All Sciences Proceedings
http://as-proceeding.com/

1st International Conference on Modern and Advanced Research

July 29-31, 2023 : Konya, Turkey

https://as-proceeding.com/index.php/icmar

Disturbance Observer based Fractional Order Iterative Learning Control of Helicopter Model

Muhammad Zulqarnain Haider Ali [1], Inam ul Hasan Shaikh [2] and Ahsan Ali [3]

[1]*Department of Electrical Engineering, University of Engineering & Technology Taxila, Pakistan*
[2]*Department of Electrical Engineering, University of Engineering & Technology Taxila, Pakistan*
[3]*Department of Electrical Engineering, University of Engineering & Technology Taxila, Pakistan*

[1] *mzulqarnain.haider@students.uettaxila.edu.pk*
[2] *inam.hassan@uettaxila.edu.pk*
[3] *ahsan.ali@uettaxila.edu.pk*

Abstract – The Twin Rotor Aerodynamic System (TRAS) provides a general representation of the aerodynamic characteristics of helicopters as well as other hovering rotor vehicles. Due to the nonlinear nature of the system and the substantial cross-coupling between the inputs and outputs of the main and tail rotors, managing such a system for either stabilization or reference tracking is a challenging challenge. The reference tracking and disturbance rejection problem for a Multi-Input Multi-Output (MIMO) TRAS is investigated in this study using a hybrid architecture based on a Fractional Order Proportional Integral Derivative (FOPID) controller with an Extended Kalman Filter (EKF) as a Disturbance Observer (DOB) and Proportional Derivative Iterative Learning Control (PD-ILC) (FOPID-EKF-DOB-PD-ILC). The system is divided into subsystems for the main and tail rotors. Since TRAS is unstable and ILC is only used for stable systems, FOPID controller is employed to stabilize the plant. Sequential quadratic programming (SQP) is used to calculate the parameters of the FOPID controller. To lessen tracking error and gradually enhance system performance, PD-ILC is applied as a feedforward controller. ILC is employed in this situation as an external controller with no effect on the current control architecture. The FOPID-EKF-DOB controller adjusts the new control input according to the PD-ILC control law. Results from the simulation are used to evaluate the efficiency of the suggested strategy based on performance metrics.

Keywords – FOPID, ILC, Extended Kalman Filter, DOB, Twin Rotor Aerodynamic System

I. INTRODUCTION

Unmanned aerial vehicles (UAVs), which have been used in a number of applications, include fixed-wing planes, quadcopters, and helicopters. Most of the time, quadcopters and helicopters are used as UAVs because they can hover. The dynamics of these systems are nonlinear and cross-coupled, which makes it very hard to design a controller for them [1, 2].

Research organizations typically use a helicopter model known as a twin rotor aerodynamic system (TRAS) in order to assess how well helicopter and unmanned aerial system controllers perform. Similar to a helicopter, the TRAS has a main rotor and a tail rotor. A helicopter's primary rotor, however, could tilt in order to go forward [3]. For designing a controller for TRAS first, we need a mathematical model of TRAS to be able to design controllers for it. In [4, 5], the differential equations for TRAS that are not linear are found. These equations are turned into a state space model by making them linear. The nonlinear model of the TRAS is determined experimentally in [6] using information from a real lab model. One of the most important things to do in autonomous applications is to track the path and ignore disturbances. Hover control is an example of another important situation. Four alternative Proportional Integral Derivative (PID) controllers with various control inputs were developed in [7] to carry out the task of tracking a trajectory. Here, a fitness function is used that is based on the system performance index.

[8] depicts a single-rotor Raptor-30 V2 helicopter simulator with a hybrid flight control setup. The underlying principles of this system are fuzzy control and traditional PID control. In [9], a GA-tuned PID controller was made to deal with the vibration damping and motion control of a twin rotor.

In most cases, it is a good idea to integrate both reference tracking and disturbance rejection when building controls for systems like TRAS. Zames was the first to come up with the idea in 1981 [10]. A model predictive controller (MPC) designed for TRAS is shown in [11] to have the shortest settling and rising times when compared to a linear quadratic regulator (LQR). MPC is a useful strategy for controlling systems with a variety of variables, but because the user must change a number of settings, it necessitates exact mathematical models and takes the longest to implement [12]. Most of the time, 2 degree of freedom (DOF) controllers are used for both noise rejection and reference tracking. In [13], a controller for DC servomotors with two degrees of freedom (DOF) and trajectory tracking is made.

In [14, 15], two DOF H controllers are made that are both reliable and can track a reference. In [16], a Model Predictive Controller (MPC) is made so that TRAS can follow its trajectory. Because the MPC approach addresses the optimization problem in real time at each iteration, it consumes a lot of processing power. Nonlinear control strategies have also been covered, based on the nonlinear model of the system. [17] talks about different kinds of Sliding Mode Controllers (SMC), [18] talks about different kinds of Back Stepping Controllers (BSC), and [19] talks about different kinds of Flatness Based Controllers (FBC). In [20], a nonlinear controller for TRAS is made with the help of feedback linearization.

In [21], an SMC is made to solve the problem of TRAS tracking a trajectory. As the SMC controller must deal with control inputs that chatter, different versions of It's been proposed. According to [22], a fuzzy sliding mode controller or a fuzzy integral sliding mode controller can be used to change the pitch and yaw angles. The TRAS trajectory tracking problem is addressed by the disturbance observer based integral BSC in [23]. However, the usage of a command filter to produce virtual BSC derivatives has adversely affected the transient performance. Sliding mode control, a method for controlling dynamic systems, is often used in literature. While the input is full, these controllers can still be used [24-25].

[26] claims that the issue of disturbance rejection for TRAS is resolved using a H_∞ based methodology and LQG as the outer loop baseline feedback controller. The outer loop baseline feedback controller in a disturbance observer (DOB)-based control system is built for reference tracking and stability, while the inner loop DOB is meant to estimate and reject disturbances and reduce uncertainty [27]. The inner loop that estimates and corrects for disturbances is not active when there are none. If the interior disturbance rejection loop and the outside loop's baseline feedback controller are created independently, you can meet both requirements that are at odds with each other. This makes DOB-based control different from some other types of control. Also, unlike the DOB-based control scheme, the nominal performance is sacrificed in most robust control approaches to make them more reliable. These approaches are called worst case-based designs.

