A Fuzzy-Active Force Control Architecture Based in Characterizing Nonlinear Systems’ Behavior

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Abstract

This paper presents Active Force Control (AFC) based architecture in characterizing the twin rotor multi-input multi-output (MIMO) system (TRMS). The proposed architecture is expected to produce an optimum control gains in both pitch and yaw responses by introducing decoupling function between pitch and yaw responses. The internal change corresponds to coupling effects, gust and wind turbulence are very difficult to compensate by the classical PID control, but both of them are stamped out as AFC scheme is implemented into the control strategy. The performance of TRMS is further optimized by the realization of hybrid strategy in which an artificial intelligence Fuzzy Logic is integrated into the control architecture.

Keywords: Active force control (AFC); Fuzzy logic (FL); High nonlinearity; Coupling effect; Decoupling function;

Nomenclature

\begin{itemize}
\item $\rho$ output of angle displacement
\item $I$ mass moment of inertia
\item $\alpha$ angular acceleration of the system
\item $\tau_i$ torque induces
\item $\tau_d$ torque disturbance
\end{itemize}

1. Introduction

Most problems we face in our daily life are complex or nonlinear in nature and it is very often difficult to understand and identify their characteristics as they are not straight forward. Many researchers have developed numerous techniques and principle to help solving real life phenomenon crisis, such as linearization, dynamics inversion, Winner-Hammerstein, polynomial identification method as well as control system [1]. Air flight dynamic is classified as nonlinear system and to a certain extent complex in behaviour. Therefore, a number of posed challenging issues aroused due to uncertainty parameters and cross coupling between their axes. Nevertheless, its applications are abundant and very common due to its capabilities with regards of agility, flexibility and high stability has led to vast usage in much application such as military, civilian uses and transportation. Continuous and very high demand on air flight systems for comfortable usage, rapid responses and accuracy of air flight during operating has driven many researchers to embark on the resolution of optimum control scheme. However, air flight dynamical tests shown that not all of new controller that had been developed could fit and cater the performance requirements.

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Among the existing controllers scheme nowadays, active force control (AFC) is an attractive feedback control system in which widely utilized by scholars due to success of the implementation in robot arm [2], suppression vibration of tool [3], high precision robot [4], and automotive applications [5]. In this study, the application of AFC will be extended to the air flight system. Generally, AFC is a mathematical formulation used to compute the torque or force disturbance presence in a particular system and make the calculation process simpler in predicting the compensate torque. Integration between active force control (AFC) and intelligent computational techniques has been continually in practice to give better results and variously implemented in many applications [6]. Among successful integration is neural network, fuzzy logic, genetic algorithm (GA), and iterative learning [7]. Hewit and colleagues found out that a very robust performance and flexibility dealing with uncertainty, disturbances and parameter changes in complex system can be obtained by means of arrangement of controller [2]. An active force control technique had shown a promising controller by means of applying to active suspension vehicle system of quarter car model using skyhook as an actuator. The Skyhook adaptive neuro was incorporate together with active force control (SANAFC) to give a comfort level of driving which has been tested with various inputs of road profiles [6]. The use of fuzzy logic in AFC has shown good performance compared to iterative learning method and crude approximation in vibration suppression of handheld tool [3]. Furthermore, AFCFL performs accurate position control through a hardware-in-loop-simulation (HILS) [8] and pneumatic artificial muscled [9-10]. Other than that, Takagi-Sugeno application also worked well on TRMS. This method used as base of LQR controller which can conserve the nonlinear characteristic [11].

Application of AFC is depending on PID setting as a general control to track the target setting at the beginning. PID parameters is derived by Ziegler-Nichols method and applied on TRMS [8]. The performance of the classical control is seems to be not sufficient to compensate the error and stabilize the responses. An extensive approach were developed to increase the performance of controller by means of integration between PID with artificial intelligent to remove the spike errors critically on yaw angle of TRMS. Among them was single neuron PID in which a neural network scheme based to optimize the PID parameters [12]. PID with acceleration feedback (PIDA) was designed based on genetic algorithm (GA) optimization to tune the parameters of feedback compensators [13]. A hybrid-PID-Based control with fuzzy logic was introduced and in this investigation, fuzzy logic was developed incorporates with PID control [10, 13]. Fuzzy switching grey prediction PID with real-value genetic algorithms (RGA) [14], where PID parameters were predicted by RGA while grey prediction were use in obtained the fuzzy switching mechanism. The combination of classical control and artificial intelligent have resulted in outstanding performance in term of responses and error compensation as compared to the classical scheme alone.

