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Experimental Verification of Lead-Lag Compensators on a Twin Rotor System

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***Abstract* – Twin rotor system is a laboratory setup resembling a simplified helicopter model that moves along both horizontal and vertical axes. The literature on control of twin rotor systems reflects a good amount of research on designing PID controllers and their extensions considering several aspects, as well as onsome nonlinear controllers. However, there is almost no previous work on design of lag-lead type compensators for twin rotor systems. In this study, by considering this open research problem, lag and lead type compensators are designed and then experimentally verified on the twin rotor system. Specifically, first, lag and lag-lag compensators are designed to obtain a reduced steady state error as compared with proportional controllers. Secondly, lead compensation is discussed to obtain a reduced overshoot. Finally, lag-lead compensators are designed to make use of their favorable properties. All compensators are applied to the twin rotor system in our laboratory. From experimental studies, it was observed that steady state error was reduced when a lag compensator was used in conjunction with a lead compensator.**

***Keywords* – Linear feedback control systems; Pitch control (position); Position control.**

I. Introduction

Twin rotor system is a laboratory setup resembling a simplified helicopter model that moves along both horizontal and vertical axes as shown in Fig. 1 [1], [2]. In the twin rotor system, two rotors, namely, the main rotor and the tail rotor, adjust the angular positions on pitch and yaw axes. The main rotor directly adjusts the movement of the nose of the twin rotor system up or down, while the tail rotor causes side to side movement of the nose of the twin rotor system.

Review of literature highlights the fact that a good amount of research was devoted to investigating several aspects of twin rotor systems. Some part of prevuious research focused on the modeling of twin rotor systems. These works can roughly be categorized as dedicated to i) physics-based modeling approaches including energy-based methods such as Newtonian, Euler–Lagrange, etc. (*i.e.*, white box system identification) [3]–[5], ii) modeling methods utilizing artificial intelligence-like approaches such as neural networks, genetic algorithms, etc. (*i.e.*, black box system identification) [6]–[9], and iii) some hybrid methods that make use of both of the above-mentioned methods (*i.e.*, grey box modeling approaches) [10]–[13].

Some other past research was devoted to designing controllers for twin rotor systems. These past works can be broadly classified as discussing linear and nonlinear controllers. The linear controllers are based on standard proportional (P), derivative (D), integral (I) feedback controllers. Ching *et al.* designed a PD controller with gravity compensation and a fuzzy PID controller for set point of control of twin rotor systems [14]. As a result of the comparison of these controllers, it was observed that fuzzy PID controller performed better than the gravity compensated PD controller by decreasing overshoot and steady state error. Jih *et al.* demonstrated the performance of a PID controller via numerical simulations where the control gains were adjusted by using real value type genetic algorithms [15]. Jih *et al.*designed a hybrid PID controller for twin rotor systems by combining PID controller with a fuzzy compensator [16]. In the mentioned study, real value type genetic algorithms were utilized to optimize the control gains of the proposed controller. Jih *et al.*used a single variable second order grey model in design of a switching grey prediction-based PID controller where the gains were adjusted by real value genetic algorithms in numerical simulations [17]. Chuan *et al.*study aimed to obtain the optimal gains of PID controllers by using model reduced and optimal methods to improve tracking performance and transient response [18]. Akbar & M. Hasan designed a hybrid fuzzy-based PID controller [19]. Comparing the hybrid controller with fuzzy controller and PID controller revealed that the hybrid controller demonstrates better steady state performance. Recently, Firat evaluated the performances of P, PI, PD and PID controllers on a twin rotor system[1].