In this paper, TRAS is controlled by a scheme based on the Hybrid FOPID-EKF-DOB-PD-ILC control approach. A decoupler separates the main and tail rotors into distinct systems. Two outer loop FOPID controllers independently control the main and tail rotors. These control the pitch and yaw angles of the TRAS. Once the FOPID controllers are made, EKF is designed as the DOB for disturbance rejection. Than outer loop baseline feedback controller is design for fast reference tracking. Results of both cases those with and without the EKF-DOB and those involving FOPID controller in the outer loop are then contrasted. Than these results are compared with hybrid FOPID-EKF-DOB-PD-ILC controller.

This paper's primary contribution consists of the application and validation of an Extended Kalman Filter as Disturbance Observer based FOPID-ILC controller for a model helicopter to improve how it responds to disturbances and make sure it stays stable. A solution for tracking the trajectory and rejecting disturbances for TRAS that leads to less overshoot and less time for the tail and main rotors as compared to that was proposed in [26]. The remaining part of the paper is structured as follows: The research methodology is presented in Section 2, the simulation findings are addressed in Section 3, and the conclusion and references are presented in Sections 4 and 5.

II. METHODOLOGY OF RESEARCH

TRAS is a complete laboratory system with a main rotor and a tail rotor positioned perpendicularly on a beam and counterbalanced. The two rotors of TRAS are firmly cross-coupled, similar, to a normal helicopter.

A. *Linearized State Space Model of TRAS*

The non-linear equations and dynamics of phenom-logical model of TRAS as presented in [26-27] are used in this paper is shown in Fig. 1. The non-linear equations are linearized by taking origin as the operating point. The state vector selected is $x = [\tau_1, \phi,\ \dot{\phi},\ \tau_2,\ \psi,\ \dot{\psi},\ M_{CR}\ ]^T$, the input vector is $u = [u_1,\ u_2]^T$, and the output vector is $y = [\psi,\ \phi]^T$. The state space model obtained is:

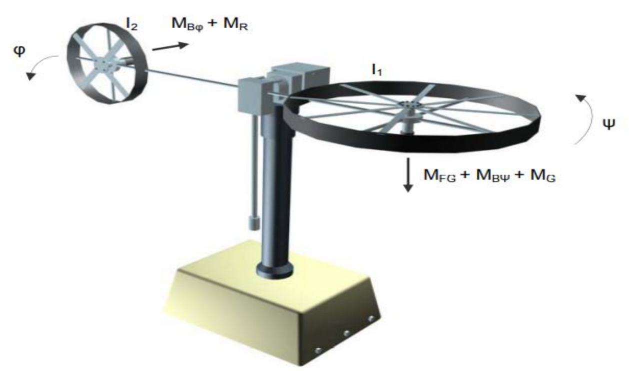
$$A = \begin{bmatrix} -0.8333 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1.246 & -4.706 & -0.08824 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1.482 & 0 & 0 & 3.6 & 0 & -5 & 18.75 \\ -0.01694 & 0 & 0 & 0 & 0 & 0 & -0.5 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

and

$$D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$



The following steps are taken to get the transfer matrix for the linearized model "M":

$$M = \begin{bmatrix} M_{mm} & M_{mt} \\ M_{tm} & M_{tt} \end{bmatrix} \quad (1)$$

$$M = \begin{bmatrix} \frac{1.246}{s^3+0.922s^2+4.76s+3.917} & 0 \\ \frac{1.481s+0.4233}{s^4+6.34s^3+7.06s^2+2.09s} & \frac{3.6}{s^3+6s^2+5.01s} \end{bmatrix} \quad (2)$$

B. *Decoupler Design*

This section focuses on the design of a decoupler for TRAS to get rid of the coupling effect brought on by the plant. A generalized decoupling method is employed to generate a decoupled plant model [27]. This method may be used to determine a decoupler for a square plant "M" using equation 1.

$$M_D = M_{inv} M_{Diag} \quad (3)$$

M_D is the decoupler, M_{inv} is the inverse of the plant M, and M_{Diag} is a diagonal matrix. Given in equation 1 above is M. So,

$$M_{inv} = \begin{bmatrix} M_{inv_{mm}} & M_{inv_{mt}} \\ M_{inv_{tm}} & M_{inv_{tt}} \end{bmatrix} \quad (4)$$

So,

The decoupled plant M_{Diag} considered can be given by

$$M_{Diag} = \begin{bmatrix} M_{Dm} & 0 \\ 0 & M_{Dt} \end{bmatrix} \quad (5)$$

Put equations 4 and 5 in equation 3 we get the decoupling matrix:

$$M_D = \begin{bmatrix} M_{D_{mm}} & M_{D_{mt}} \\ M_{D_{tm}} & M_{D_{tt}} \end{bmatrix}$$

So,

$$M_D = \begin{bmatrix} 1 & 0 \\ \frac{-0.45s^6-3.14s^5-7.08s^4-17.1s^3-22.3s^2-9.6s+5.5e^{-14}}{s^6+6.91s^5+15.23s^4+37.1s^3+47.04s^2+19.4s+4.75e^{-14}} & 1 \end{bmatrix}$$

(6)

C. *FOPID Control Approach*

The system's stability is the intended objective of the FOPID controller. GorPodlubny [28] proposed the FOPID Controller in 1999. There exists an integrator and differentiator of fractional order. The usual mathematical expression for FOPID is:

$$G_{FOPID}(s) = k_p + \frac{k_i}{s^\alpha} + k_d s^\beta \quad (7)$$

k_p= proportional gain, k_i= integral gain and k_d= derivative gain, α and β are the integrator's and the differentiator's respective fractional powers. They have values between 0.1 and 2. When $\alpha = \beta = 1$, a

FOPID controller transforms into a simple PID controller. The fact that FOPID comprises five unknown parameters, three PID controller parameters, and an extra two parameters α and β, leading to a variety of controllers, is readily obvious from Equation (7).

