 3.

A. ADRC design

Nonlinear system can be represented as

$$y(t)^n = f + u_1(t) \tag{14}$$

Where f is the whole structural information of the system including disturbances, Where $u_1(t) = \hat{\alpha}u(t)$ is the control law and

$$u_1 = u_0 - z_n \tag{15}$$

With Z_n being the extended state.

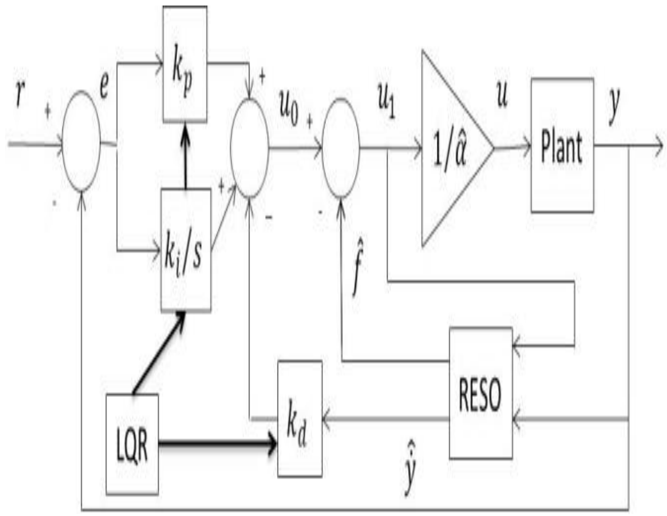

Fig 3 Block Diagram of Composite ADRC

On rearranging and simplification (14),

$$y(t)^n = u_0(t) \quad (16)$$

Where

$$u_0(t) = k_p e(t) + k_i \int e(t)dt + k_{d1}\frac{de}{dt} +$$
$$k_{d2}\ddot{e}(t) + .. k_{d_{n-1}} e^{(n-1)}(t) \quad (17)$$

(17) is the general control law. With regard to system order, the equation changes. The number ‘n' represents the selected system's order. It is 3 in the case of a magnetic levitation

.

The tracking error is as.

e(t)=r–y(t) (18)

Set point reference r is

$$\ddot{e} = -\ddot{y}(t) \quad (19)$$

$$e(t)^{n+1} = -\dot{u_0}(t) \quad (20)$$

$$\dot{v}(t) = Fv(t) + G\dot{u_0}(t) \quad (21)$$

LQR formulation of the ADRC is

$\dot{u_0}$(t) = -$[k_1 \quad k_2 \quad k_3 \quad \dots\dots.. \quad k_{n+1}]$ (22)

Gain values are

$$[k_i \quad k_p \quad k_{d_1} \quad k_{d_2} \quad \dots \quad k_{d_{n-1}}] =$$
$$-[k_1 \quad k_2 \quad k_3 \quad \dots \quad k_{n+1}] \quad (23)$$

P matrix is

$$P=\begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots. & p_{1,n+1} \\ p_{12} & p_{22} & p_{23} & \cdots. & p_{2,n+1} \\ p_{13} & p_{23} & p_{33} & \cdots. & p_{3,n+1} \\ \cdots & \cdots & \cdots & \cdots. & \cdots. \\ p_{1,n+1} & p_{2,n+1} & p_{3,n+1} & \cdots. & p_{1,n+1} \end{bmatrix} \quad (24)$$

Optimal feedback gain is

$$K=\rho^{-1}G^{T}P \quad (25)$$

B. Optimal design

As previously stated, ADRC is based on the separation concept, which permits considering unknown dynamic and disturbances in a physical process as generalised disturbances, building an ESO to estimate them in real-time, and then cancelling their influence using the estimate as part of the control signal.

In PID-ADRC method,

$$\dot{z}(t) = Az(t) + Bu_1(t) + L(\dot{y} - \hat{y}) \quad (26)$$

$$\hat{y} = Cz(t). \quad (27)$$

Replacing $A \leftarrow A^T$, $B \leftarrow C^T$ and $K \leftarrow L^T$.

$$J = \int_0^\infty \left(z(t)^T Q_0 z(t) + \rho_0 u_1^2(t) \right) dt \quad (28)$$

$$AM + MA^T + Q_0 - \rho_0^{-1} M C^T C M = 0 \quad (29)$$

The subsystem for RESO is designed using the following extended state space equation.