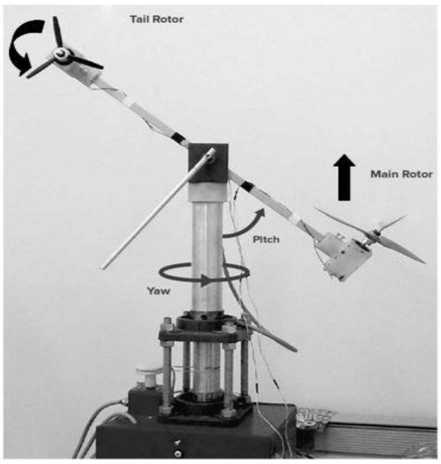

Fig. 1. The twin rotor system in our laboratory.

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After careful revision of the relevant literature on control of twin rotor systems, it was observed that a good amount of research was conducted on designing PID controllers and their extensions considering several aspects, as well as on some nonlinear controllers. However, there is almost no previous work dedicated to design lag-lead type compensators for twin rotor systems. In this study, this open research problem is investigated. Specifically, lag, lag-lag, lead and lag-lead compensators are designed for control of both pitch and yaw motions of the twin rotor system. Lag compensators, without changing the transient characteristics of a system much, has a significant decreasing effect on the steady-state error, lag-lag compensators have even stronger similar effect. Lead compensators are usually preferred to change the transient behavior of the systems. Lag-lead compensators are also designed to make use of the properties of both compensators. These compensators are then experimentally tested on the twin rotor system in our laboratory.

II. Lag Compensation

The main principle of the lag compensator is based on phase lagging of a sinusoidal input signal [20]. Necessary phase delays at high frequencies are provided by utilizing this main principle. Lag compensator is a compensator type that is used instead of P or PI controllers. Some disadvantages of PI controllers like integrator windup due to actuator saturation can be eliminated with the help of a lag compensator. Although lag compensators have some disadvantages like reduced gain crossover frequency due to increased rise and settling time that cause worse system stability and transient response, it is considered one of the most important solutions for improving steady state error. This important property of lag compensators will be utilized throughout this study.

General structure of the transfer function of a lag compensator is expressed in two different forms that are given as

$$D(s) = K\frac{s - z_0}{s - p_0} \text{ or } D(s) = \frac{a_1 s + a_0}{b_1 s + 1}, \tag{1}$$

where K, z_0, p_0 are gain, zero and pole of the compensator, respectively, and a_0, a_1, b_1 are constants that can be obtained from K, z_0, and p_0, or vice versa [21]. In general, designs are usually based on a transfer function of the form

$$D(s) = K\frac{s+a}{s+b}, \tag{2}$$

which is very similar to the first part of (1) with $a = -z_0$ and $b = -p_0$.

In (1), pole p_0 must be closer to the origin than zero z_0 which is the mandatory condition of lag compensator design (*i.e.*, $|p_0| < |z_0|$). Pole-zero location of the lag compensator should be adjusted appropriately to reduce possible negative effects of the lag compensator to the transient response, which can be provided by selecting pole and zero locations so as not to change the root locus much. When the performance of a lag compensator is not at the desired level in reducing steady state error an alternative is to utilize a double lag compensator,

$$D(s) = K\left(\frac{s+a}{s+b}\right)^2, \tag{3}$$

which is commonly called a lag-lag compensator. The experimental results obtained from running the twin rotor system are now presented (All experiments were conducted at least 5 times and similar performances were obtained). In these experiments, the performances of the proportional controller, lag compensator and lag-lag compensator are compared. These controllers are evaluated first for set-point control of only the pitch motion and then for set-point control of both pitch and yaw motions. The desired pitch and yaw angular positions were set at 30° and 20°, respectively. In the experiment results, after the error settled down, its maximum deviation from the desired value till the end of the experiment is considered as the steady state error.

