Comparison and Evaluation of Restrain Control in Wind Turbine with Various Shock Absorber Considering the Time-Delay

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Abstract

In this research the behavior of small-scaled wind turbine system is evaluated against strong wind input considering round trip delay. Generally, the wind turbine system is generating energy from the revolution of blades. The revolution of blades is depended on the velocity of wind. Therefore, if there is strong wind then the revolution of blade is increased and more energy will generated. Therefore, according to this situation the wind turbine systems are located in gale area in order to generate energy efficiency. However, there are specific limits of the revolution of blades or the angular velocity of blades. If the angular velocity exceeds the limit then wind turbine system may breakdown. Also, in this research time-delay element is considered due to the distance observation of behavior of system. Time-delay occur during the transposition of data between the observer and plant. Therefore, in this occasion round trip delay occurs in system. Hence, the closed loop of system may become unstable due to existence of time-delay element. Thus in this paper, in order to avoid the malfunction of wind turbine system and instability due to storm and time-delay element, respectively, restrained control is suggested. Restrained control is consist of pitch angle and axis friction control. The proposed method is to evaluate the restrained control with setting the reference angular velocity from low to high speed and different value of spring and damper. As consequences, for high speed reference signal and the restrained control contains better performance with strong damper.

Keywords: *Wind Turbine System, Adaptive Control, Non-linear Control, Angular velocity and pitch angle, Round Trip Delay*

1. Introduction

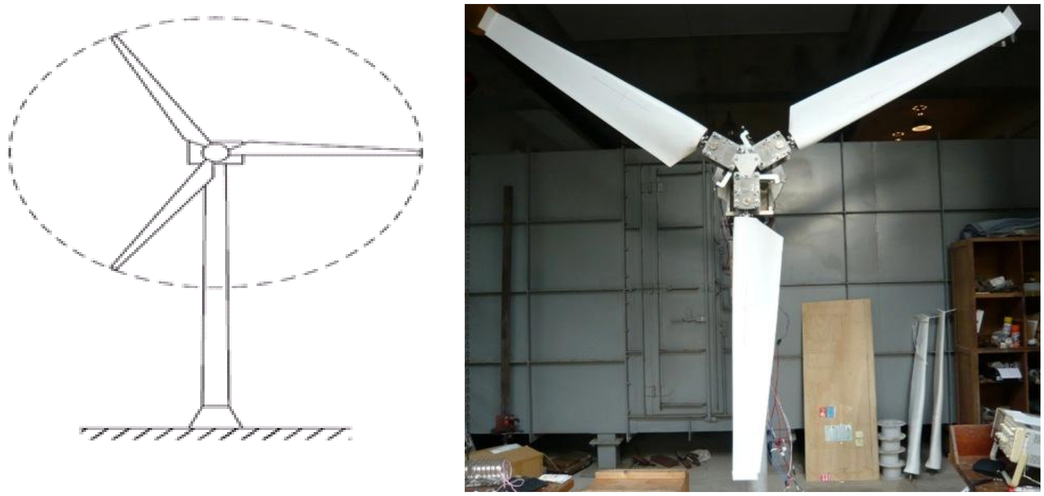
The purpose of this research is to control and evaluate the performance of the angular velocity of blades in the case of strong wind such as tropical storm. In general, the wind turbine system is located in gale area in order to generate energy efficiency. However, in the case of storm the wind turbine must stop the operation. Thus, no energy will generate. So, in order to avoid this wasteful period, we have suggested the restrained control of wind turbine which is consisting of pitch angle and axis friction control. By utilization of friction and pitch angle control of blade, the angular velocity of blade is controllable even in storm. So, in this paper two different schemes is proposed. Also due to existence of time-delay element in input and output sides, in other words the round trip delay that may cause the degradation of performance of system is considered. Basically, round trip delay occurs during the observation of output signal and sending the optimized input signal to wind turbine. Therefore, two time-delay element exist in closed loop system. In this research, the aim of using axis friction is to decrease the angular velocity by friction between blades and axis of internal turbine of ring. Moreover, pitch angle is controller in order to decrease the angular velocity by friction which made by collision between wind and surface of blade. In next chapters, the detail dynamics and control method of wind turbine system and the comparison of adaptive control are shown.

2. Introduction to Small-scaled Wind Turbine System

From old times, the utilization of small-sized wind turbine is widely used for pumping up and so on. In the spite of this, in these days the importation of electronic power generator of small scaled wind turbine is not volunteered. The important problem of small scaled wind turbine is the establishment of stall control against strong wind. As a result, there are many excessive rotations that may cause the damage accident. If this problem is solvable, then hereafter it will contribute large amount of energy. Thus, the innovation of small-sized wind turbine is very important part of the energy generation. In this research, the wind turbine system is considered to be located in gale area and by axis friction and pitch angle control the angular velocity of blade. The wind turbine rotates clockwise from the front perspective. In general, the blades of wind turbine descend 3 to 5 to the front and lays on the center axis with a slant of 2-4 degree. The axis is propped up by 2 springs which cross to the right angle of center axis. In this moment, pitch angle is optimized.

As a matter of fact, when angular velocity reached to the stall control level, the angular velocity depends on spring factor. In this research by repeating experiments and numerical analysis, we consider the improvement of mechanism of spring installation inside turbine. The stall control mechanism is as follows. At first, in windless or calm, the attitude of blade is on axis. When wind turbine receive the strong wind to the area of swept by blade, the blades is strongly pushed to the backward. As a result the blades reach to stall angle and angular velocity is reduced. Secondly, when turbine receive strong wind, the centrifugal force will increase and with that force, the axis of blades shift to the central axis line and at the same time the slop angle become reverse pitch that reduce the angular velocity. These stall control dynamics are possible to realize by the movement of the blade to backward or forward and independently axis rotation.

Finally the stall control is realized and angular velocity of blade is reduced and by this centrifugal force is vanished then the mechanism of blades, return to its origin position and it will start to rotate again. In other words, by passive control of installed spring to the blades, mechanism of stall control is realizable.



(a) (b)

Figure 1. Illustration of Wind Turbine (a) and (b) Actual Wind Turbine

Dynamics of horizontal-axis wind turbine with pitch angle control is indicates as follows.

$$\textit{Dynamics of angular velocity}$$

$$J_\omega \frac{d\omega(t)}{dt} = \frac{1}{2} C_T \rho A R \int_0^t V^2(t) e^{-(\tau - t)} d\tau \Theta(\theta(t-L)) - \frac{1}{2} I_G \omega^2(t) - f_r \omega(t) \quad (1)$$

$$\textit{Dynamics of pitch angle}$$

$$J_b \frac{d^2\theta(t)}{dt^2} = MR^2 \omega^2(t)\theta(t) - L\theta(t)k - c\frac{d\theta(t)}{dt} \quad (2)$$

which we have:

$\Theta(\theta) = \frac{\tilde{\theta}(t)}{\theta_{max}}$ and $\tilde{\theta}(t) = \theta_{max} - \theta(t)$ and L is time-delay.

Where, the parameters are indicates in the below table 1.

