Helicopter Pitch Control System

Nenad Popovich, Christian R. Bonaobra

***Abstract*—**The helicopter was subjected to a few different optimization methods such as Root Locus, Ziegler-Nichols Tuning method, Systematic Trial Tuning method and Integral Absolute Error criteria. These are essential to find the "optimal' gain(s) of a controller. This paper is focused on creating a system that can provide reliable pitch altitude control while being cost effective under outside disturbances.
In order to have outstanding controller for our helicopter pitch control system, controller needs to have a stable response, low overshoot, together with a fast response, which means a quick settling time. We also kept in mind that we need to protect its mechanical components.

***Keywords*—**helicopter pitch control, Simulink, optimal parameters, *IAE* criteria.

I. Introduction

The purpose of this paper is to analyze helicopter pitch control system and to find the "ideal" parameters through P, I and D controller parameters. Helicopter requires a stable control system as defective controller can lead to accidents. In this project, we are focused on an Integral Absolute Error criteria (*IAE*) to reduce the error and try to get the best response. The response will need to have a low overshoot, peak time, rise time and a fast settling time. This paper will cover the procedures that we have done from researching a transfer function leading to achieving the desired response of the helicopter pitch control system.

II. Mathematical Model

A. Dynamical Model and Transfer Functions

The helicopter has, same as all other flying objects, six degrees of freedom: heave, sway, surge, pitch, roll and yaw. In this paper, our focus is a pitch control dynamical behavior.
The transfer function for our research is taken from the Black Hawk helicopter [17]. That transfer function is mathematical model description (model) of the helicopter movement (rotation around its y-axis).
Two transfer functions: dynamical behaviour of the helicopter (1), as well as a transfer function of its sensor and actuator, combined (2), taken from [1], [2], [17]:

$$\frac{5.95}{s^2 - 0.346s} \tag{1}$$

$$\frac{2500s^2 + 10000s + 10000}{4s^2 + 400s + 10000} \tag{2}$$

Responses of those two transfer functions to the step input, Fig. 1(a) and Fig. 1(b), respectively:

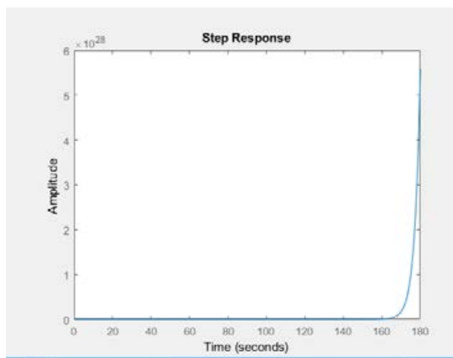

Fig. 1(a) Dynamical response of the helicopter

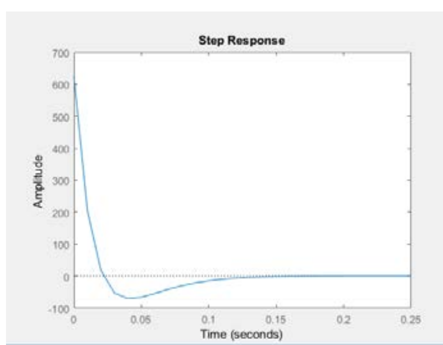

Fig. 1(b) Sensor and actuator response, combined

Open loop response transfer function for the whole system (helicopter, sensor and actuator), (3) and its response to a unit step input, Fig. 2:

$$\frac{14875s^2 + 59500s + 59500}{4s^4 + 398.64s^3 + 9862s^2 - 3460s} \tag{3}$$

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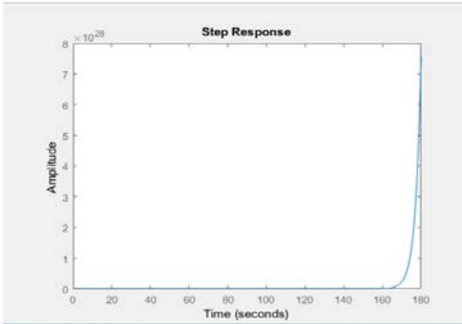

Fig. 2 Open loop response

As you can see from the dynamical response of the helicopter, as well as from the open loop response, system is unstable, due to integrator in the open loop system ("type-1"). In addition, one of four poles is unstable pole, (s=0.346).