The results of these experiments are presented in a comparative manner by calculating the steady state error while one of these results is presented graphically. Specifically, angular pitch position for proportional controller with a gain of 10 for only main motor is given in Fig. 2. Angular pitch position is shown in Fig. 3 when lag compensator of form $10\frac{s+0.1}{s+0.01}$ is applied on the main motor. Lag-lag compensator of the form $10\left(\frac{s+0.1}{s+0.01}\right)^2$ is applied on the main motor, the resulting angular pitch position is shown in Fig. 4. Secondly, angular pitch and yaw positions for a proportional controller with gains of 10 and 3000 for main and tail motors, respectively, are given in Fig. 5. Results obtained when lag compensators of the form $10\frac{s+0.1}{s+0.01}$ and $3000\frac{s+0.1}{s+0.001}$ are applied on the main and tail motors, respectively, are shown in Fig. 6. Results from applying lag-lag compensators $10\left(\frac{s+0.1}{s+0.01}\right)^2$ and $3000\left(\frac{s+0.1}{s+0.001}\right)^2$ on the main and tail motors, respectively, are given in Fig. 7. As expected, the lag-lag compensator performed best among the three compensators while proportional controller was the worst in the steady state error. It is clear from Figs 5 and 6 that the steady state error has improved with the lag compensator ascompared to the proportional controller. In Fig. 7, it is shown that the steady state error improves with the lag-lag compensator.

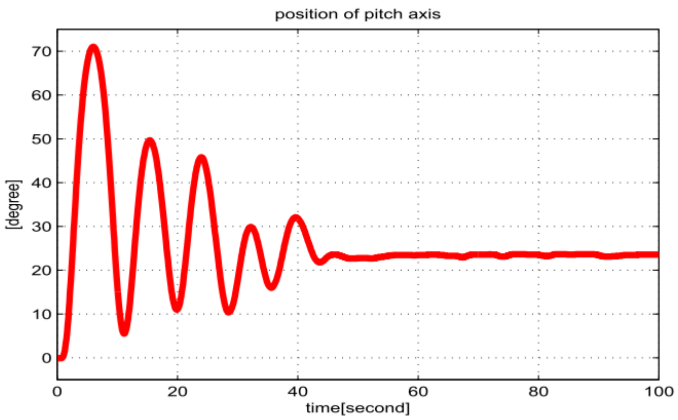

Fig. 2. Angular pitch position when proportional controller with gain 10 was applied on the main motor.

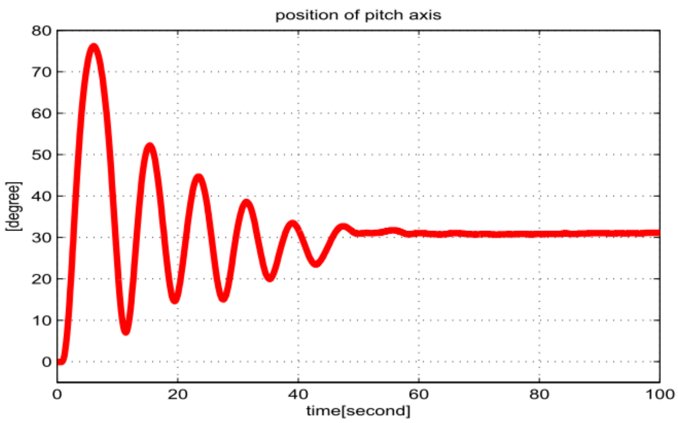

Fig. 3. Angular pitch position when lag compensator of the form $10\left(\dfrac{s+0.1}{s+0.01}\right)$ was applied on the main motor.

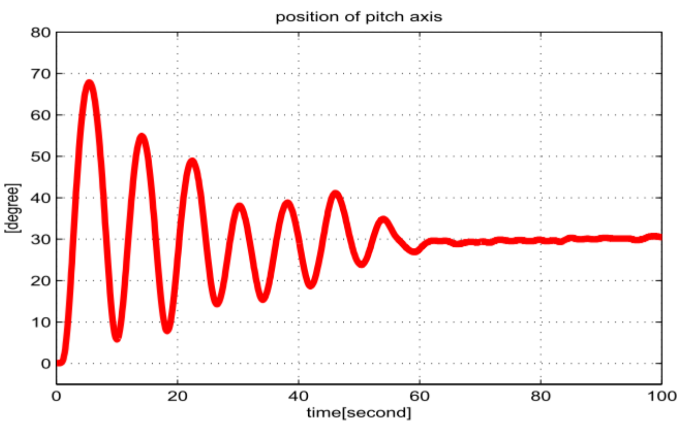

Fig. 4. Angular pitch position when lag-lag compensators of the form $10\left(\dfrac{s+0.1}{s+0.01}\right)^2$ was applied on the main motor.