Table 1. Identification of Parameters

$\theta(t)$	Pitch angle
J_ω	Inertia moment of blade
$\omega(t)$	Angular velocity
C_T	Torque factor
ρ	Density of atmosphere
A	Area swept by blade
R	Length of blade
V(t)	Speed of wind

$\Theta(\theta)$	Wind turbine stall factor
I_G	Power Generation Inertia Moment Factor
f_r	The axis friction factor
J_b	Inertia moment of a plate of blade
M	Mass of a blade
L	The distance from spring to the edge of blade
k	Factor of spring
c	damper
θ_{max}	Initial values of pitch angle

As it is clear in above table and equation (1) and (2), the angular velocity to the second power is concerned as input of the equation (2) which is dynamic of pitch angle. In other words, the dynamic of pitch angle is proportional to the square of angular velocity. So, it is clear that if angular velocity is large value then the input force to the pitch angle become very strong. Moreover, after obtaining the pitch angle, the stall factor is obtained which is $\Theta(\theta)$ and then the stall factor is fedback to equation (1) which is dynamic of velocity of blade angle in order to reduce the velocity. However, as it is clear in equation (1) in stall factor there is a delay, so it is not synchronized to the output signal. Therefore, for two main reasons the restrained control is required. One is to avoid the large input to the equation (2) and the other is to synchronize the input and the output of equation (1).

3. Adaptive Control of Axis Friction

As we discussed previously, the resistance control is considered to avoid exceeding the angular velocity from the limitation and synchronization of input and output. Therefore, by rewriting the equation (1) the dynamics of wind turbine system of angular velocity is can be indicates as follows that if angular velocity exceed the limit the adaptive friction $\gamma(\omega(t))$ works and decrease the velocity. Otherwise $\gamma(\omega(t))$ has no influence.

$$\gamma(\omega(t)) = 1 + e^{\omega(t)-\omega_c} \tag{3}$$

Dynamics of angular velocity with adaptive friction

$$J_\omega \frac{d\omega(t)}{dt} = \frac{1}{2} C_T \rho AR \int_0^t V^2(t) e^{-(\tau - t)} d\tau \Theta(\theta) - \frac{1}{2} I_G \omega^2(t) - f_r \gamma(\omega(t))\omega(t) \tag{4}$$

Also in order to have better performances, pitch angle control is required. Therefore, first we linearize the equation (2). Then we have:

Here, we fix the angular velocity. Then we have:

Dynamics of pitch angle

$$J_b \frac{d^2\theta(t)}{dt^2} = MR^2\omega^2\theta(t) - \alpha L\theta(t)k - c\frac{d\theta(t)}{dt} \tag{5}$$

The Laplace transform of above equation is:

$$\textit{Laplace transform}$$

$$J_b(s^2\theta(s) - s\theta(0) - \dot{\theta}(0)) = (MR^2\omega^2 - \alpha Lk)\theta(s) + c(s\theta(s) - \theta(0))$$
$$\downarrow$$

$$G_\theta(s) = \frac{(1-s)\theta(0)}{s^2 + \frac{c}{J_b}s + \frac{Lk\alpha - MR\omega^2}{J_b}} \tag{6}$$

$\dot{\theta}(0)$ =0 and $\theta(0) = \theta_{\max}$. Here, if $\alpha = \frac{J_b + MR\omega^2}{Lk}$ and substitute to equation (6), then we have：

$$G_\theta = \frac{(1-s)\theta(0)}{s^2 + \frac{c}{J_b}s + 1}.$$

According to final value theorem the steady step response is:

$$\theta_{steady} = \theta(\infty) = \lim_{s\to 0} sG_\theta \frac{1}{s} = \theta(0)$$

So, by choosing the $\alpha(\omega^2(t)) = \frac{J_b + MR\omega^2(t)}{Lk}$, the performance of turbine is improved.

4. Simulation and Analysis

In order to evaluate the adaptive and passive resistance control [1-5], we have simulated the non-linear model [6-7] of wind turbine system. The specification of simulation is shown as follows:

$$\begin{cases} J_\omega \frac{d\omega(t)}{dt} = \frac{1}{2} C_T \rho AR \int_0^t V^2(t) e^{-(\tau - t)} d\tau \Theta(\theta) - \frac{1}{2} I_G \omega^2(t) \\ - f_r \gamma(\omega(t-L))\omega(t) \\ \qquad J_b \frac{d^2\theta(t)}{dt^2} = MR^2\omega^2\theta(t) - \alpha L\theta(t)k - c\frac{d\theta(t)}{dt} \end{cases}$$

$$where, \quad L = 2[\text{sec}], \quad \gamma(\omega(t)) = 1 + e^{\omega(t) - \omega_c} \quad and \quad \alpha(\omega(t)) = \frac{J_b + MR\omega^2(t)}{Lk}.$$

Table 2. Identification of Parameters

Parameters	Values	Units
J_{ω}	16	kg・m^2
$\omega(t)$	Variable	rad/s
C_T	0.2	N・m
P	1.2	Kg/m^3
A	7.0686	m^2
R	1.5	m
V(t)	Reyleigh distribution	m/s
$\Theta(\theta)$	Variable	——
I_G	4.5185	kg・m^2
f_r	0.001	kg・m^2
J_b	8	kg・m^2
M	14	kg
L	0.2	m
K	5000	N/m
c	1000	kg・m^2
θ_{max}	0.0873	rad
ω_c	reference	rad/s
θ	Variable	deg

Operation factor in Figure 2 is indicates as below:

$$f(\omega) = 1 + e^{\omega(t)-\omega_c}, \quad z(\theta) = \frac{\theta_{max} - \theta(t)}{\theta_{max}}, \quad g(\omega) = \frac{J_b + MR\omega^2}{Lk}$$

Where, ω_c is chosen from 10, 20, 30 and 40.

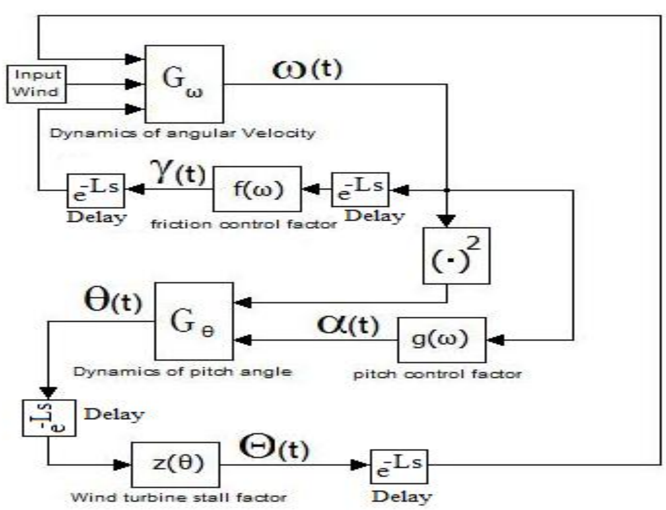


Figure 2. Block Diagram of Adaptive Friction Control

Above block diagram shows the adaptive friction control and performance control of wind turbine. As it is shown, the friction control factor and pitch control factor are controlled by observing the angular velocity of blade. Finally the wind turbine stall factor is fed back to dynamics of angular velocity of blade. By this circulation angular velocity is controlled. In results we will see the behavior of angular velocity and pitch angle of blade. Here, the desirable reference angular velocity is considered as 30 [rad/s]. The input wind is Rayleigh distribution with average speed of 50[m/s] that in ordinary case wind turbine must stop running. The Rayleigh distribution is a continuous probability distribution. A Rayleigh distribution is often observed when the overall magnitude of a vector is related to its directional components.

The simulation process is to observe the angular velocity of blade and pitch angle of blade for different $\omega_{c.}$ After choosing the best ω_c, we simulate for different damper and springs. Eventually, compare and evaluate the performance of the angular velocity whether it converges to desirable value or not. In the same way for the pitch angle, it should converge to zero in order to get better performance and preserve the stability. Also the specification of dynamics of the angular velocity and the pitch angle control are shown in the frequency domain for each different condition. Moreover the power spectral density of input wind is indicated in result.