B. Closed Loop System

Simulation model of the closed loop system in Fig. 3:

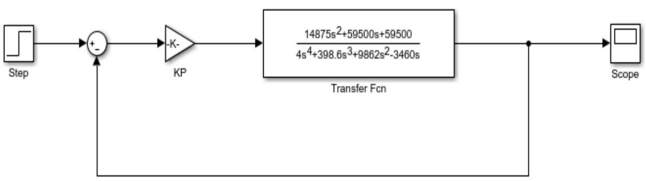

Fig. 3 Simulation model for a closed loop system

The closed loop system uses a feedback to stabilize the system. A correct selection of the K_P (proportional gain constant) can produce a stable system, but not necessarily the best dynamical behavior of the entirely system (overshoot, steady-state error, rise, peak and settling times).

Our first step is to find a range of stability and then to make an "optimal" response of the system.

In this paper the Root Locus, graph-analytical method for defining a critical gain is used, Fig. 4(a) and Fig. (4b):

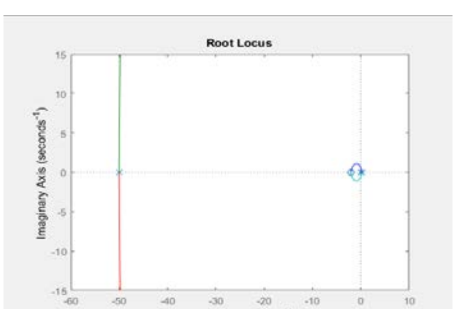

Fig. 4(a) Root Locus

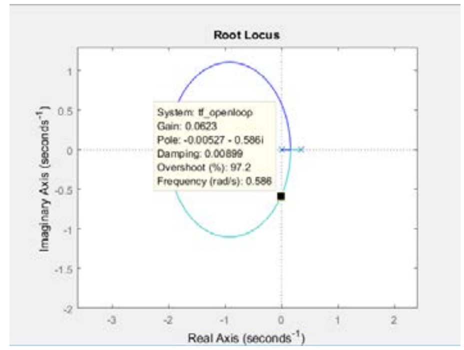

Fig. 4(b) Root Locus (enlarged)

From Fig. 4(b), with two dominant poles, is seen a point where locations of the poles, in s-plane, cutting imaginary axis. Which means that critical gain (ultimate gain) is: $G_U=0.0623$.

Note: it is not a typical case, because in this case a bigger gain gives us a stable system (usually, it is just an opposite: bigger gain leads to unstable system), [7], [12] and [14].

III. Controller Design

A. Ziegler-Nichols Second Tuning Method

As mentioned earlier, our system is "type-1", which means Ziegler-Nichols First tuning method (Open Loop tuning method, based on "S-shape" response of the system) is not possible to implement, because integrator will not produce "S-shape" response, [14].

Ziegler-Nichols Second tuning method is a closed loop method and it starts with a proportional controller (i.e. disable integral and derivative controller). Then, start up the process with the proportional gain, K_P at "low level" and gradually increase gain until the system oscillate with ultimate period, P_U, Fig. 5.

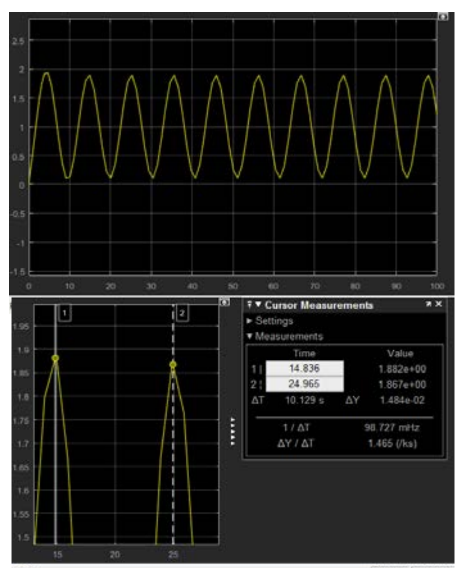

Fig. 5 Sustain oscillatios, P_U=10.129 seconds

Ultimate gain which causing sustain oscillation is, G_U=0.0678 (slightly different than in using Root Locus method).