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ . \\ . \\ \dot{z}_n \end{bmatrix} = \begin{bmatrix} \beta_1 & 1 & 0 & : & 0 \\ \beta_2 & 0 & 1 & : & 0 \\ : & : & : & : & : \\ : & : & : & : & : \\ \beta_n & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ : \\ : \\ z_n \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ : \\ 1 \\ 0 \end{bmatrix} u_1 + \begin{bmatrix} \beta_1 \\ \beta_2 \\ : \\ : \\ \beta_n \end{bmatrix} \dot{y} \quad (30)$$

Where

$z = [z_1 \quad z_2 \quad : \quad : \quad z_n]^T = [\hat{y} \quad \hat{\dot{y}} \quad : \quad : \quad \hat{f}]^T$ are extended states.

β_1, β_2,… are observer gains.

The optimal RESO gain is

$$L = \rho_0^{-1} M C^T = [\beta_1 \quad \beta_2 \quad \ldots\ldots\ldots. \quad \beta_n]^T \quad (31)$$

Because this is normally a high-frequency signal, a big number for observer gain will amplify the influence of measurement noise. A trade-off between response time and noise immunity is required.

IV. RESULTS AND DISCUSSIONS

A. Open loop response of magnetic levitation system

Giving direct input to the system and analysing its attributes is the open loop response of the system. To determine the process time constant, process gain, and process dead time, the open loop response test is utilised. Because the output is not feedback, it has no effect on the system's reaction.

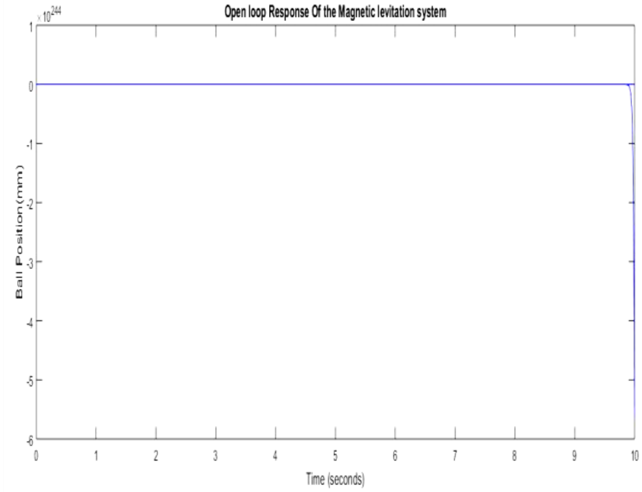

Fig. 4 Open loop response of magnetic levitation system

From the open loop response shown in Fig 4, it is inferred that MAGLEV is inherently unstable and does not settle at any time. The answer is exponentially rising since there is only one right half pole. In the system, the ball will not maintain a position.

B. Without disturbance

In comparison to the typical PID controller, which has some overshoot in the response, the composite ADRC controller produces a response with no overshoot. In terms of overshoot, Composite ADRC outperforms traditional ADRC as shown in Fig 5.