2. Mathematical Modeling

Twin Rotor represent a helicopter model, whereby the helicopter driven by two rotors which are the main rotor blades at the head and tail rotor blades at helicopter tail. The main rotor is pivoted point location and acting for lift positioning where it controlling by varies of rotor velocities. Since the main rotor blades is cyclic control, it allow a multi directional or vary of positioning by governor the main rotor blades angle. For the tail rotor blade act as a counter balance of angular momentum that has been create by main rotor blades. Both of rotor blades are activated by engine. However the significant of helicopter has been captured into nonlinear twin rotor which is cross coupling behavior between two rotors. Simplifications of twin rotor are made without neglecting the important characteristic existing in a helicopter. There was interaction movement between pitch and yaw position, if activate the pitch position the twin rotor will also turn in yaw axis and this dynamical behavior of helicopter.

2.1. Twin Rotor

Simplified helicopter consist a two propellers and driven separately by DC motor, the propellers are located at the end of cylinder beam and each of them is positioned perpendicularly. The cylinder beam is connecting both propellers and it rotates freely in pitch and yaw planes. The pivot located at nearly center of the cylinder beam between both rotors and it attached to the tower. The propellers consists a main rotor and a tail rotor, main rotor giving a positioning in pitch directional while the tail rotor allowing the beam moving in yaw plane. These two rotors interaction each other and causing a cross coupling in dynamic system. For this reason, the counter balance mass is equipped together in the twin rotor system. The counter balance mass is hanging on the cylinder beam which is locate same point as pivot point. The twin rotor has two inputs where the currents supplied for two separate DC motor which locate at main rotor and tail rotor. For the outputs, the twin rotor consist two outputs which are pitch angle. The schematic diagram illustrated as Fig. 1.
Dynamic equation of twin rotor system is derived based on Newton Mechanics. The inputs of the system for pitch planes are $M_1$, $M_{FG}$, $M_{b\rho}$ and $M_G$, which are the nonlinear static characteristic of motor, the gravity momentum, the friction forces momentum and the gyroscopic momentum respectively. And the output of angle displacement is $\rho$ and the dynamic equation of twin rotor as follows:

$$
M_1 = f(\tau_1) \\
M_{FG} = f(\rho, \dot{\rho}, \ddot{\rho}, \gamma, \dot{\gamma}, \ddot{\gamma}) \\
M_{b\rho} = f(\rho, \dot{\rho}, \ddot{\rho}, \gamma, \dot{\gamma}, \ddot{\gamma}) \\
M_G = f(\rho, \dot{\rho}, \ddot{\rho}, \gamma, \dot{\gamma}, \ddot{\gamma})
$$

The inputs of the system for yaw planes are $M_2$, $M_{B\gamma}$ and $M_R$ which are the nonlinear static characteristic, friction forces momentum and the cross reaction momentum respectively. And the output of yaw is $\gamma$ and the dynamic equation for yaw planes as follows:

$$
M_2 = f(\tau_2) \\
M_{B\gamma} = f(\rho, \dot{\rho}, \ddot{\rho}, \gamma, \dot{\gamma}, \ddot{\gamma}) \\
M_R = f(M_2)
$$

Where $f$ are function of $\rho$ and $\gamma$, their derivatives and system parameters.

Twin rotor is driven by two DC motors, each of them located at main rotor and tail rotor. The relation between voltage ($v$) and torque ($u$) for both motors are shown in Fig 2. It is obtained by changing the voltage range between 0V to 10V in SIMULINK environment and measure the torque output. The relationship behavior identified that the output of torque load between both motors are different and it exhibited nonlinear characteristic.
2.2. Decoupling Function

Fig. 3. Schematic diagram of AFC for pitch and yaw

As mentioned before, the main key feature of modeling twin rotor is cross coupling dynamics that replicates helicopter behavior. The main rotor or pitch movement is activated by varying of velocity in which it generates angular momentum. This angular momentum affects the tail rotor or yaw angle; even though the tail rotor is triggered to encounter the moment reaction from main motor, however the yaw response reacting and give unstable response. The effects are represented by functional blocks of Twin Rotor in Fig 3.