Based on Pu and Gu, controller settings can be determined according to Table 1, [14]:

PID	PI	P
$K_P = 0.65G_u$	$K_P = 0.45G_u$	$K_P = 0.5G_u$
$T_I = \frac{P_u}{2}$	$T_I = \frac{P_u}{1.2}$	
$T_D = \frac{P_u}{8}$		

Table 1.

where: K_P -Proportional gain constant
K_D -Derivative gain constant
K_I -Integral gain constant
T_I -Integral time constant
T_D -Derivative time constant

Note: Ziegler-Nichols Second tuning method is based on empirical formula and it is not so occurate. That means, calculating controller's parameters does not lead us to an "optimal" system, and rather gives us a range of the controller's parameters for a fine tuning.

Parameters for P, PI and PID controllers have been calculated from Table 1, and responses for those three cases are shown on Fig. 6(a), Fig. 6(b) and Fig. 6(c), respectively:

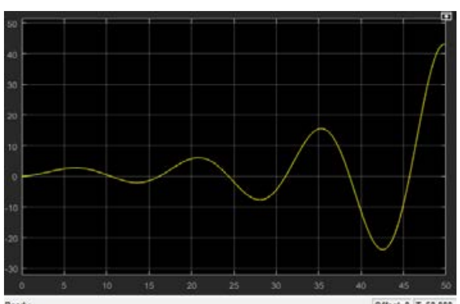

Fig. 6(a) System response with P controller K_P=0.039

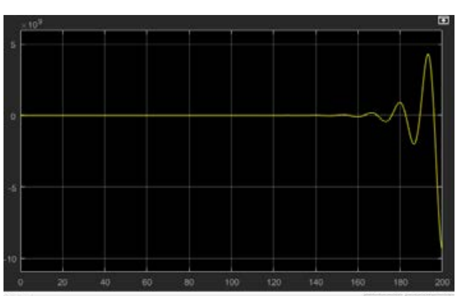

Fig. 6(b) System response with PI controller K_P=0.0305, K_I=3.61e-03

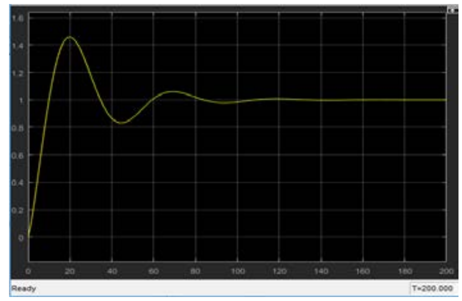

Fig. 6(c) System response with PID controller K_P=0.044, K_D=0.558, K_I=8.7e-0.3

Simulation model for those three responses is on Fig. 7:

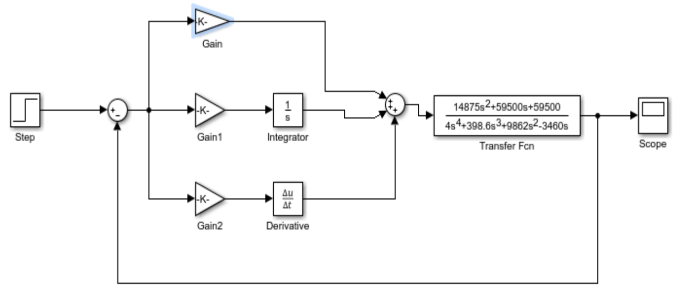

Fig. 7 Simulation model for P, PI and PID controller (Gain=K_P , Gain1= K_D and Gain2= K_I)

As you can see from Fig. 6(a) (with P controller) and Fig. 6(b) (with PI controller), system responcnses are unstable. On the other hand, system response with PID controller is stable, but with not so satisfying dynamical characteristics (overshoot around 50%, and setlling time around 100 seconds). Only, steady state error is goo, ess=0 (due to "type-1" system). However, this is a good starting point for a fine tuning and getting better system parameters.

B. *Systematic Trial Tuning Method*

Systematic Trial tuning method is a Fine tuning method to get better (or even "optimal") system performance.