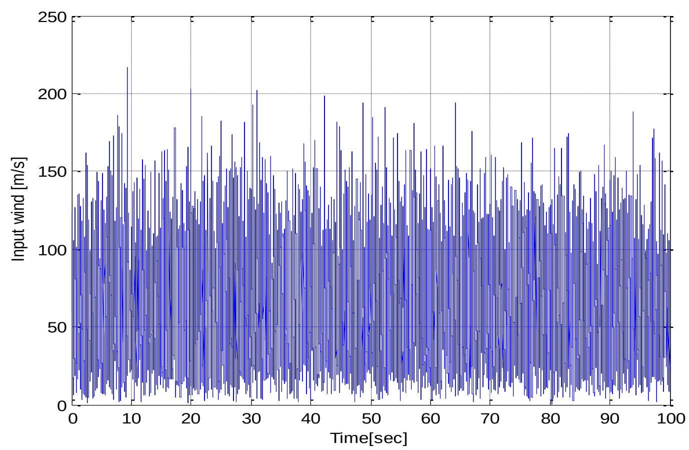


Figure 3.The Input Wind to Turbine (Reyleigh distribution)

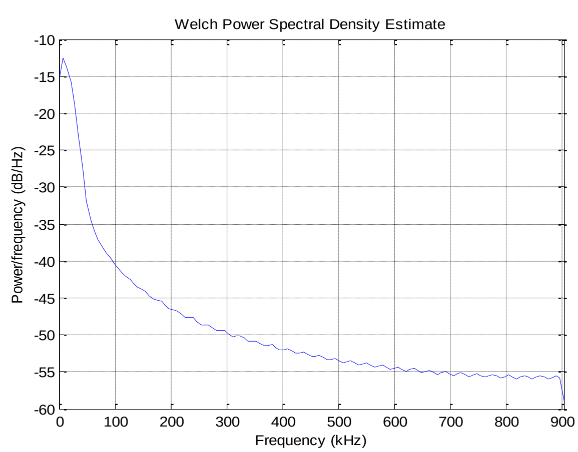


Figure 4. Power Spectrum Density of the Input Wind

Result1 with c=1000 and k=10000

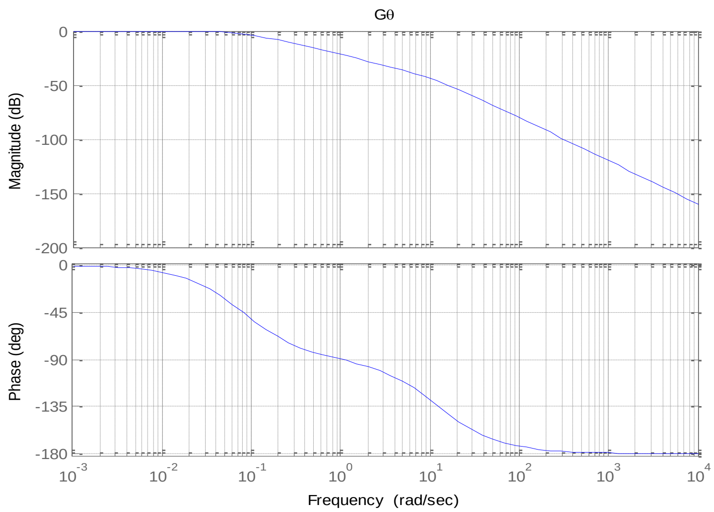


Figure 5. Bode Diagram of Pitch Angle System

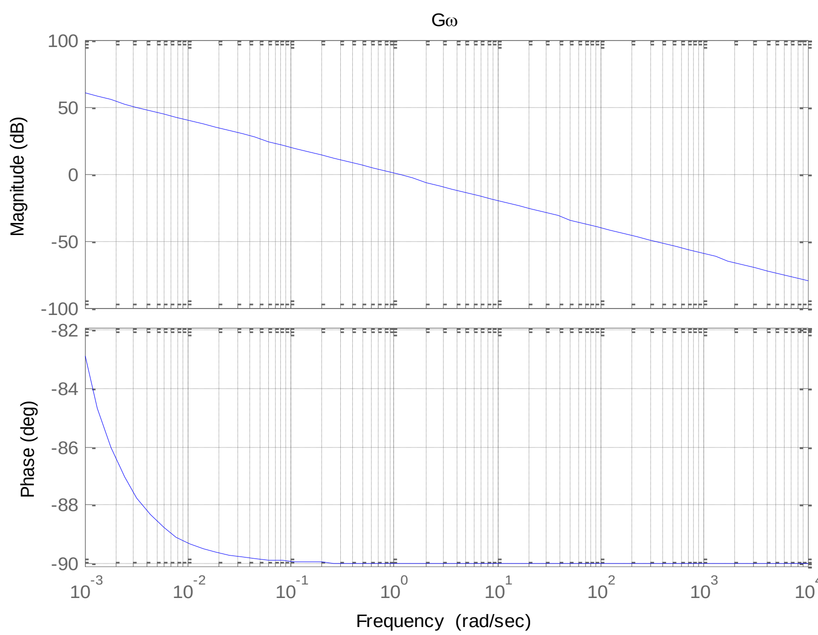


Figure 6. Bode Diagram of Blade Angle System

Result1 with c=1000 and k=10000

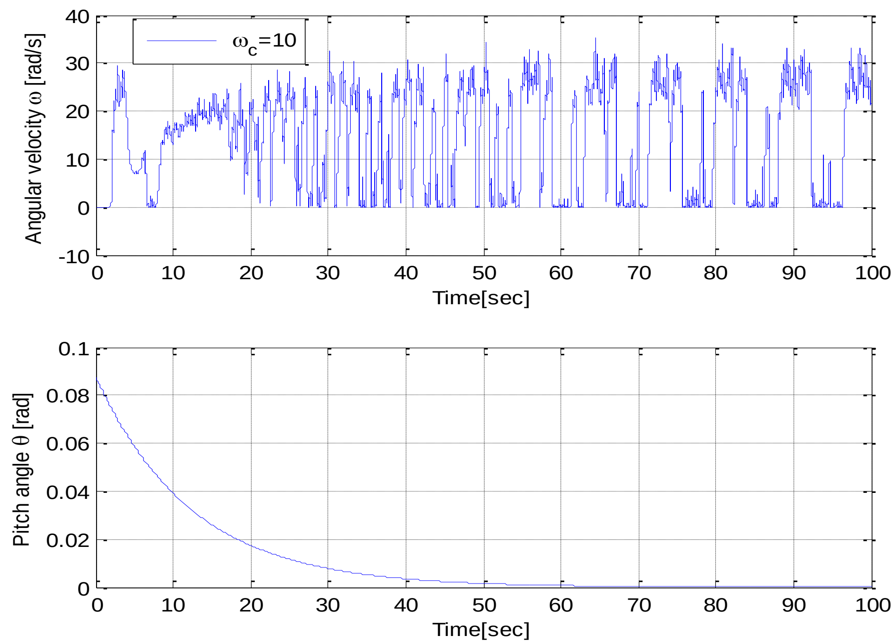


Figure 7. Angular Velocity and Pitch Angle of Blade for ω_c=10

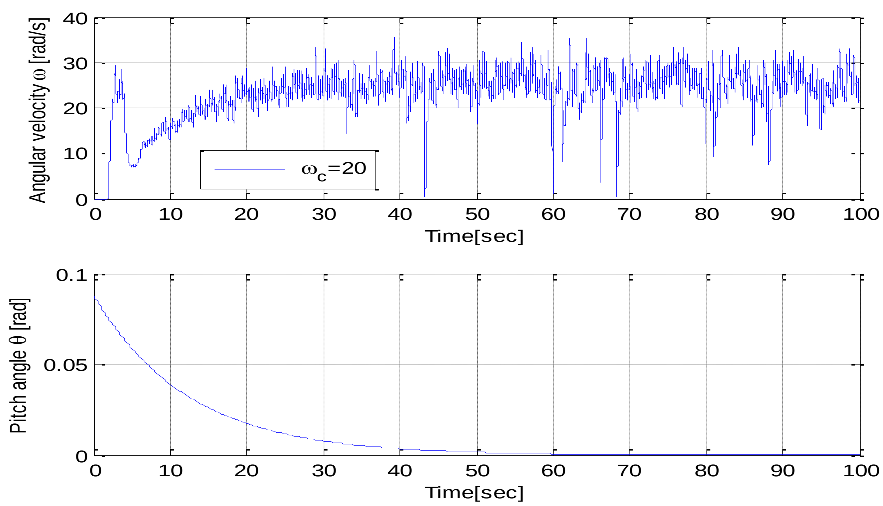


Figure 8. Angular Velocity and Pitch Angle of Blade for ω_c=20

Result1 with c=1000 and k=10000

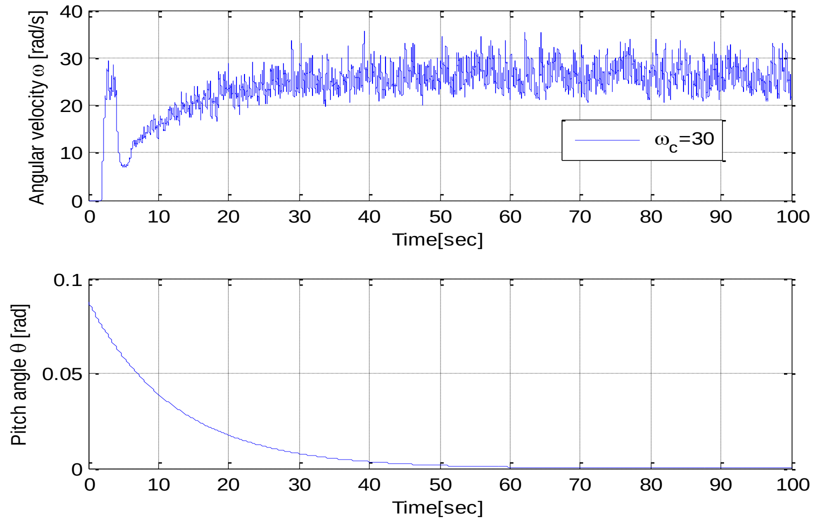


Figure 9. Angular Velocity and Pitch Angle of Blade for ω_c=30

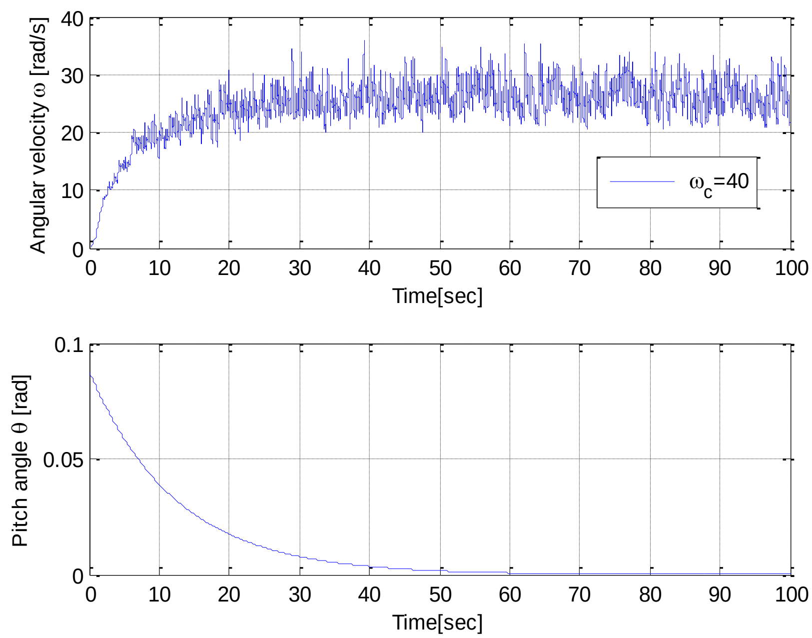


Figure 10. Angular Velocity and Pitch Angle of Blade for ω_c=40

Result2 with c=500 and k=1000