FOPID has five unidentified parameters. There are various conventional and modern techniques to modify these parameters. In this study, a FOPID controller is built using the dominating pole placement method. The objective function is adjusted to produce the FOPID controller settings using MATLAB's FMINCON package. The objective function is optimized using SQP in order to identify the values of the controller parameters k_p, k_i, k_d, α and β [29]. In comparison to a traditional PID, the stability margins are improved when the system is specified in fractional order while preserving robustness. The block diagram of FOPID controller in close loop feedback system is shown in Fig. 2. Table 1 shows the FOPID controllers parameter values for tail and main rotor.

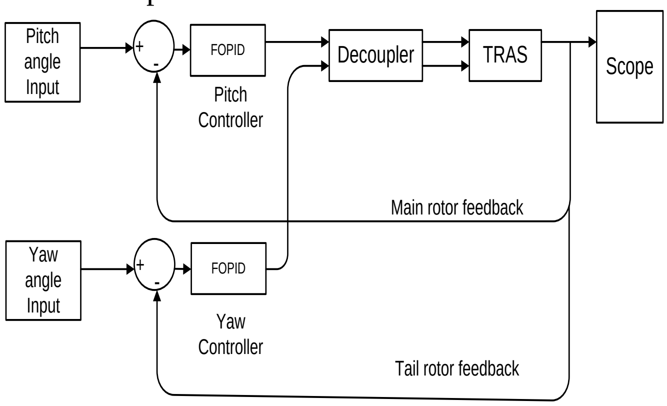


Fig. 2 FOPID controller in close loop feedback system

Table 1. FOPID Controller Parameters for Main and Tail Rotors

Parameter	Main Rotor	Tail Rotor
K_p	73.2120	0.6154
K_i	49.0348	15.8390
K_d	519.5926	217.3322
α	0.8793	0.8655
β	0.9999	0.9999

D. Extended Kalman Filter as Disturbance Observer (EKF-DOB)

For estimating noisy measured system states, several approaches have been developed. In this section, we will implement an extended Kalman filter to reduce noise from helicopter system states for the FOPID-EKFDOB-PD-ILC controller.

The main problem with the Kalman filter is that both the measurement model and the dynamic system model must have linear state variables. When the system doesn't react linearly, the simple Kalman filter can't always be used to provide an accurate estimate. The EKF is a nonlinear modified Kalman Filter that is used to estimate the states of dynamic systems that exhibit some range nonlinearity. Using the EKF approach, the nonlinear models are linearized into linear systems at each time interval. The typical estimation strategy employing the extended Kalman filter is shown in Fig. 3 [30].

There are two steps in an EKF estimate: In the prediction step, the apriori state and Kalman covariance were derived from the input and previous state data. Then, using the observation from the update step, the Kalman aposteriori state and Kalman covariance are computed [30–31].

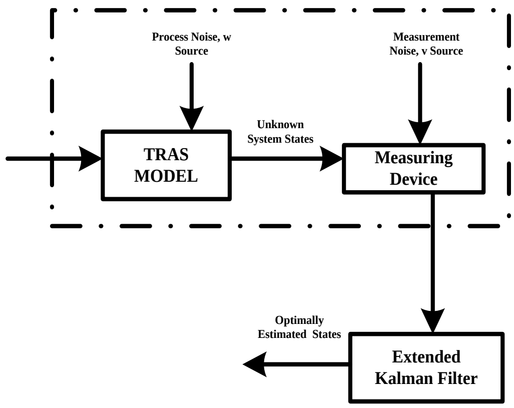


Fig. 3 Using the EKF, general estimating layout [30]

A disturbance in a control system is an unauthorized or unacknowledged input that alters the output and increases system error. Disturbance signals commonly found in almost all control systems and alters the functionality of the system. Disturbance is something that really happens to the actual physical system, enters the system via actuators and results in generation of system vs model mismatch. The control loop should react to the disturbance signal in a way it to be cancelled. Noise on other hand is something that happens to sensors and not to physical system. It will corrupt the sensor measurements but will not induce any dynamics in the system. The loop gain must be very high at low frequencies to reject disturbances successfully and must be low at high frequencies to attenuate noise. To reject external disturbances among various other methods one method is to design and use disturbance observer.

Fig. 4 shows the general structure of the disturbance observer for a general plant $G_2(s)$, where $G_2(s)$ represents the actual physical system, $C(s)$ represents the outer loop feedback controller in charge of performance and stability in the absence of disturbances, $G_1(s)$ represents the disturbance model, $G_n(s)$ represents the nominal model of the plant used to design the controller, $G_n^{-1}(s)$ represents the inverse of the nominal model, and $Q(s)$ represents the perturbation observer.
The core idea of DOB is to extrapolate known values, such control signal $\hat{u}(s)$ and plant output $y_m(s)$, to predict unknown ones, including disturbances and uncertainties. This disturbance estimate $\hat{d}$ is finally lowered from the controller output u after being eliminated by the low pass filter $Q(s)$. The DOB design's filter design step is essential for maintaining the causality and robustness of the DOB. Its opposite will be improper, non-causal, and physically impossible to create since $G_n(s)$ is always causal and proper. To ensure that $Q(s)G_n^{-1}(s)$ is suitable and causal, $Q(s)$ must be constructed in this way. Additionally, if there is any uncertainty in the actual physical system $G_2(s)$, $Q(s)$ must be built in a method that ensures DOB resilience [26].