In Table I, steady state errors obtained from several experiments after applying different lag and lag-lag compensators for set-point control of only pitch angular position are presented. The zero and the constant gain were the same for all lag compensators and the location of the pole varied, and no control was applied on the tail motor. As expected, the lowest steady state error was observed when the zero-pole ratio was the highest and when the zero-pole ratio decreased the steady state error increased. All of these steady state errors were less than the steady state errors obtained when proportional control was applied. It can also be observed that the lag-lag compensator demonstrates improved performance compared to the lag compensator in the steady state error.

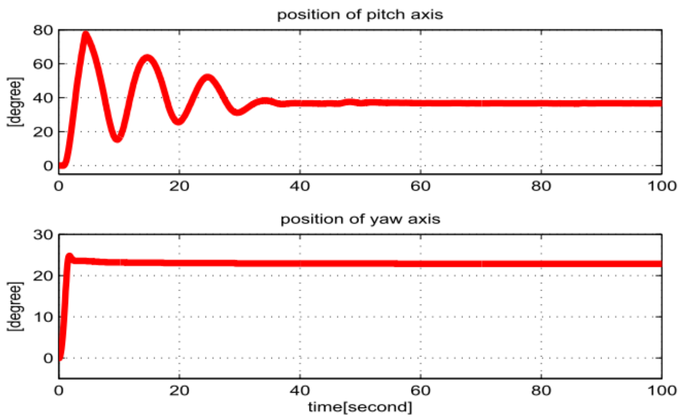

Fig. 5. Angular pitch (top) and yaw (bottom) positions for proportional controllers with gains 10 and 3000 for the main and tail motors, respectively.

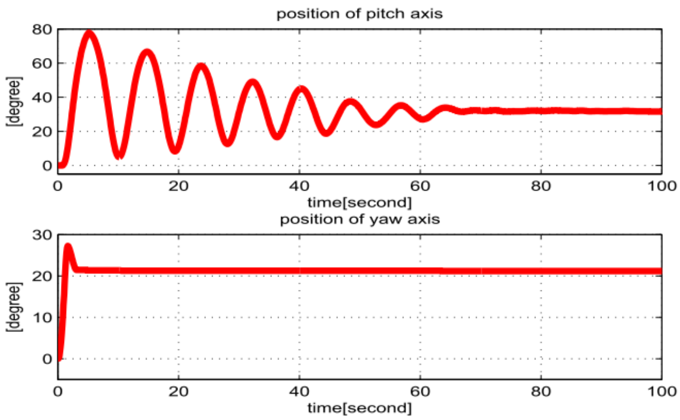

Fig. 6. Angular pitch (top) and yaw (bottom) positions for lag compensators of the form $10\left(\dfrac{s+0.1}{s+0.01}\right)$ and $10\left(\dfrac{s+0.1}{s+0.001}\right)$ applied on the main and tail motors, respectively.

In Table II, steady state errors obtained after applying different lag and lag-lag compensators to both motors of the twin rotor system are given. In these experiments, the compensators applied on the tail rotor were kept the same since satisfactory performance was obtained and thus only the compensators applied on the main rotor varied. When the zero-pole ratios of the lag and lag-lag compensators were the highest, the lowest steady state error in both axes was observed. The steady state error increased as the zero-pole ratio decreased.