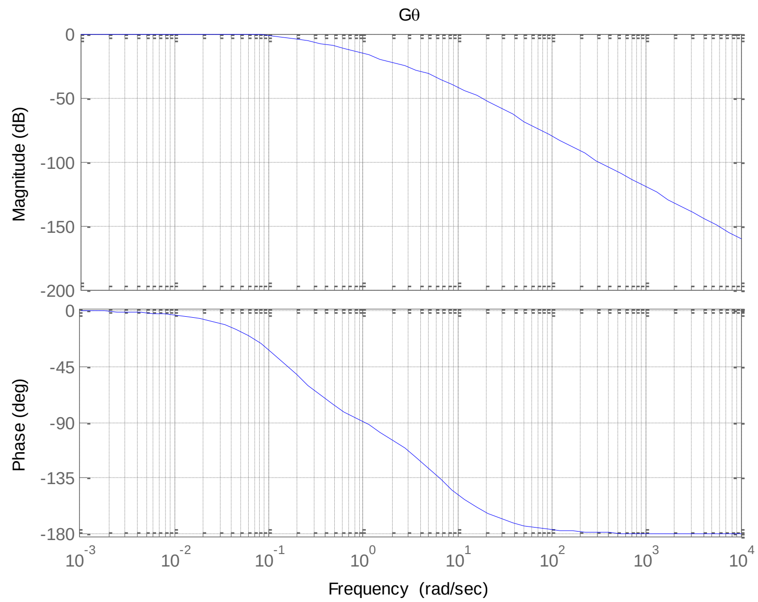


Figure 11. Bode Diagram of Pitch Angle System

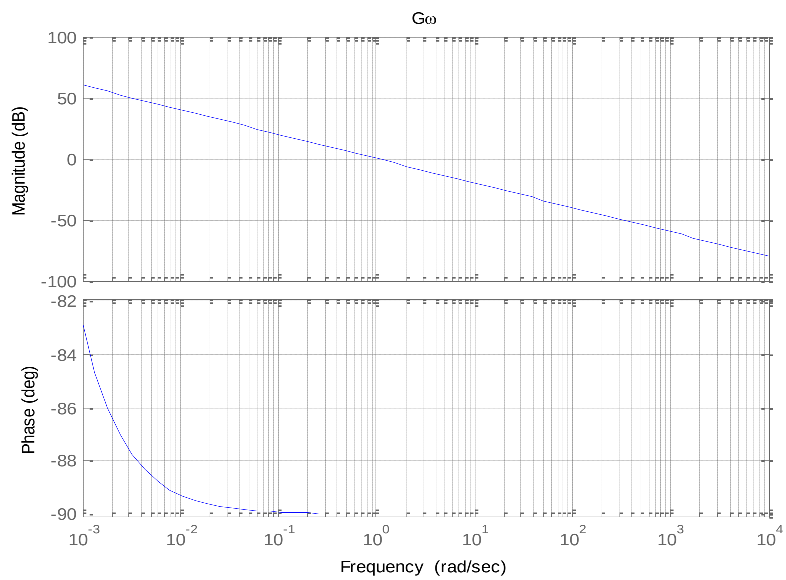


Figure 12. Bode Diagram of Blade Angle System

Result2 with c=500 and k=1000

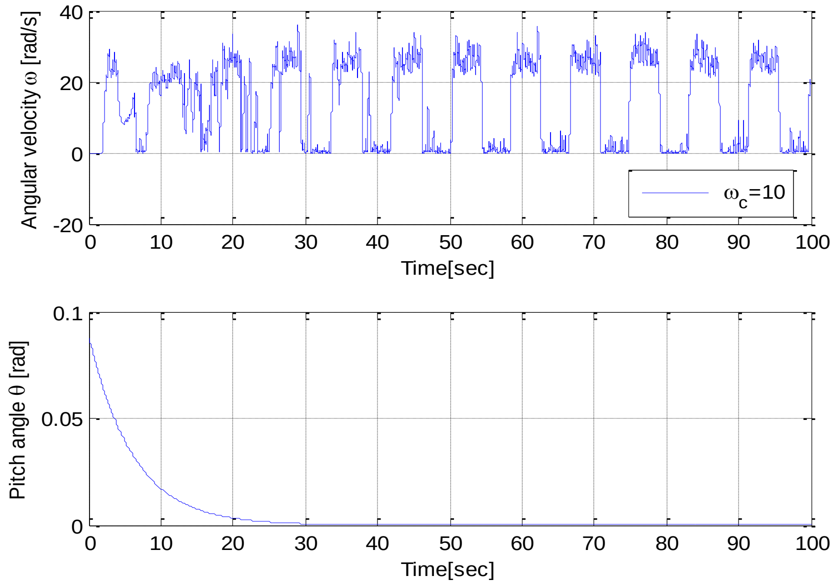


Figure 13. Angular Velocity and Pitch Angle of Blade for ω_c=10

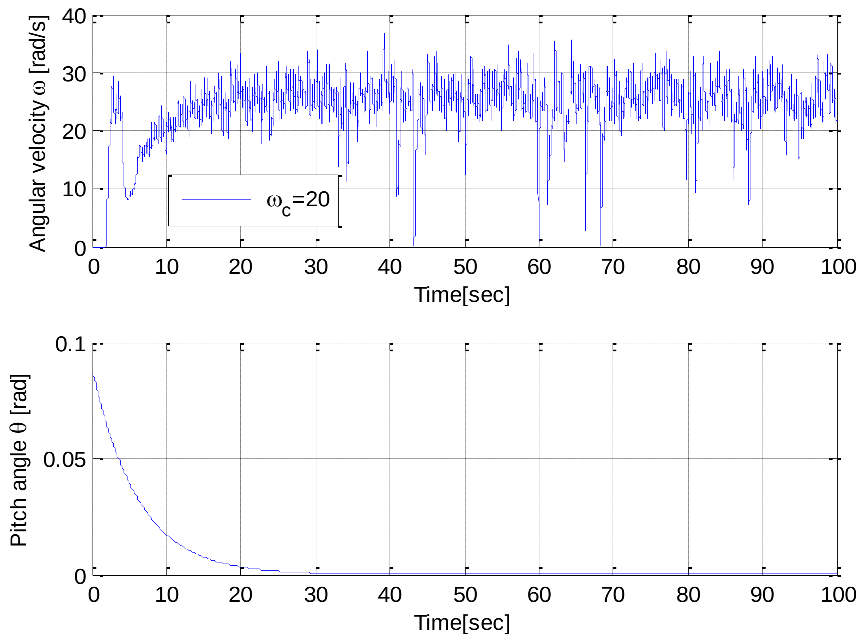


Figure 14. Angular Velocity and Pitch Angle of Blade for ω_c=20

Result2 with c=500 and k=1000

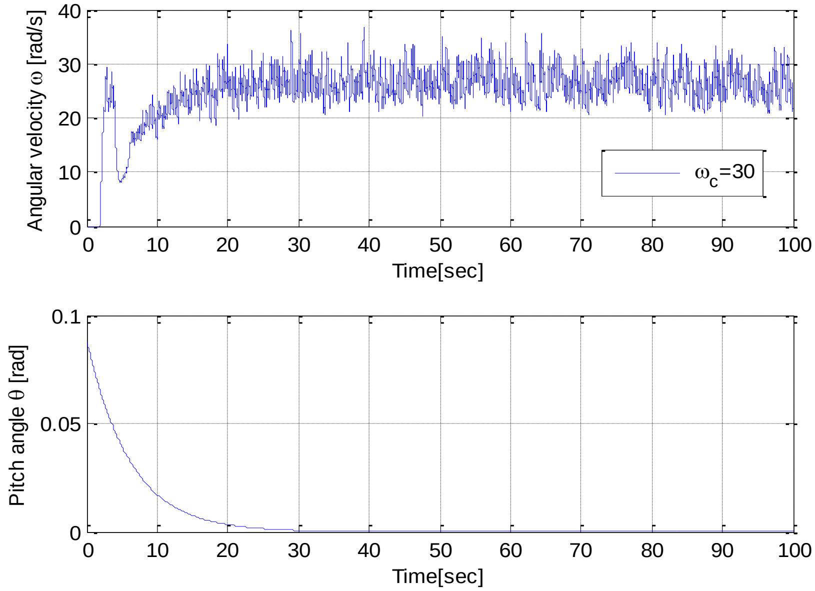


Figure 15. Angular Velocity and Pitch Angle of Blade for ω_c=30

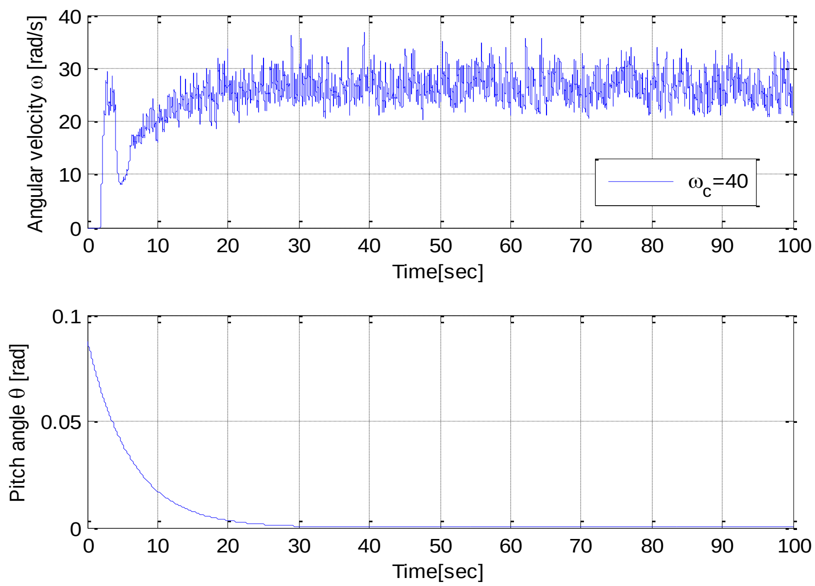


Figure 16. Angular Velocity and Pitch Angle of Blade for ω_c=40

Result3 with $c=0$ and $k=100$

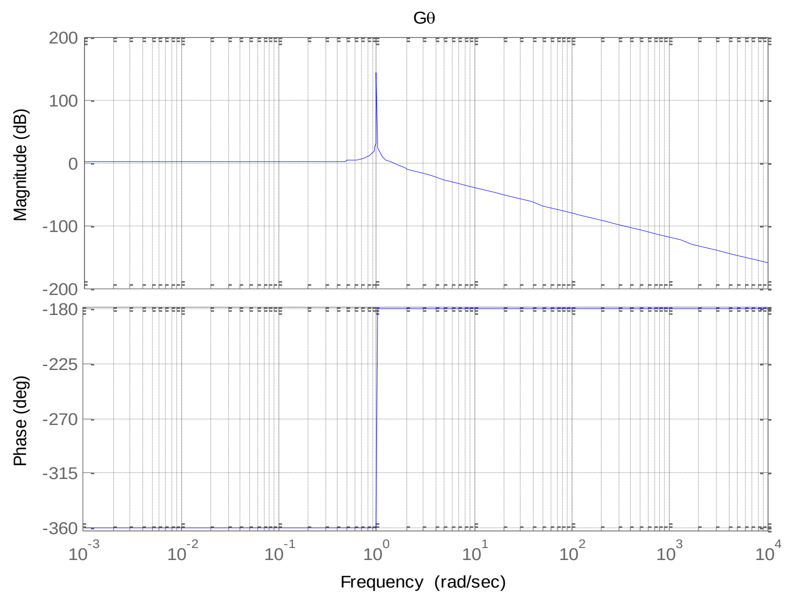


Figure 17. Bode Diagram of Pitch Angle System

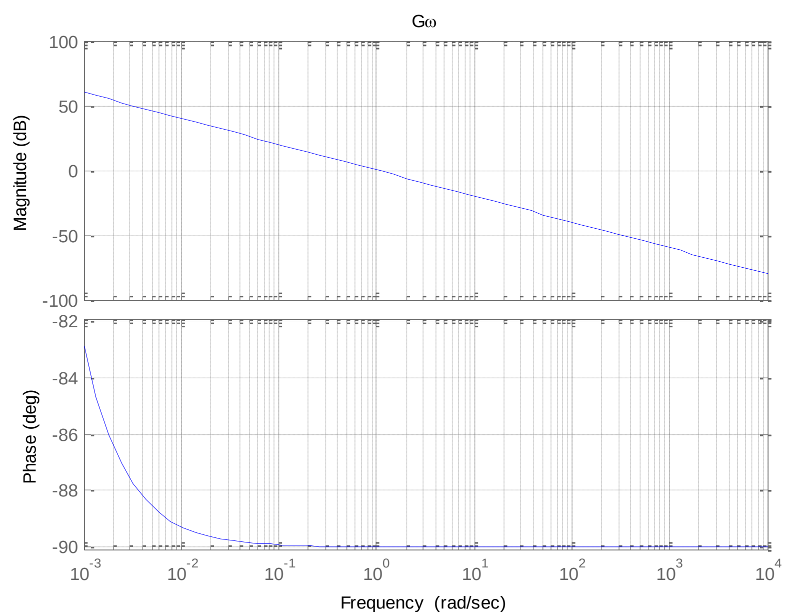


Figure 18. Bode Diagram of Blade Angle System

Result3 with c=0 and k=100

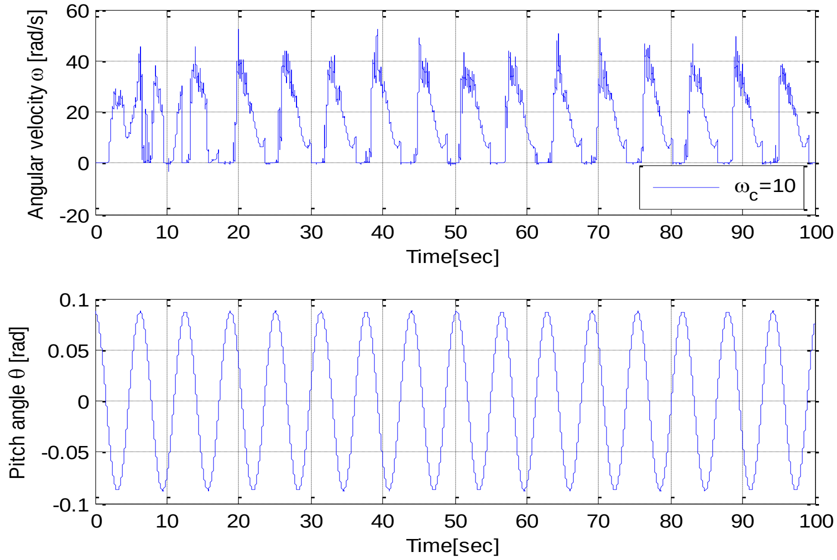