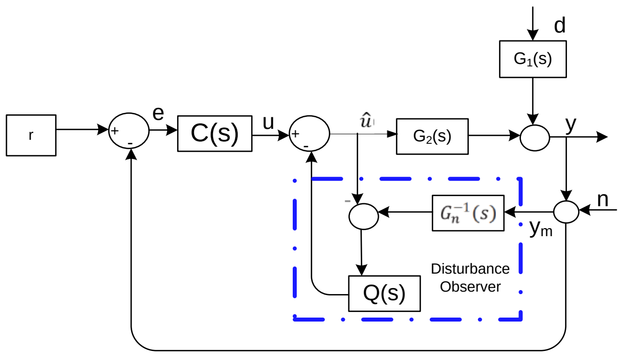


Fig. 4 General Structure for disturbance observer [26]

The relationship for the disturbance estimate $\hat{d}$ found in Figure 4 with $G_2(s) = G_1(s) = G(s)$ and $X(s) = \left(1 + G(s)C(s)\right)^{-1}$ is given by:

$$\hat{d} = \frac{Q(s)\{G_n^{-1}(s)G(s)+G(s)C(s)\}X(s)}{(1-Q(s))+Q(s)\{G_n^{-1}(s)G(s)+G(s)C(s)\}X(s)} d \quad (8)$$

Now to make a perfect estimate of disturbance i.e., $\hat{d} = d$ we need to make $Q(s) = 1$ and $G^{-1}(s)G(s) = 1$ in equation 8, which is the ideal case. Fig. 5 shows the EKF based DOB design structure.

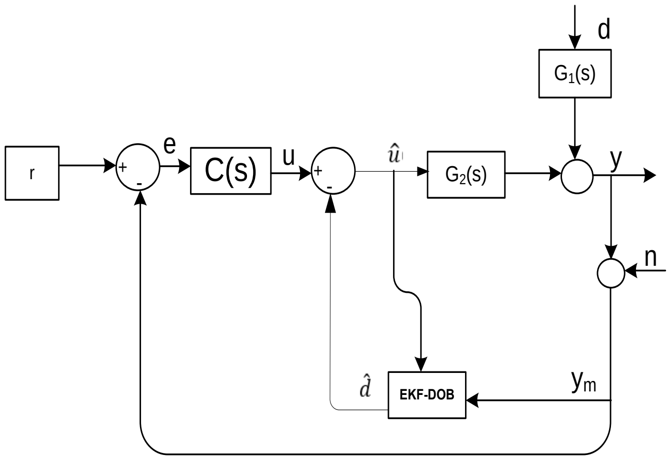


Fig. 5 EKF based DOB design structure

E. *FOPID-EKF-DOB-PD-ILC Control Approach*

To reduce mistakes as much as feasible in subsequent runs, ILC utilizes the data from earlier attempts. In order to achieve accurate tracking, also known as perfect tracking, the control input from the preceding attempt is stored in a memory and added to the prior control signal with some function on error. To create a new control input for the current trail, you can try anything. One can use P, PD, PI or merely proportional, integral, and derivative control rules to update the new control input [24-25]. In this work, PD type ILC is used. Both proportional and derivative functions on the error signal are applied to produce a new control signal in PD type ILC [25, 32–33]. The mathematical form is shown in equation 9, k_p (Proportional Gain) parameter is responsible for reducing settling time,

$$u(i,k+1) = u(i,k) + k_p e(i,k) + k_d \dot{e}(i,k) \quad (9)$$

Values for PD-ILC parameters k_p and k_d is obtained by Zeigler Nichols method, the values are given in Table 2.

Table 2. PD-ILC Controller Parameters for Main and Tail Rotors

Parameter	Main Rotor	Tail Rotor
K_p	1.2	2.0
K_d	0.48	0.25

A few assumptions are made when creating ILC in an effort to enhance learning over techniques that are already successful. We presumptively assume the following:

- If the system starts at t=0 with a magnitude of 0, then all following trails must likewise start with the same condition because each iteration starts at the same location.
- After each repetition, the error should have converged, meaning that the error of the second trail should be lower than the error of the first trail, and so on.
- Each iteration should have a fixed time; for instance, if the first trail took 5 seconds to complete, all subsequent trails should similarly take 5 seconds.

Fig. 6 below illustrates the basic structure of an ILC, where u(i,k) stands for the current control input, y(i,k) for the current output, and u(i,k+1) for a new control input generated by the ILC. The (i,k) specifies the i^{th} time interval and the k^{th} batch or iteration. When the system is given u(i,k), it responds with the required output. By storing all values in a memory and creating a new control input in this way, the intended signal $y^d(i)$ is carefully monitored. where Memory is represented by M, whereas System is represented by S.

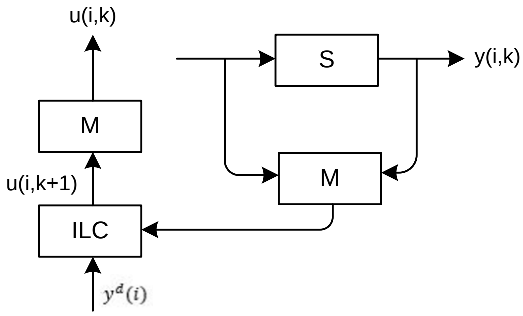


Fig. 6 ILC basic structure [25]

A few standard combinations are used in ILC. They may be divided into two main categories: embedded and cascaded [31]. While embedded ILC is used by making certain modifications to the actual loop of the system, cascaded ILC is added independently without changing any of the system's present setup. In this paper we have used cascaded ILC approach. ILC can only be used to stable systems. ILC is frequently used in conjunction with other tehniques since real-time systems are nonlinear and unstable. Since TRAS is a specific form of system with a nonlinear open loop instability, the system requires a stabilizing feedback mechanism.

PD-ILC is the feedforward controller, while FOPID is the feedback controller. The desired signal and the error that was saved from the previous cycle are used by the PD-ILC to create a new reference trajectory for the active control process. To produce the required signal in the present loop, just a small number of instructions must be changed. The following path will be preferable to the previous one if the convergence condition is preserved in cascaded ILC. The Simulink environment was used to create both controllers. The recommended hybrid control technique's overall block diagram may be shown in Fig. 7.