There are a few general "rules" how to improve sytem's dynamics [9]:

- Add a proportional control to improve the speed of the system response (particularly a rise time).
- Add a derivative control to improve the overshoot and the transient response.
- Add an integral control to eliminate the steady state error.
- Adjust each of those controller's parameters until obtain a desired overal response.
- And last, but not the least: make a controller as simple as possible.

The most likely effect of each of the controller parameters: K_p, K_i and K_d (proportional, integral and derivative gain constants, respectively), on the closed loop system response, can be tabulated, as in Table 2, [9]:

Parameter	Rise time	Overshoot	Settling time	Steady-state error	Stability[9]
K_p	Decrease	Increase	Small change	Decrease	Degrade
K_i	Decrease	Increase	Increase	Eliminate	Degrade
K_d	Minor change	Decrease	Decrease	No effect in theory	Improve if K_d small

Table 2.

Note: Those correlations may not be exactly accurate, because K_p, K_i and K_d are dependant on each other. In fact, changing one of those parameters can change the effect of the other two. For that reason, the table should be use as a reference or a guidance, only. [4], [5], [9].

Multiple parameters were put in simulation model (Fig. 7) to try to decrease overshoot, peak, rise and settling times.
On the folowing, randomly chosen, two graphs are shown a few of "trial and error" attempts to achieve a better response, Fig. 8(a) and Fig. 8(b):

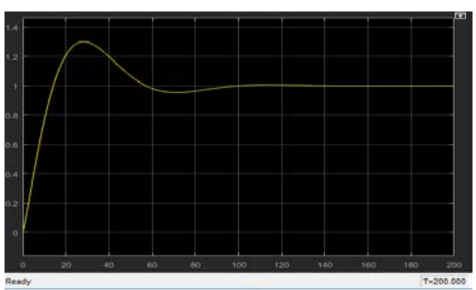

Fig. 8(a) System response with PID controller K_P=0.044, K_D=0.558, K_I=3.5e-0.3

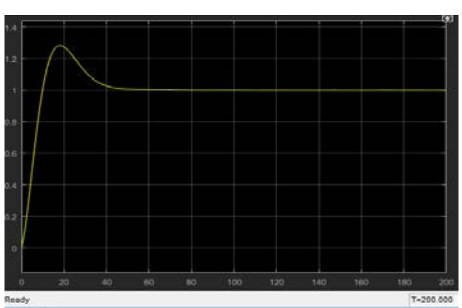

Fig. 8(b) System response with PID controller K_P=0.0155, K_D=0.145, K_I=0.855e-0.3

Overshoot is reduced, as well as rise, peak and settling times, comparing with the system response with "original" controller parameters by using Ziegler-Nichols Second tuning method.
However, we still have a moderate settling time of 45 seconds, mainly because we used the Black Hawk model of the helicopter, which has inherited a moderate settling time.

A further improvement will be done through the *IAE* (Integral Absolute Error criteria).

C. Integral Absolute Error (IAE) Criteria

The Cost Functions, (4) and (5) are used in order to find the most efficient values for K_P, K_D and K_I. Those criteria will not necessarily produce the "best" output response with the smallest overshoot nor the fastest system. They are simply used to determine gain values that will make the control cost more efficient. In the industry, those criteria are used mostly to lower fuel consumption. The name: "Cost Function" is derived from the meaning of the least cost as possible. They are calculated by using following formulae for Integral Squared Error (*ISE*) and Integral Absolute Error (*IAE*), respectivelly, [4], [5], [12]:

$$ISE = \int_0^t e(t)^2\,dt \rightarrow \min \quad (4)$$

$$IAE = \int_0^t |e(t)|\,dt \rightarrow \min \quad (5)$$

In this paper we used *IAE* only. It tends to produce a slightly slower response than "optimal" system using *ISE* criteria, but usually with less oscillations in the system response.