3. Twin Rotor Control

3.1. Active Force Control

Recently, measuring the force or torque as a feedback for controlling the dynamic systems has been used and offered such as impedance control [15-17], explicit force control [18], and hybrid force/position control [3]. AFC is capable of offering a robust and stable response under uncertainties parameters without reducing the performance objective. Active force control one of scheme using force or torque as the input to compute the optimize gain and imposing it into the actuator. The scheme has been initiated by Hewit and Burdess in the early eighties to robot arm and it performs well in rejecting the disturbances [19]. It is based on Newton’s second law, AFC measure the internal disturbance or excessive torque in TRMS. For the rotational bodies, the summation of torque produces ($\tau$) from the system equivalence to the product of the mass moment of inertia (I) and the angular acceleration ($\alpha$) of the system [5]. The equation of rotational motion can be written as follows:

$$\sum \tau = I\alpha$$

By considering the internal disturbance, the summation of torque ($\tau$) equal to the torque induces ($\tau_i$) and the torque disturbances ($\tau_d$). The summation of moment becomes:
From the equation (8-9), the disturbance torque computes as follows:

\[ \tau_{d} = \tau_{i} - \mathbf{IN}\ddot{\Theta} \]  

(10)

Where the \( \mathbf{IN} \) is estimated inertia matrix and \( \dot{\Theta} \) is angular acceleration. Fuzzy Logic was used as an intelligent parameter estimator in approximating the inertia matrix. The induced torque \( \tau_{i} \) was obtained by DC motor relationship between voltage and torque induced. For the angular acceleration, it is obtained by calculating the summation of moments and divided by the moment of inertia. If all parameter successful required, then the disturbance torque can be compute without knowing the mathematical background. To induce the compensation voltage into the DC motor, the inverse dynamic of DC motor need to be obtained in order to convert the estimation disturbances torque into the voltage. Then, the computation of compensate voltage is imposed to DC motor to react on the presence disturbance. Two Loops of AFC has been organized for pitch and yaw as per Fig 4.

![Fig. 4. Schematic diagram of AFC for pitch and yaw](image)

3.2. Design of Fuzzy Control

Fuzzy Logic is used as an alternative intelligent solver to design the nonlinear and complex control model. The literature found that it is a robust and good estimator when incorporated in AFC [20]. The designed rules are based on the behavior of the twin rotor and the properties of the inertia matrix. Regarding to fuzzy structure in AFC loop, it consist of single input to fuzzy inference where it correspond to the position of twin rotor, and single output which represent inertia matrix parameter. The membership function of fuzzy based on Mandani trapezoidal [21] depicted in Fig 5:

![Fig. 5. Membership function for (a) input fuzzy; (b) output fuzzy](image)
The fuzzy rules are depending on the system to be controlled and the kind of control schemes to be implemented based on practical experiences [9]. According to two memberships’ function of the input variable and the output variable the rule of fuzzy developed as follows:

- If angle output is **NB** and **IN** is **S**;
- If angle output is **NS** and **IN** is **MS**;
- If angle output is **ZE** and **IN** is **M**;
- If angle output is **PS** and **IN** is **MB**;
- If angle output is **PB** and **IN** is **B**;

3.3. **PID control Scheme**

The PID controller is planned to positional the desired control of twin rotor system. This controller provide a preliminary satisfaction by eliminated the errors, increased the rise time and reduced the settling time with acceptable performance characteristics. However this traditional PID was unsuccessful to eliminate or even reduce the internal disturbance and external parametric change such as turbulence wind come from the pitch and yaw displacement. Essentially PID is not the main control parameter design but it serve as initial platform prior to implementation of AFC. The mathematical expression of the PID in Laplace Domain is given as

\[ G_c(s) = K_p + \frac{K_i}{s} + K_d s \]  \hspace{1cm} (11)

Where \( K_p, K_i \) and \( K_d \) are proportional, integral and derivative gain respectively.