Figure 19. Angular Velocity and Pitch Angle of Blade for ω_c=10

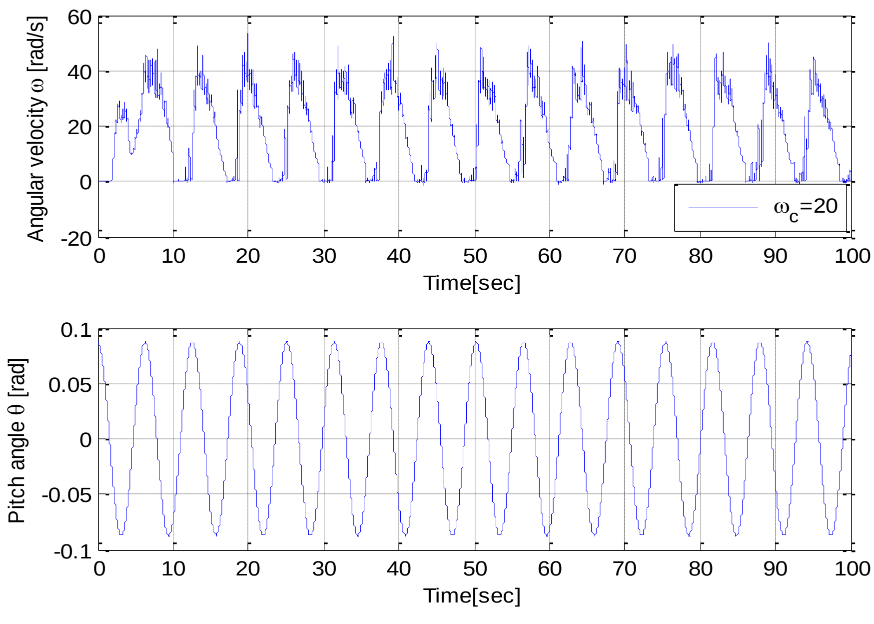


Figure 20. Angular Velocity and Pitch Angle of Blade for ω_c=20

Result3, with c=0 and k=100

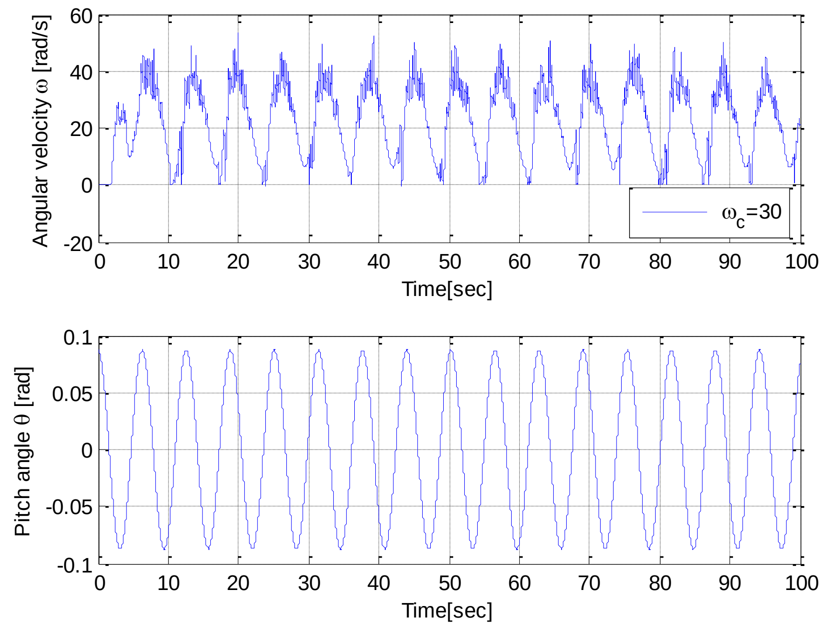


Figure 21. Angular Velocity and Pitch Angle of Blade for ω_c=30

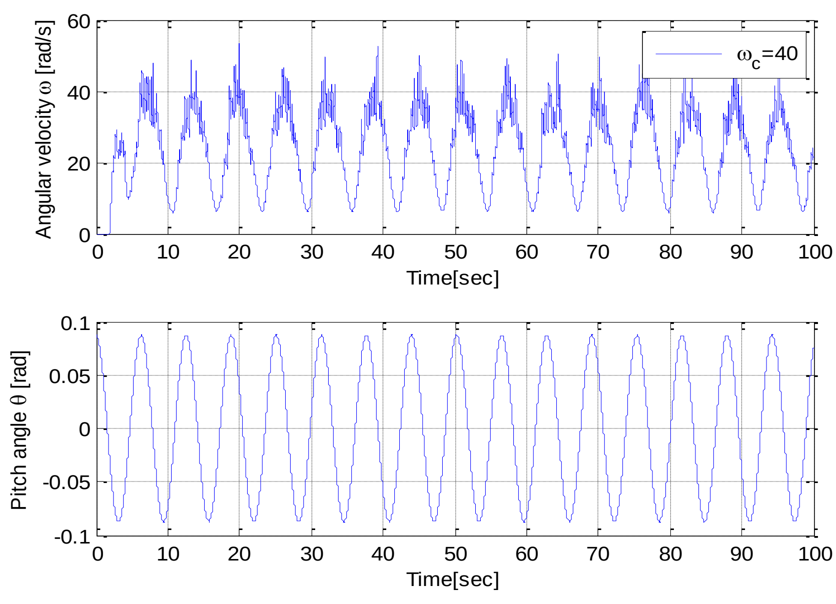


Figure 22. Angular Velocity and Pitch Angle of Blade for ω_c=40

Result 4 with c=100 and k=0.001

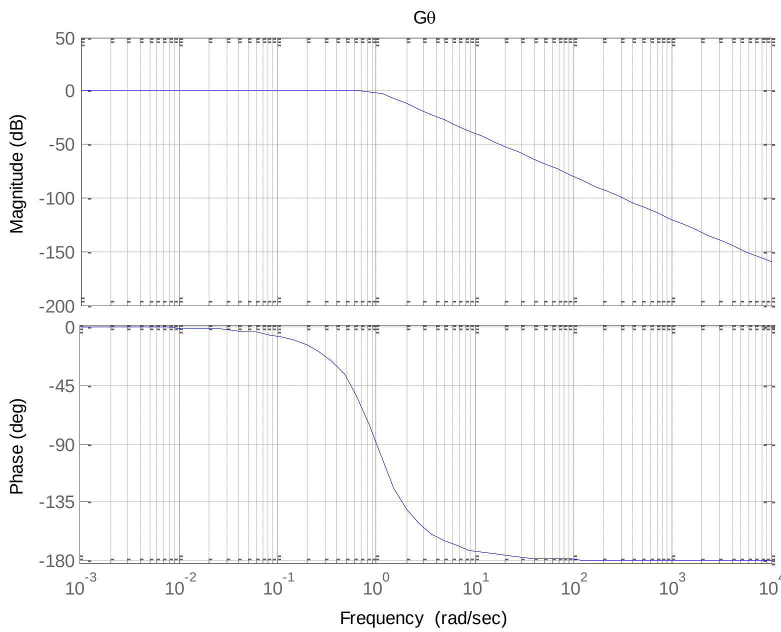


Figure 23. Bode Diagram of Pitch Angle System

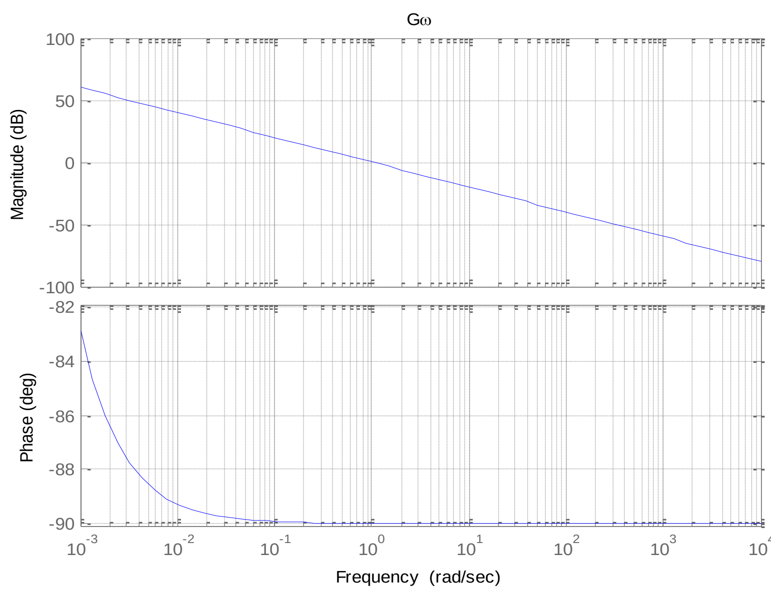


Fig.24. Bode diagram of blade angle system

Result 4 with c=100 and k=0.001

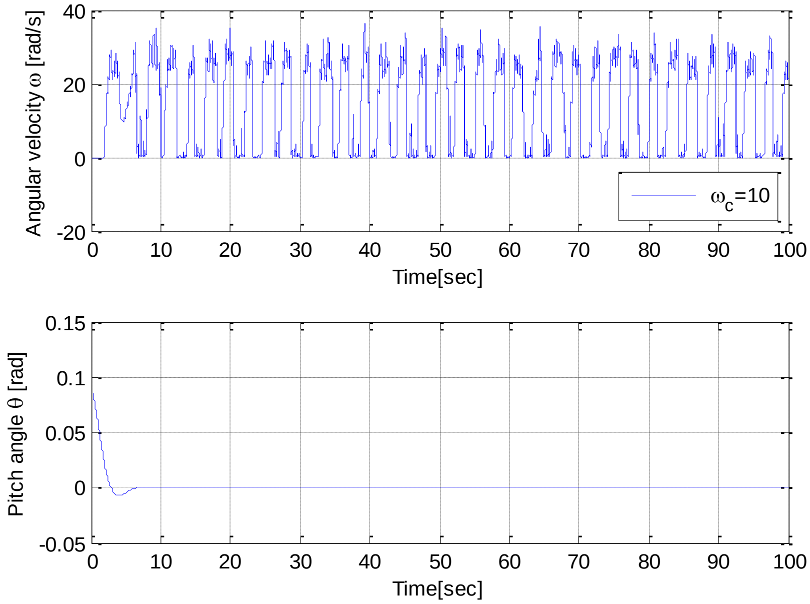


Figure 25. Angular Velocity and Pitch Angle of Blade for ω_c=10

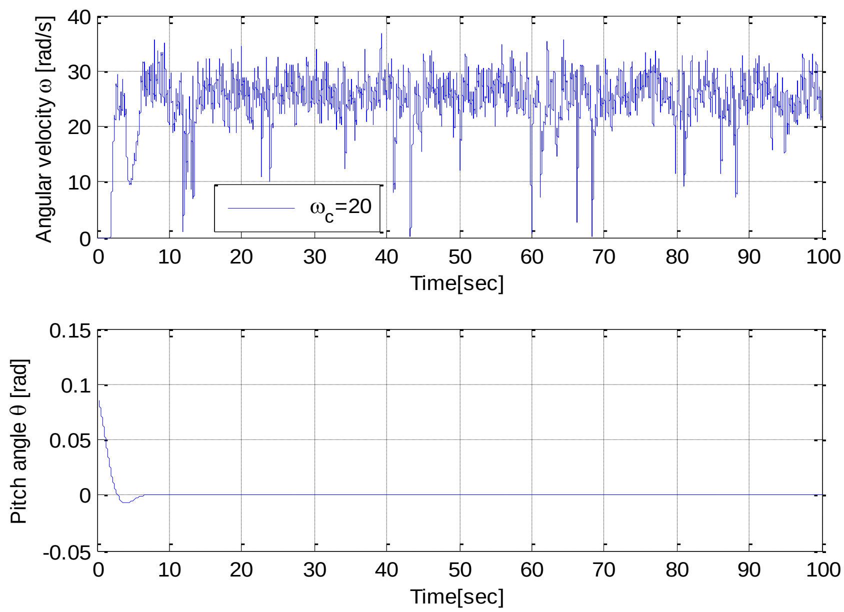


Figure 26. Angular Velocity and Pitch Angle of Blade for ω_c=20

Result 4 with c=100 and k=0.001

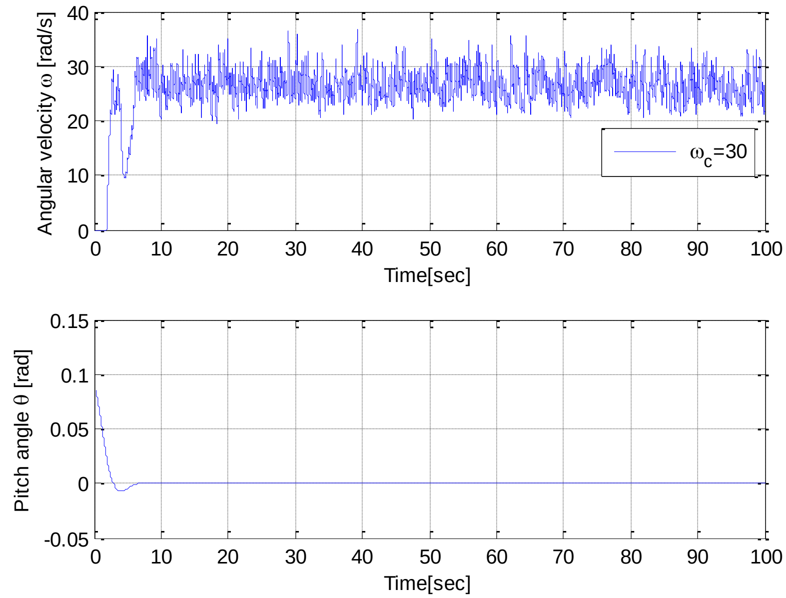