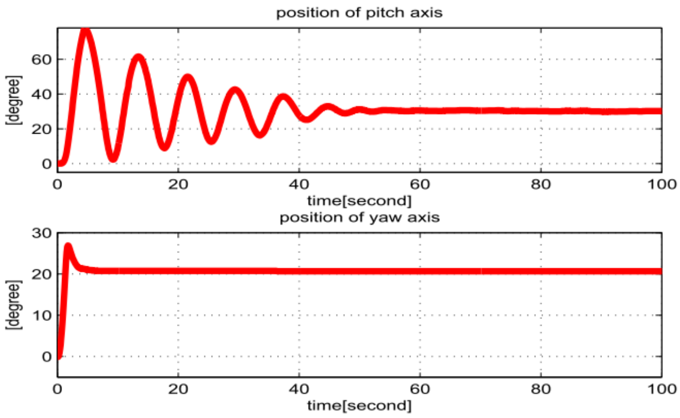

Fig. 7. Angular pitch (top) and yaw (bottom) positions for lag-lag compensators of the form $10\left(\frac{s+0.1}{s+0.01}\right)^2$ and $10\left(\frac{s+0.1}{s+0.001}\right)^2$ applied on the main and tail motors, respectively.

In view of the experimental results obtained testing the twin rotor system in our laboratory, the lag type compensation significantly improves the steady state error when compared with proportional controllers.

III. Lead Compensation

Lead compensator is a compensator type that is used instead of PD or PID controllers. Some disadvantages of the mentioned controllers can usually be eliminated by with the help of a lead compensator. Amplification of the sensor noise that may be caused by a derivative controller, higher control efforts that may be caused by an integral controller can be considered among these disadvantages. The main principle of a lead compensator is based on phase leading of the sinusoidal input signal[22]. Lead compensator also provides better low pass filter property when compared with PID control due to this main principle. Improving the transient response of the system is the main purpose of the lead compensator and this is realized by increasing the phase of open loop system, which is another capability of the lead compensator. General structure of the transfer function of the lead compensator is expressed in two different ways that are given as

$$D(s) = K\frac{s-z_0}{s-p_0} \text{ or } D(s) = \frac{a_1 s + a_0}{b_1 s + 1}, \tag{4}$$

where K, z_0, p_0 are gain, zero and pole of the system, respectively, and a_0, a_1, b_1 are constants that can be written in terms of K, z_0 and p_0, or vice versa. In general, designs are usually established on the following transfer function type

$$D(s) = K\frac{s+a}{s+b}, \tag{5}$$

which is very similar to the first part of (4) with $a = -z_0$ and $b = -p_0$.

As it was said before, improving the transient response is the main aim of the lead compensator design and this aim can be achieved by changing rise time, settling time, overshoot, gain/phase margin or damping ratio that determine the behavior of transient response. Since these adjustments affect the pole locations of the controlled system it is clear that the lead compensator changes the root locus. As a natural result, pole-zero locations become important in lead compensator design. Providing relatively fast response without losing the stability is the first aspect that must be considered while selecting these locations. In other words, a dominant pole placed in the left–half–plane must be selected. In addition to these, zero z_0 must be closer to the origin than pole p_0 which is the mandatory condition of lead compensator design (*i.e.*, $|z_0| < |p_0|$) in (4)). In this study, among other transient response characteristics overshoot is considered to be the characteristic of the twin rotor system that is focused on. Now, the experimental results obtained testing the twin rotor system are presented for different lead compensators. Several lead compensators are applied to control angular pitch and yaw positions. The experiments were conducted for 100 sand the desired pitch and yaw angular positions were set as 30° and 20°, respectively. In these experiments, only the pole of the lead compensator for main motor was varied while keeping other control parameters unchanged. The tail motor compensator was kept the same during the experimental studies. The overshoot in pitch axis is evaluated and presented in Table II. It was observed that when the pole of the lead compensator moves away from the imaginary axis, the overshoot in pitch axis decreases.