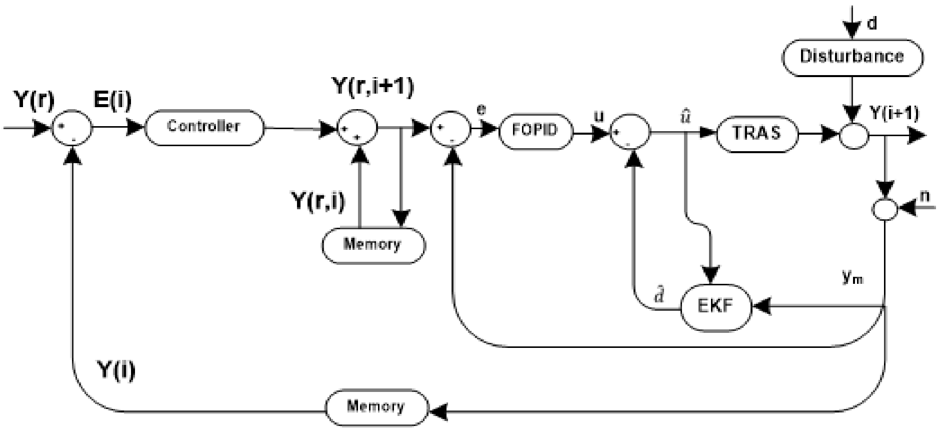


Fig. 7 Block diagram of Hybrid FOPID-EKF-PD-ILC control of TRAS.

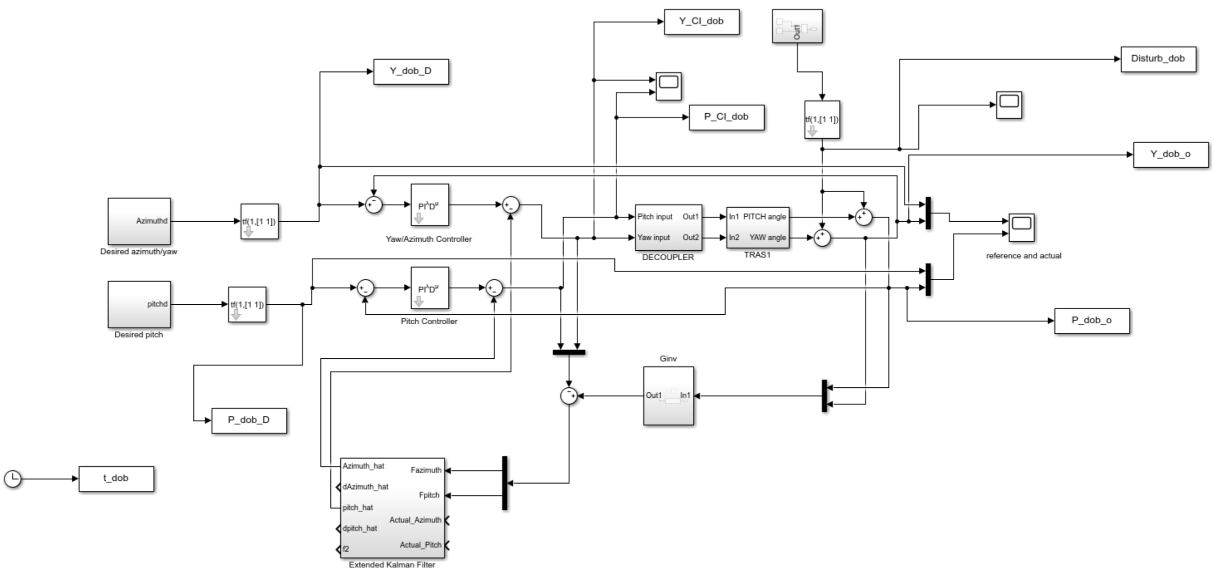


Fig. 8 TRAS with FOPID-EKF-DOB

III. Simulation and Results

The results of using the recommended hybrid controller strategy on TRAS data are shown in this section. The results of the strategy are compared to the representative control obtained using techniques that have already been described in the literature. In this regard, four control approaches are selected for comparison: LQG-DOB control, FOPID control, FOPID-EKF-DOB control, and FOPID-EKF-DOB-PD-ILC control. Reference inputs are chosen in a way that allows them to govern the pitch angle and azimuth angle movements of TRAS. TRAS is first moved leftward horizontally by increasing azimuth angle while keeping pitch angle zero, and then both upward and downward by increasing pitch angle. The TRAS beam is simultaneously shifted rearward (azimuth angle is lowered) while remaining in the highest position possible ($\psi = 1.5$ rad) and vice-versa. The TRAS's movement may be controlled both vertically and horizontally using these reference inputs. The TRAS has disturbance observers on both the main and tail rotors. A disturbance is added in the system at t = 55-57 s. Fig. 8 shows the simulation of FOPID-EKF-DOB control. Fig. 9-10 shows the pitch and yaw responses of TRAS with FOPID and FOPID-EKF-DOB controls. The dotted lines show the reference inputs for pitch and yaw angles, whereas the solid line shows the FOPID and FOPID-EKF-DOB responses. By observing the plots in Fig. 9-10, we can see that the controllers are tracking the reference inputs, Disturbance rejection is improving, though. There are some irregularities in the main rotor charts both with and without DOB, as well as an overshoot in the tail rotor plots, and the response is not adequately smooth.