4. **Simulation Environment**

For this study, classical PID with Active Force Control and Fuzzy logic (PID-AFCFL) has been derived to be the control architecture of TRMS in which it is expected to be robust and effective as the success of previous studies. AFC loop offer a simple computation compared to conventional methods in controlling dynamical structures. The decoupling function strategy was embedded into the control architecture to isolate the coupling effect of twin rotor and facilitate the PID in tracking the target.

Simulation works were performed using MATLAB SIMULINK. Step input and wave input are chosen to test the capability of controller schemes and also the robustness of the controllers is analyzed under presence of pulse and harmonic function as external disturbances. Four different strategies i.e.: PID-AFC without Decoupling Function (NonDecAFC), PID-AFC-FL without Decoupling Function (NonDecAFCFL), PID-AFC with Decoupling Function (DecAFC), and PID-AFC-FL with Decoupling Function (DecAFCFL) were identified and put to the test and the outcome of each strategy was analyzed and compared to observe and investigate which one of the four could stand out among others.

Fig. 6(a) shows the pitch response of the twin rotor positional in tracking the desired output without external disturbances.

The results revealed that all the control strategies were able to track the step response. However, the performance criteria in tracking and the desired were different between proposed controllers. NonAFCFL is observed to be rapid response from
the others with rise time less than 3 second and settling in 12 second but the percentage overshoot is greatest. For DecAFCFL also demonstrate fast response but it still less than NonAFCFL. The adoption of Fuzzy Logic into the control architecture assists the twin rotor system response quickly than without. Fig. 6(b) shows the yaw response of the twin rotor positional in tracking the desired output for each control schemes. The existence of decoupling function in the system reduces the overshoot. It can be proved by both decouple DecAFC and DecAFCFL have less overshoot compare both non-decouple schemes. Rise time for all controllers were almost same and decouple function is effectively counter the cross coupling.

Fig. 7. Simulation result of pitch base on single step input with disturbances.

Fig. 8. Simulation result of yaw base on single step input with disturbances.

Fig.7 and Fig.8, impulse disturbance: $\tau_{imp} = 0.2$ Nm applied into the dynamic system controllers and it replicate as a wind disturbance. The figure illustrates clearly the robustness and effectively of non-decouple PID-AFCFL controls system in rejecting the impulse disturbance. It can prove by observing the amplitudes for both pitch and yaw in which the amplitudes were 1.15 radian and 1.075 radian respectively and it perform better than others. For non-decoupled PID-AFCFL showed great in settling the impulse disturbances compare to others for pitch response but for yaw response decoupled PID-AFCFL is rapidly in absorb the external disturbances.

Fig. 9. Simulation result of pitch base on wave input with disturbances.
Fig. 9 and Fig. 10 showed the performance of controllers in tracking the wave input with impulse disturbance: $\tau_{imp} = 0.2$ Nm. Initial tracking of wave input in pitch responses exhibit a slight drop due to the gravity effect. For compensation the external disturbances, decouple PID-AFCFL exhibited greater in absorbing the external disturbances and can be evaluated by less amplitude and rapid settling time during inducing impulse disturbance compared to the others controllers scheme.

5. Summary

Based on the simulation results, the proposed architecture has proven to give reasonably good performance and capable of compensating disturbances by tuning the inertia matrix in AFC loop viz the intelligent system; fuzzy logic. Decoupling function has shown great reliability in manipulating the uncertainty characteristic of yaw response and stabilizes it. The potential of fuzzy scheme was also very obvious and have given excellent reaction in maintaining the right range of inertia matrix for AFC throughout the tracking. The results clearly show that non-decoupling and decoupling PID-AFCFL approaches provide a quite excellent performance in presence of impulse disturbances compare to non-decoupling and decoupling PID-AFC. For the record, the twin rotor is simplified helicopter and the impulse disturbance can be replicated as a wind disturbance when the helicopter in motion and reflecting to the results and observations, non-decoupling PID-AFCFL strategy is fit for rapid and agile performance where it is best for unmanned air flight system while the decoupling PID-AFCFL strategy appropriate for civilian uses or transportation where less rapid and agile response required.

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