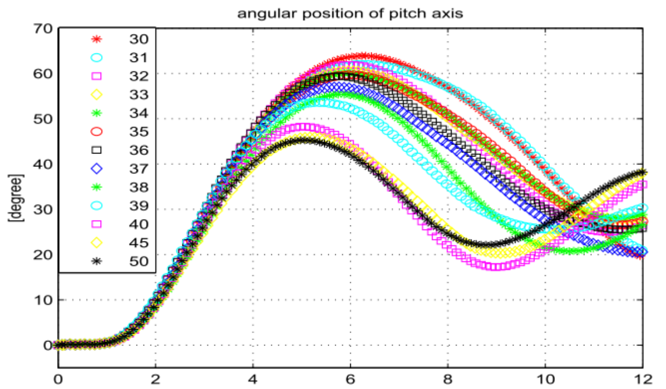

Fig. 8. Comparison of overshoot in pitch axis for different pole values of the lead compensator.

The first 12 s of experiment results for the lead compensators in Table II are demonstrated in Fig. 8. In view of the experimental results, by changing the location of the pole of the lead compensator, the significant amount of overshoot was decreased.

IV. Lag-Lead Compensation

As it was mentioned in the previous sections of this study, both lag and lead compensators have positive effects on different parts of system performance. The findings can be summarized as follows – lead compensator does not affect the steady state performance much while improving the transient response, and lag compensator improves the steady state performance while slowing down the transient response [20].

As a result, using the two together is seen a useful solution to alter the transient response of a system while improving its steady state response. Since it offers satisfactory solutions for possible problems of PID control such as saturation, noise amplifying, integrator windup and ensures better low pass filter characteristic than PID controller, the lag-lead compensator is preferred to PID controllers in control systems. One disadvantage of lag-lead compensators is that the order of the system increases as a result of two new poles and two new zeros. Transfer function of the lag-lead compensator contains the transfer functions of both lag and lead compensators with same properties and are expressed as

$$D(s) = K\frac{s+a}{s+b}\cdot\frac{s+c}{s+d}, \quad (6)$$

where K is the gain of the compensator, $\frac{s+a}{s+b}$ is the lead part and $\frac{s+c}{s+d}$ is the lag part. Experiment results obtained from the twin rotor system by using lag-lead compensators are now presented. Lag-lead compensators were designed to drive angular pitch and yaw positions to the desired angular positions chosen as 30° and 20°, respectively. In the design of the lag-lead compensators, lead compensators from section 3 are focused with the lag part that was chosen as $\frac{s+0.1}{s+0.001}$ which was one of the lag compensators from section 2.

The steady state error performances of the lag-lead compensators were compared with the lead compensators. The results are given in Table III, from which it is clearly seen that the addition of lag compensators affected the decrease of the steady state error.

V. Conclusions

This study was devoted to designing lag and lead compensators and their experimental verification on the twin rotor system. Firstly, lag compensators, which are commonly utilized to decrease steady state errors without changing the transient characteristics much, were designed. Several experiments were conducted that demonstrated the proof of the concept. Lead compensation was considered next to decrease the high amount of overshoot that was observed in most of the experiments performed on lag compensation of the twin rotor system. A good amount of reduction in overshoot was achieved by changing the location of the pole of the lead compensator. Finally, to achieve reduced overshoot while at the same time decreasing the steady state errors, lag and lead compensators were fused to yield lag-lead compensation. Experimental results confirmed that the reduced steady state error was obtained when the lag compensator was used in conjunction with the lead compensator.

Compared with the existing literature on twin rotor systems, the main novelty of this study according to our best knowledge is that lag and lead type compensation techniques were for the first time applied to twin rotor systems to overcome several shortcomings of PID controllers. We sincerely believe that our findings can be considered as an experiment in an undergraduate control course.