Figure 27. Angular Velocity and Pitch Angle of Blade for ω_c=30

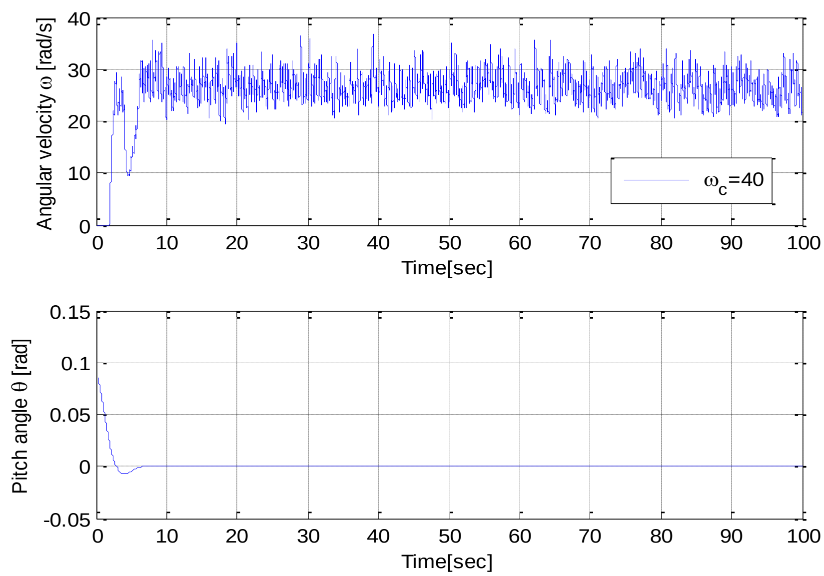


Figure 28. Angular Velocity and Pitch Angle of Blade for ω_c=40

In Figure 5, 6, 11, 12, 17, 18, 23, 24, each figure indicates the bode diagram of dynamics for the blade angle and the pitch angle for different damper and spring. For example, in the case of c=1000 and k=10000, the gain of blade angle system it contains no peak. However, by decreasing the value of damper, especially when damper is not loaded, the gain of blade angle contains big peak in Figure 17. Also as it is clear, in Figure 7, 8 for result 1 and for in Figure 13, 14 for result 2, the performance is degraded. However, in figure 9, 10 for result 1 and in

Figure 14, 15 for result 2 the performance of the angular velocity is enhanced only when ω_c is more than 30[rad/s]. For result 3, from Figure 19 to 22, there is no convergence to reference value for every different