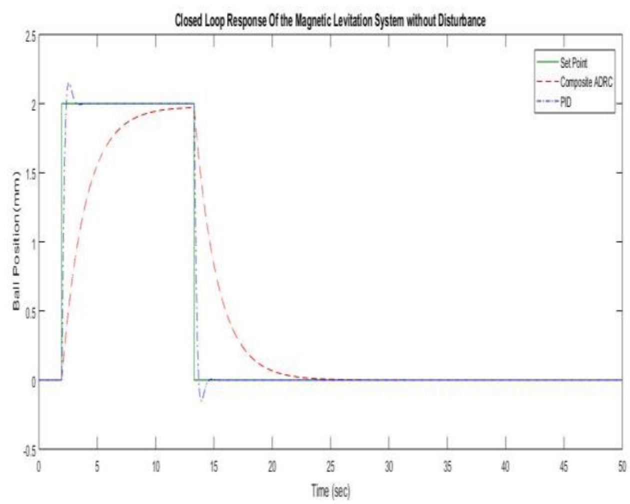

Fig.5 Closed loop response without disturbance

C. With disturbance

In the face of a disturbance, Composite ADRC performs well. As a result, the final reaction is overshootless. PID provides a reasonable settling time but fails to eliminate overshoot. PID was unable to offer an optimal outcome after causing step disruption as shown in Fig. 6.

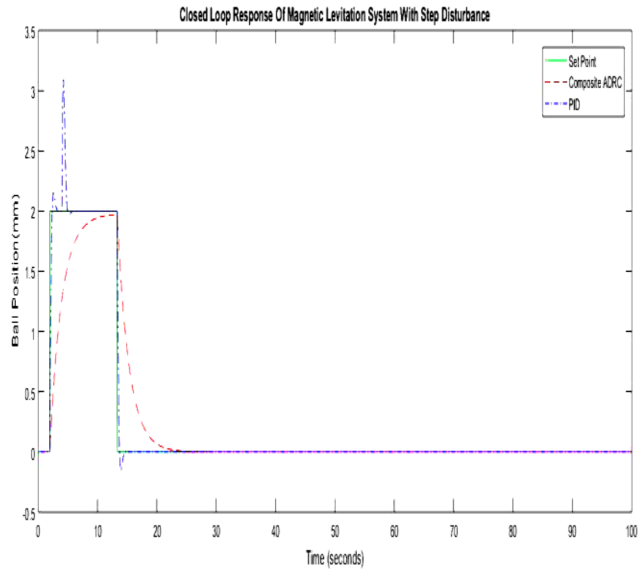

Fig.6 Closed loop response with step as disturbance

D. With random disturbance

When compared to Composite ADRC, the PID controller's response becomes bad when random disturbance is introduced. In this situation, the precise disturbance rejection can be seen. As a result, as demonstrated in Fig 7, Composite ADRC is a better controller for disturbance rejection.

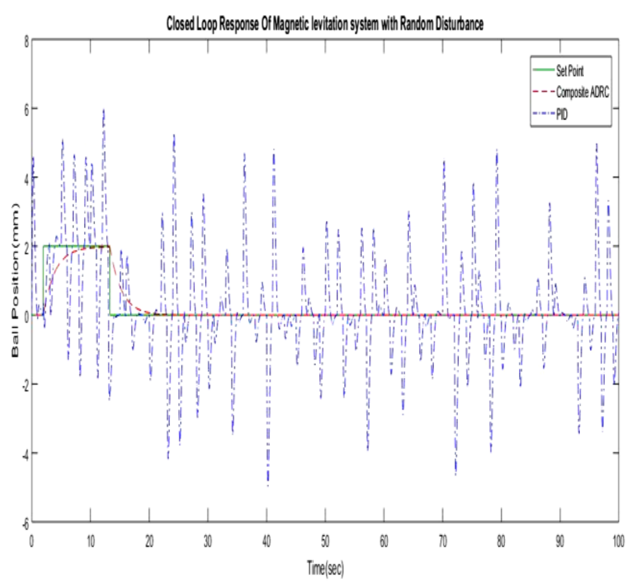

Fig 7.Closed loop response with random disturbance

V. CONCLUSION

In real time, most PID controllers are used, however the composite ADRC does not rely on the plant model and instead treats the disturbance as one of the states, which is then cancelled out by the Reduced Extended State Observer's subsequent action (RESO). PID has a poor reaction when diverse disturbances are applied to the system, especially when a random source is used as a disturbance. After setting the desired specifications and comparing the two controllers, Composite ADRC provides a decent response without overshoot, whereas PID provides an overshoot response. As a result, the Composite ADRC provides a more accurate answer. The Composite ADRC has a settling time of 10 seconds, whereas the PID has a settling time of 2 seconds. When comparing Composite ADRC to standard ADRC, Composite ADRC produces superior results, with an ADRC response of 18 seconds, which is longer than Composite ADRC's. Despite the longer settling period, there is no overshoot in the presence of any disturbances. Overshooting occurs as a result of the PID controller.