Acknowledgment

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TABLE I

COMPARISON OF STEADY STATE ERRORS OF ANGULAR PITCH POSITION WHEN DIFFERENT CONTROLLERS ARE APPLIED ONLY ON THE MAIN MOTOR

Controller			Steady state error		
proportional	lag	lag-lag	proportional	lag	lag-lag
main motor			pitch axis		
10	$10\frac{s+0.1}{s+0.01}$	$10\left(\frac{s+0.1}{s+0.01}\right)^2$	3.545	1.436	0.117
10	$10\frac{s+0.1}{s+0.02}$	$10\left(\frac{s+0.1}{s+0.02}\right)^2$	3.545	1.963	0.557
10	$10\frac{s+0.1}{s+0.03}$	$10\left(\frac{s+0.1}{s+0.03}\right)^2$	3.545	2.49	1.611
10	$10\frac{s+0.1}{s+0.04}$	$10\left(\frac{s+0.1}{s+0.04}\right)^2$	3.545	2.93	2.139
10	$10\frac{s+0.1}{s+0.05}$	$10\left(\frac{s+0.1}{s+0.05}\right)^2$	3.545	3.457	2.578

TABLE II

COMPARISON OF OVERSHOOT IN ANGULAR PITCH POSITION AND PERCENTAGE FOR DIFFERENT LEAD COMPENSATORS APPLIED ON THE MAIN MOTOR

Steady state error	Lag-lag	yaw	0.225	0.400	0.400	0.400	0.488
		pitch	1.523	1.875	2.842	3.721	3.984
	lag	yaw	0.255	0.412	0.488	0.664	1.104
		pitch	2.051	2.139	3.193	3.896	4.160
	proportional	yaw	2.598	2.598	2.598	2.598	2.598
		pitch	6.621	6.621	6.621	6.621	6.621
Controller	Lag-lag	tail motor	$3000\left(\frac{s+0.1}{s+0.001}\right)^2$	$3000\left(\frac{s+0.1}{s+0.001}\right)^2$	$3000\left(\frac{s+0.1}{s+0.001}\right)^2$	$3000\left(\frac{s+0.1}{s+0.001}\right)^2$	$3000\left(\frac{s+0.1}{s+0.001}\right)^2$

		main motor	$10\left(\frac{s+0.1}{s+0.001}\right)^2$	$10\left(\frac{s+0.1}{s+0.01}\right)^2$	$10\left(\frac{s+0.1}{s+0.02}\right)^2$	$10\left(\frac{s+0.1}{s+0.03}\right)^2$	$10\left(\frac{s+0.1}{s+0.04}\right)^2$
	lag	tail motor	$3000\frac{s+0.1}{s+0.001}$	$3000\frac{s+0.1}{s+0.001}$	$3000\frac{s+0.1}{s+0.001}$	$3000\frac{s+0.1}{s+0.001}$	$3000\frac{s+0.1}{s+0.001}$
		main motor	$10\frac{s+0.1}{s+0.001}$	$10\frac{s+0.1}{s+0.01}$	$10\frac{s+0.1}{s+0.02}$	$10\frac{s+0.1}{s+0.03}$	$10\frac{s+0.1}{s+0.04}$
	proportional	tail motor	3000	3000	3000	3000	3000
		main motor	10	10	10	10	10

TABLE III

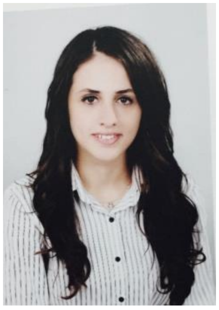
COMPARISON OF OVERSHOOT IN ANGULAR PITCH POSITION AND PERCENTAGE FOR DIFFERENT LEAD COMPENSATORS APPLIED ON THE MAIN MOTOR