ω_c due to the damper is not loaded in shock absorber. In result 4 as same as result 1 and 3, performance of angular velocity is enhanced for $\omega_{c,}$ more than 30 [rad/s] in Figure 27, 28. However, in Figure 25 and 26 the performance is degraded. Thus, regarding the result 1 to result 4, we can conclude that for ω_c greater than 30 [rad/s], even though the angular velocity is oscillating, but it converges to reference signal and the oscillating amplitude is less than the reference value which is 30[rad/s]. Therefore, we can set the angular velocity reference value to ω_c =30 [rad/s]. Also from Figure 22 to 25, it shows that angular velocity is controllable even for the extremely low factor of spring. Therefore, from result 4 we can conclude that the optimized and low cost process for realization of restrain control for small-scaled wind turbine is to set the damper and spring with low factor and set the reference signal to ω_c =30.

5. Conclusion

In this paper restrain control of angular velocity is compared and evaluated in different case of desired signal setting including shock absorber which contains damper and spring. Also reference value of the angular velocity is able to be set by adaptive control and preserve the stability simultaneously. Moreover, in this paper even though time-delay is considered, the performance is improved with setting the reference signal more than 30 [rad/s]. However, still there is oscillation in the steady state which is inappropriate in actual case. Therefore, as a future work the reduction of the amplitude of this oscillation in the steady state is required. Also, in this research the time-delay was considered as known value. However, time-delay may become variable due to the communication system. Therefore, uncertainty of time-delay must be considered in the future works.

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