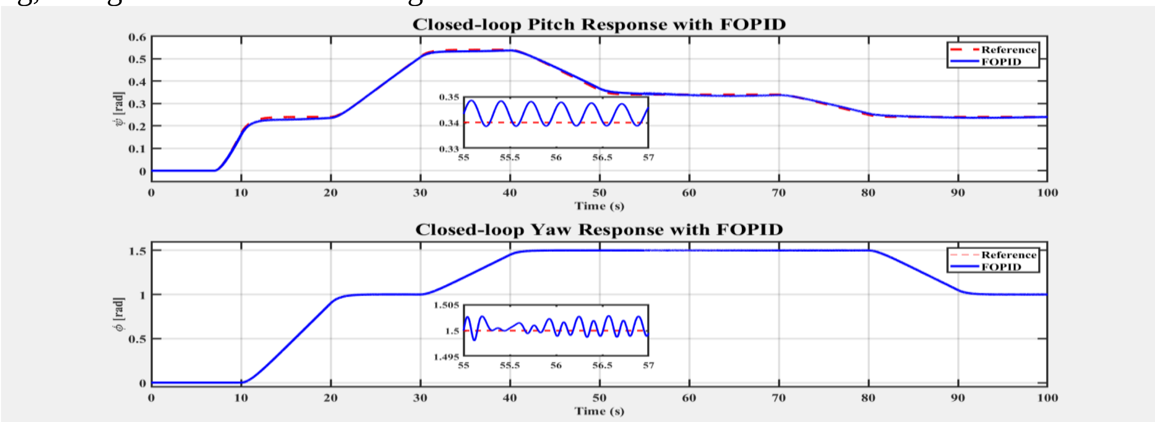


Fig. 9 Close Loop Response with FOPID

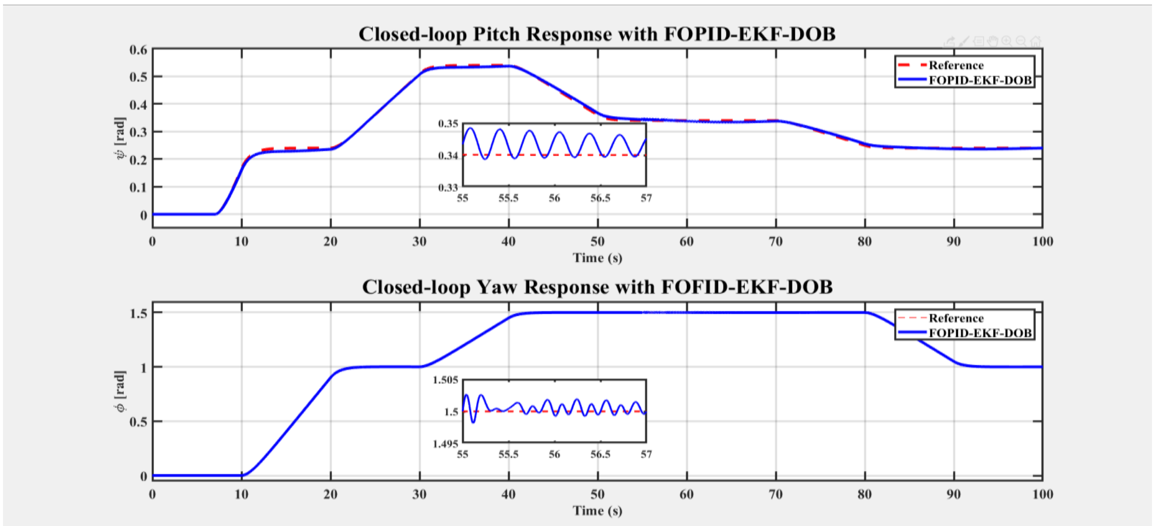


Fig. 10 Close Loop Response with FOPID-EKF-DOB

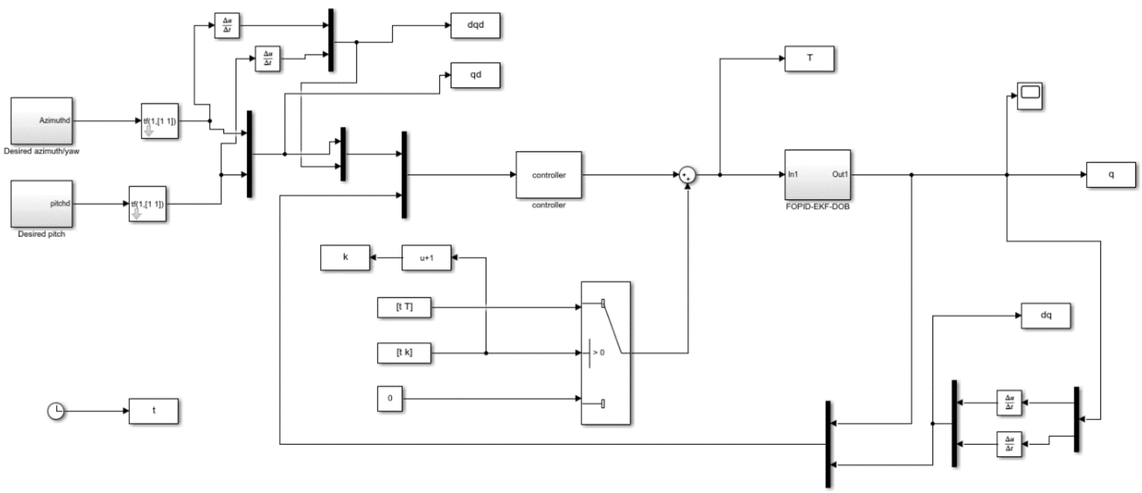


Fig. 11 Complete simulation of Hybrid FOPID-EKF-DOB-PD-ILC control approach

This is true since the nominal performance criteria need the outer loop controller. When using FOPID-EKF-DOB with a trustworthy reference tracking controller, improved responsiveness may be expected.

Fig. 11 shows the complete simulation of proposed hybrid technique. The reference tracking with smooth input trajectories at 10 iterations for main and tail rotor are shown in Fig. 12-13.