Lead Compensator		Overshoot	Percent Overshoot
main motor	tail motor	pitch	pitch
$0.1\frac{s+10}{s+30}$	$600\frac{s+10}{s+20}$	33.90	113.000 %
$0.1\frac{s+10}{s+31}$	$600\frac{s+10}{s+20}$	31.96	106.530 %
$0.1\frac{s+10}{s+32}$	$600\frac{s+10}{s+20}$	31.88	106.266 %
$0.1\frac{s+10}{s+33}$	$600\frac{s+10}{s+20}$	30.47	101.560 %
$0.1\frac{s+10}{s+34}$	$600\frac{s+10}{s+20}$	30.03	100.100 %
$0.1\frac{s+10}{s+35}$	$600\frac{s+10}{s+20}$	29.68	98.930 %
$0.1\frac{s+10}{s+36}$	$600\frac{s+10}{s+20}$	29.41	98.030 %
$0.1\frac{s+10}{s+37}$	$600\frac{s+10}{s+20}$	26.95	89.830 %
$0.1\frac{s+10}{s+38}$	$600\frac{s+10}{s+20}$	25.37	84.560 %
$0.1\frac{s+10}{s+39}$	$600\frac{s+10}{s+20}$	23.61	78.700 %
$0.1\frac{s+10}{s+40}$	$600\frac{s+10}{s+20}$	18.25	60.830 %
$0.1\frac{s+10}{s+45}$	$600\frac{s+10}{s+20}$	15.88	52.930 %
$0.1\frac{s+10}{s+50}$	$600\frac{s+10}{s+20}$	15.18	50.600 %

TABLE IV

COMPARISON OF STEADY STATE ERRORS OF ANGULAR PITCH AND YAW POSITIONS FOR LAG-LEAD COMPENSATORS COMPARED WITH LEAD COMPENSATORS APPLIED ON BOTH MOTORS

Lead compensator		Steady state error	Lag-lead compensator		Steady state error
main motor	tail motor	pitch axis	main motor	tail motor	pitch axis
$0.1\frac{s+10}{s+30}$	$600\frac{s+10}{s+20}$	5.50	$0.1\frac{s+10}{s+30}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	3.50
$0.1\frac{s+10}{s+31}$	$600\frac{s+10}{s+20}$	6.70	$0.1\frac{s+10}{s+31}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	4.42
$0.1\frac{s+10}{s+32}$	$600\frac{s+10}{s+20}$	2.60	$0.1\frac{s+10}{s+32}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	2.14
$0.1\frac{s+10}{s+33}$	$600\frac{s+10}{s+20}$	5.60	$0.1\frac{s+10}{s+33}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	3.10
$0.1\frac{s+10}{s+34}$	$600\frac{s+10}{s+20}$	10.30	$0.1\frac{s+10}{s+34}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	6.21
$0.1\frac{s+10}{s+35}$	$600\frac{s+10}{s+20}$	4.50	$0.1\frac{s+10}{s+35}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	4.01
$0.1\frac{s+10}{s+36}$	$600\frac{s+10}{s+20}$	3.20	$0.1\frac{s+10}{s+36}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	2.90
$0.1\frac{s+10}{s+37}$	$600\frac{s+10}{s+20}$	9.70	$0.1\frac{s+10}{s+37}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	7.90
$0.1\frac{s+10}{s+38}$	$600\frac{s+10}{s+20}$	5.90	$0.1\frac{s+10}{s+38}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	5.50
$0.1\frac{s+10}{s+39}$	$600\frac{s+10}{s+20}$	10.50	$0.1\frac{s+10}{s+39}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	3.20
$0.1\frac{s+10}{s+40}$	$600\frac{s+10}{s+20}$	9.08	$0.1\frac{s+10}{s+40}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	6.01
$0.1\frac{s+10}{s+45}$	$600\frac{s+10}{s+20}$	7.76	$0.1\frac{s+10}{s+45}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	4.10
$0.1\frac{s+10}{s+50}$	$600\frac{s+10}{s+20}$	12.86	$0.1\frac{s+10}{s+50}\cdot\frac{s+0.1}{s+0.001}$	$600\frac{s+10}{s+20}\cdot\frac{s+0.1}{s+0.001}$	5.04



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