Simulation model for the whole system is shown below:

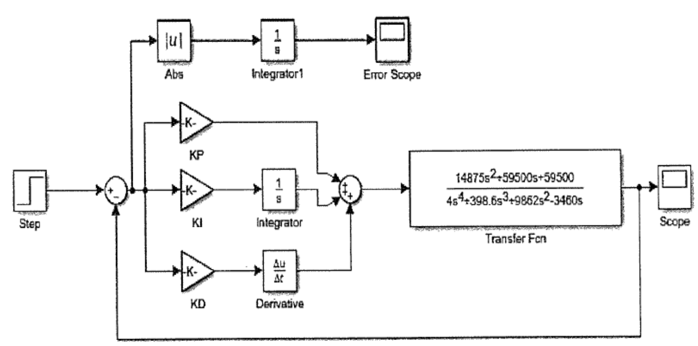

Fig. 9 Simulation model with PID controller (including *IAE* criteria)

The previous values of the PID controller, obtained from the Systematic Trial (and Error) method were used in the *IAE* procedure. The procedure for this is, as follow: one parameter of the controller will be changed, while another two will stay unchanged. That means: only one parameter will be changed at the time, to be able to see what influence that particular parameter has on the system response. All parameters will be changed in the range of the Systematic tuning method (K_P=0.0155, K_D=0.145, K_I=0.855e-0.3).

Values of Integral Absolute Error (*IAE*) will be recorded for each set of parameters and the smallest value (minimum value) will give us the "optimal" parameters of the controllers (i.e. the smallect "Cost Function".

Each of those three groups of changing parameters, results are tabulated in those three tables: Table 3(a), Table 3(b) and Table 3(c), by changing K_D, K_I and K_P, respectively.

K_p	K_I	K_D	*IAE*
0.0155	0.855e-03	0.01	1.16e08
		0.03	5.158e04
		0.07	2.256e01
		0.1	9.797
		0.145	1.007e01

Table 3(a) Results when varying K_D controller parameter

K_p	K_I	K_D	*IAE*
0.0155	0.100e-0.3	0.145	9.305 ***
	0.300e-0.3		1.073e01
	0.500e-0.3		1.059e01
	0.700e-0.3		1.029e01
	0.855e-0.3		1.007e01

Table 3(b) Results when varying K_I controller parameter

K_p	K_I	K_D	*IAE*
0.002	0.855e-03	0.145	9.467e01
0.004			4.928e01
0.006			2.997e01
0.008			2.070e01
0.0155			1.007e01

Table 3(c) Results when varying K_P controller parameter

Note: Shaded numbers are "local" minimum for each of those particular groups.

From those three tables, it is obvious that a minimum value for *IAE* criteria, for the whole range of the initial settings is 9.305 (a "global" minimum, showing with three stars, ***).

That means, using K_P=0.0155, K_I=0.100e-0.3 and K_D=0.145, gives us the "optimal" unit step response, Fig. 10.

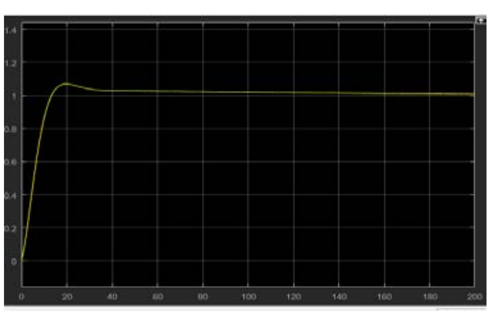

Fig. 10 "Optimal" system response

In conclusion, response with the "optimal" parameters significantly improve overshoot (around 6%), as well as a settling time (around 30 seconds).

IV. Adding Protection Unit

Adding Protection Limiter is essential in order to protect the system's mechanical components (i.e. actuator- final control element) from being damage, especially when controller output produces a big value, mainly due to controller derivative part (so called a "derivative kick"), [4], [15]:

Introducing protection limiter (usually Saturation block) will restrict extensive movement of the actuator. However, too much restriction tends to make system unstable (if not properly design). In addition, it causes that system becomes non-linear and then, a superposition and a linear theory do not work.