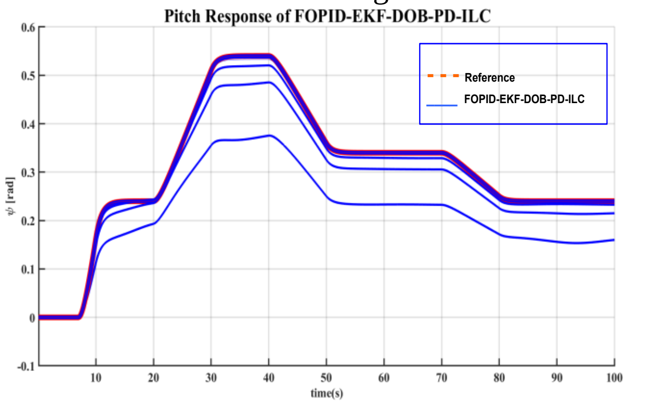


Fig. 12 Close loop Pitch angle response of Hybrid FOPID-EKF-DOB-PD-ILC control approach

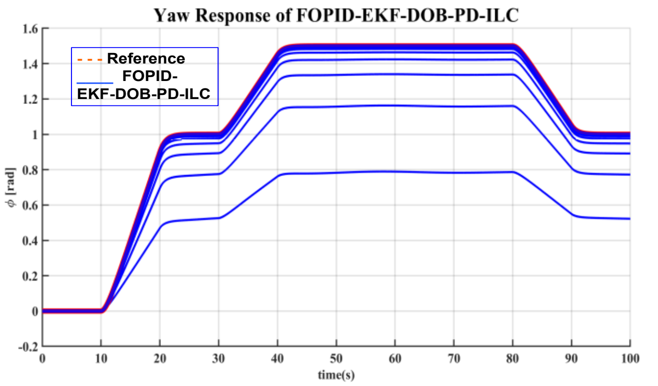


Fig. 13 Close loop Yaw angle response of Hybrid FOPID-EKF-DOB-PD-ILC control approach

In each subsequent iteration, it can be observed that the outputs are becoming closer to the desired output while the tracking error is being reduced and external disturbances are being rejected. The control effort decreases as the number of iterations rises. Fig. 12-13 also shows that the control effort for the first iteration is more than the effort for the sixth iteration, which is greater than the effort for the previous iteration. In other words, the control effort gets smaller with each repetition. In addition to improving reference tracking, the hybrid FOPID-EKF-DOB-PD-ILC also lowers external disturbance.

The tracking error output for the hybrid FOPID-EKF-DOB-PD-ILC at various iterations is shown in Fig. 14. It is clear that the error decreases monotonically with each iteration before approaching zero at the eighth iteration, demonstrating the swift responsiveness of the proposed hybrid method. Table 3 compares the performance of the proposed hybrid FOPID-EKF-DOB-PD-ILC controller with that of the current controllers from the literature for the main and tail rotors. Comparison shows that in addition to enhanced disturbance rejection capability the proposed approach Hybrid FOPID-EKF-DOB-PD-ILC delivers better performance. Where T_s is the settling time and %OS is the percentage overshoot.

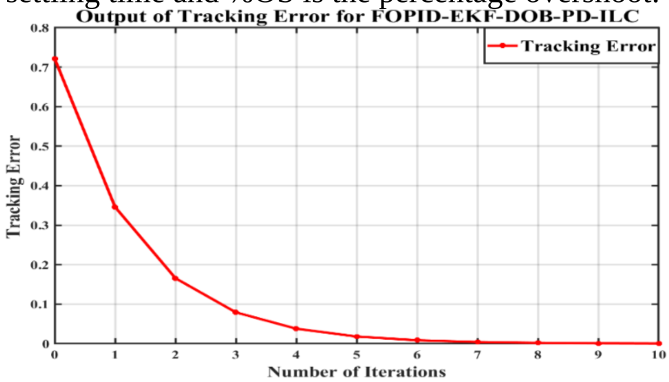


Fig. 14 Tracking error output for the hybrid FOPID-EKF-DOB-PD-ILC at different iterations

Table 3. Comparison of proposed strategy with other approaches

Control Schemes	Main Rotor		Tail Rotor	
	Ts	% OS	Ts	% OS
LQG-DOB [26]	14.1	0	4.15	0.11
FOPID	3.7	8	2.5	6
FOPID-EKF-DOB	3.5	5	2.2	4
Hybrid FOPID-EKF-DOB-PD-ILC	1.8	0	1	0

IV. CONCLUSION

The The development of Hybrid FOPID-EKF-DOB-PD-ILC controller for TRAS in this study leads us to the conclusion that this is a workable method for managing TRAS systems and for obtaining the desired trajectory by rejecting external disturbances. FOPID is more reliable and accurate than a traditional PID controller. In order to reject outside disturbances and decrease overshoot and rising time, an observer for disturbances called EKF is also added to the inner loop. PD-ILC act as a feedforward controller which not only reduces the steady state error but also increase response of the system by its fast iterative technique. The non-linear Simulink model is used to conduct more simulations, and the closed loop systems with and without DOB are compared. Comparisons show that the suggested hybrid approach performs better and has better disruption resilience. The results also show how the architecture of the outer loop feedback controller, and the inner loop disturbance observer allows for the simultaneous attainment of reference tracking and disturbance rejection. The study's overall findings indicate that the Hybrid FOPID-EKF-DOB-PD-ILC control strategy is a promising one for a reference tracking while rejecting external disturbances.

REFERENCES

[1] Chen, M., Ge, S.S. and How, B.V.E., 2010. Robust adaptive neural network control for a class of uncertain MIMO nonlinear systems with input nonlinearities. IEEE Transactions on Neural Networks, 21(5), pp.796-812.

[2] Juang, J.G., Huang, M.T. and Liu, W.K., 2008. PID control using presearched genetic algorithms for a MIMO system. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 38(5), pp.716-727.

[3] Venkatesan, C., 2014. Fundamentals of helicopter dynamics. CRC Press.

[4] Ahmad, M., Ali, A. and Choudhry, M.A., 2016. Fixed-structure H∞ controller design for two-rotor aerodynamical system (TRAS). Arabian Journal for Science and Engineering, 41(9), pp.3619-3630.

[5] Ahmad, U., Anjum, W. and Bukhari, S.M.A., 2013. H 2 and H∞ controller design of twin rotor system (TRS).

[6] Nejjari, F., Rotondo, D., Puig, V. and Innocenti, M., 2012, July. Quasi-LPV modelling and non-linear identification of a twin rotor system. In 2012 20th Mediterranean conference on control & automation (MED) (pp. 229-234). IEEE.

[7] Juang, J.G., Huang, M.T. and Liu, W.K., 2008. PID control using presearched genetic algorithms for a MIMO system. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 38(5), pp.716-727.