References

1. Ahmed El Hajjaji and M Ouladsine, "Modelling and Nonlinear control of magnetic levitation systems," IEEE Transactions on industrial electronics., Vol.48,No.4,August 2001.
2. Wen-Hua Chen, Jun Yang, LeiGuo, and Shihua Li, "Disturbance-Observer-Based Control andRelated Methods—An Overview," IEEE Transactions on Industrial Electronics, Vol. 63, no.2, 2016.
3. Jacob-.J.Vasquez-sanjuan,JesusLineares Flores,Luis I Olivos Perez, "Comparison between the algebraic and the reduced order extended state observer approaches for on-line load torque estimation in a speed control for PMSM system,"IEEE Transactions On Industrial Electronics.,Vol.5,No.4,2015.
4. PedroTeppa-Garran,Germain Garcia,"Optimal Tuning of PI/PID controllers in Active Disturbance Rejection Control," CEAI.,Vol.15,No.4,pp.26-36,2013.
5. Han, Jingquing ,"From PID to active disturbance rejection control,"IEEE transactions on Industrial Electronics.,Vol.56,No.3,pp.900-906,2014.
6. Rao, C. Sankar and M. Chidambaram, "Subspace Identification Of Unstable Transfer Function Model for a Magnetic Levitation System,"IFAC Proceedings., Vol.47,No.1, 394-399, 2014.
7. Shangyao Shi,Jun Li and Shiping Zhao, "On design Analysis of Linear Active Disturbance Rejection Control for uncertain systems", International Journal for control and automation., Vol.7,No.3,2014.
8. Elahi,Tooraj Hakim and Abdolmir Nekoubin, "Optimal Controller Design for Linear Magnetic Levitation Rail system," International Journal of Computer,Electrical, Automation, Control and Information Engineering., Vol.5,No.10,2011.
9. M.Przybyla,M.Kordasz, "Active Disturbance Rejection Control of 2DOF manipulator with significant modeling and uncertainty,"International Journal Of Polish Academy Of Science.,Vol.60,No.2,December,2012.
10. Inou and Ishida, "Design Of a model followingController using a decoupling Active Disturbance Rejection control
11. method,"Journal Of Electrical and Electronic Systems.,February, 2016.
12. Huang ,Yi and Wenchao Xue, "Active disturbance rejection control:methodology and theoretical analysis," ISA Transactions.,Vol.53,No.4,pp.963-976,2014.
13. Zhe Gao,"Active disturbance rejection control for nonlinear fractional-order systems,"International Journal Of Robust and Nonlinear Control.,Vol.26,No.4,2010.
14. Guo Dong,Fu Yongling,Lu Ning,Long Manlin,"Application of ADRC technology in electrohydraulic force servo system,"Journal of Beijing University of Aeronautics and Astronoutics.,Vol.13,No.4,2013.
15. Kumar, Elumalai Vinodh and Jovitha Jerome. "LQR based Optimal Tuning of PID Controller for Trajectory Tracking of Magnetic Levitation System." *Procedia Engineering* vol.64, 254-264, 2013.
16. P. Teppa-Garran and G. Garcia, 'ADRC Tuning Employing the LQR Approach for Decoupling

Uncertain MIMO Systems', Vol.43,No.2,2014

17. Kumar E, Vinodh & Jerome, Jovitha, 'Algebraic Riccati equation based Q and R matrices selection algorithm for optimal LQR applied to tracking control of 3rd order magnetic levitation system' Archives of Electrical Engineering, Vol.65, No.1, 2016.
18. Y. Eroğlu and G. Ablay, "PI-V plus sliding mode based cascade control of magnetic levitation," 2015 9th International Conference on Electrical and Electronics Engineering (ELECO), 2015, pp. 785-789.