Usually, a position of the protection limiter (Saturation block) is, as shown on Fig. 11:

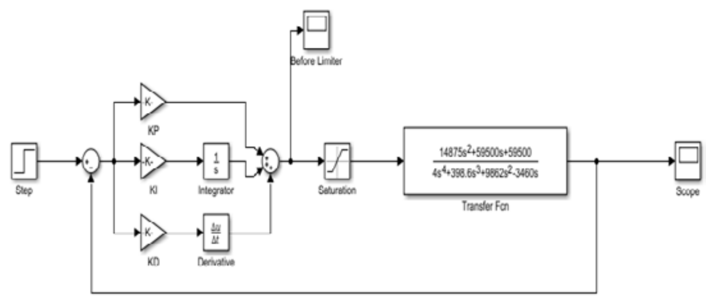

Fig. 11 System with protection limiter (Saturation)

Fortunately, in our case saturation block is not necessary to implement, because the output of PID controller is not so extensive (from -0.005 to 0.005), and cannot damage our mechanical components, as seen on Fig. 12:

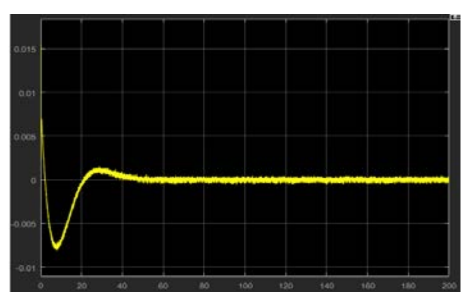

Fig. 12 Output of PID controller

V. Disturbance

Every control system is prone to outside interference or unwanted signals, referred as a disturbance.

Disturbance is represented by a Step1 input, set at 0.1, (see Fig. 13). Since the initial step value of the system is 1, the disturbance value of 0.1 suggests that helicopter will experience 10% extra force in the direction of travel or a push backwards (if it sets at -0.1).

One example of that disturbance is wind (ambient conditions), with its specified direction and strength. This external disturbance can cause the system to have steady state error, as well as more oscillation of the output. Very high values of disturbances can even cause instability.

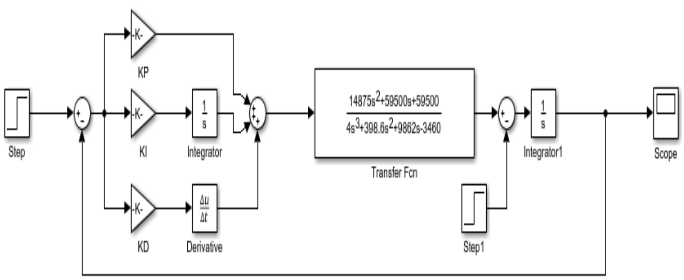

Fig. 13 Simulation model with a disturbance

From the Fig. 14, it can be seen that 10% disturbance (wind) causes that system experiences big overshoot (60%) and slower settling time (more than 40 seconds).

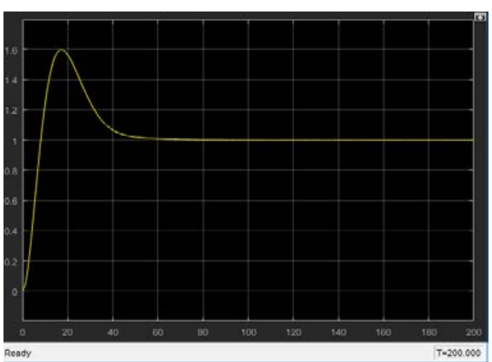

Fig. 14 System response with 10% disturbance

VI. Conclusion

The helicopter pitch control system went through the procedures to obtain the desired parameters in order to stabilize the system. System was analyzed in Matlab through Root Locus to evaluate the variation of the poles of the open loop transfer function. Subsequent to open-loop analysis, closed-loop system was created in Simulink. This is when trial and error was done in order to determine the critical or ultimate gain (Gu) and ultimate period (Pu) which were used in Zeigler-Nichols Second tuning method to calculate the values for P, PI and PID controller.

Furthermore, Systematic Trial tuning method was done to improve PID controller parameters, which gave better system's response. Integral Absolute Error (*IAE*) criteria proceeded from Systematic Trial tuning method to get the "optimal' parameters, which was used in our final response for the helicopter pitch control system.

Optimal values were tested with protection limiter, but were not taken into consideration in the final model, because "derivative kick" does not exist. Disturbance was also added into the system which suggests that the object will experience 10% extra force in the direction of travel.

Acknowledgment

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