[8] Khizer, A.N., Soomro, A.M. and Ali, S.A., 2015. A hybrid flight control for a simulated raptor-30 V2 helicopter. Mehran University Research Journal Of Engineering & Technology, 34(2), pp.176-182.

[9] Aldebrez, F.M., Alam, M.S. and Tokhi, M.O., 2005, June. Input-shaping with GA-tuned PID for target tracking and vibration reduction. In Proceedings of the 2005 IEEE International Symposium on, Mediterrean Conference on Control and Automation Intelligent Control, 2005. (pp. 485-490). IEEE.

[10] Wolovich, W.A. and Falb, P.L., 1967. Decoupling in the design and synthesis of multivariable control systems.

[11] Ulasyar, A. and Zad, H.S., 2015, November. Robust & optimal model predictive controller design for twin rotor MIMO system. In 2015 9th International Conference on Electrical and Electronics Engineering (ELECO) (pp. 854-858). IEEE.

[12] Duţescu, D.A., Radac, M.B. and Precup, R.E., 2017, January. Model predictive control of a nonlinear laboratory twin rotor aero-dynamical system. In 2017 IEEE 15th International Symposium on Applied Machine Intelligence and Informatics (SAMI) (pp. 000037-000042). IEEE.

[13] Umeno, T. and Hori, Y., 1991. Robust speed control of DC servomotors using modern two degrees-of-freedom controller design. IEEE Transactions on industrial electronics, 38(5), pp.363-368.

[14] Hoyle, D.J., Hyde, R.A. and Limebeer, D.J., 1991, December. An h/sub infinity/approach to two degree of freedom design. In [1991] Proceedings of the 30th IEEE Conference on Decision and Control (pp. 1581-1585). IEEE.

[15] Fujimoto, Y. and Kawamura, A., 1995. Robust servo-system based on two-degree-of-freedom control with sliding mode. IEEE Transactions on Industrial Electronics, 42(3), pp.272-280.

[16] Ahmad, S.M., Chipperfield, A.J. and Tokhi, O., 2000, October. Dynamic modeling and optimal control of a twin rotor MIMO system. In Proceedings of the IEEE 2000 National Aerospace and Electronics Conference. NAECON 2000. Engineering Tomorrow (Cat. No. 00CH37093) (pp. 391-398). IEEE.

[17] Rahideh, A. and Shaheed, M.H., 2011. Stable model predictive control for a nonlinear system. Journal of the Franklin Institute, 348(8), pp.1983-2004.

[18] Butt, S.S., Sun, H. and Aschemann, H., 2016. Comparison of backstepping-based sliding mode and adaptive backstepping for a robust control of a twin rotor helicopter. Variable-Structure Approaches: Analysis, Simulation, Robust Control and Estimation of Uncertain Dynamic Processes, pp.3-30.

[19] Sun, H., Butt, S.S. and Aschemann, H., 2016, July. Discrete-time flatness-based control for a twin rotor helicopter with an Extended Kalman filter. In 2016 IEEE International Conference on Advanced Intelligent Mechatronics (AIM) (pp. 507-512). IEEE.

[20] Lopez-Martinez, M., Diaz, J.M., Ortega, M.G. and Rubio, F.R., 2004, June. Control of a laboratory helicopter using switched 2-step feedback linearization. In Proceedings of the 2004 American Control Conference (Vol. 5, pp. 4330-4335). IEEE.

[21] Zeghlache, S., Bouguerra, A. and Ladjal, M., 2016, May. Sliding mode controller using nonlinear sliding surface applied to the 2-DOF helicopter. In 2016 International Conference on Electrical and Information Technologies (ICEIT) (pp. 332-337). IEEE.

[22] Tao, C.W., Taur, J.S., Chang, Y.H. and Chang, C.W., 2010. A novel fuzzy-sliding and fuzzy-integral-sliding controller for the twin-rotor multi-input–multi-output system. IEEE Transactions on Fuzzy Systems, 18(5), pp.893-905.

[23] Rashad, R., Aboudonia, A. and El-Badawy, A., 2016. A novel disturbance observer-based backstepping

controller with command filtered compensation for a MIMO system. Journal of the Franklin Institute, 353(16), pp.4039-4061.

[24] Mobayen, S., Majd, V.J. and Sojoodi, M., 2012. An LMI-based composite nonlinear feedback terminal sliding-mode controller design for disturbed MIMO systems. Mathematics and Computers in Simulation, 85, pp.1-10.

[25] Saleem, F., Ali, A., Shaikh, I.U.H. and Wasim, M., 2021. A Hybrid H infinity control based ILC design approach for trajectory tracking of a Twin Rotor Aerodynamic System. Mehran University Research Journal Of Engineering & Technology, 40(1), pp.169-179.

[26] Ali, H., Ali, A. and SHAIKH, I.U.H., 2020. Disturbance observer based control of twin rotor aerodynamic system. Turkish Journal of Electrical Engineering and Computer Sciences, 28(4), pp.2213-2227.

[27] Pratap, B. and Purwar, S., 2010, July. Neural network observer for twin rotor MIMO system: An LMI based approach. In Proceedings of the 2010 International Conference on Modelling, Identification and Control (pp. 539-544). IEEE.

[28] Podlubny, I., 1999. Fractional-order systems and PI/sup/spl lambda//D/sup/spl mu//-controllers. IEEE Transactions on automatic control, 44(1), pp.208-214.

[29] Bhimte, R., Bhole, K. and Shah, P., 2018, May. Fractional order fuzzy PID controller for a rotary servo system. In 2018 2nd international conference on trends in electronics and informatics (ICOEI) (pp. 538-542). IEEE.

[30] Nasir, F.E., Fotuhi, M.J. and Bingul, Z., 2018, October. Linear and extended kalman filter estimation of pitch and yaw angles for 2 dof double dual twin rotor aero-dynamical system. In 2018 6th International Conference on Control Engineering & Information Technology (CEIT) (pp. 1-6). IEEE.

[31] Chen, Y. and Wen, C. eds., 1999. Iterative learning control: convergence, robustness and applications. London: Springer London.