Disturbance Response and Stability Analysis of Wireless Tele-Control System for MIMO Plant

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Abstract

In this research we aim to analyze the disturbance response of MIMO plant and wireless communication system. In order to realize a distant control system wireless communication can be applied to control system that contain channels. The effects of channels are reduced by equalizer. Moreover we consider there are disturbances. The plant is set to be a drone that aims to control the attitude. In conclusion we discussed about the disturbances response against drone that is in stationary status.

Keywords-- Wireless Tele-Control System, Multipath Channel, Equalization, MIMO system, Unmanned Aerial Vehicles

1. Introduction

The utilization of Tele-Control system is one of the significant issues in the servo systems. Especially, when system requires control in distant. The advantage of wireless Tele-Control system is that maintenance and management of controller can be done easily since controller is located in observation center and plant may be located in distant. One more thing is that by wireless Tele-Control system since controller is not loaded on plant it could be considered as reduction of load in plant and this make system performance enhanced. Let us clarify the wireless Tele-Control system. Basically, in wireless Tele-Control system they are always two channels. One is the feedforward channel to send the optimal or compensated input to the control plant and the other one is the feedback channel since output signal should be sent to the controller side in order to calculate the error and to minimize it or stabilize the closed-loop. So, these channels are disadvantages of utilization of wireless Tele-Control system. First of all due to the usage of communication system in the closed-loop system we would have some impairment such as phase noise, Doppler effects, frequency offset, delays and attenuations. The mentioned impairment can be solved by implanting the system that has high function capabilities. Therefore, phase noise, Doppler effects, frequency offset can be repaired by installing the advanced function capability. However, the received signal should be equalized to get the original information from sender. Therefore, in order to get the exact data from sender it is required to equalize the received signal. The received signal may be distracted by the multipath channel. Multipath channel effect occurs concerning the circumstances of the environment of control plant. In other words, multipath channel is inclusion of accumulated delayed and attenuated direct path signal. Even though sender has sent the original signal but distracted signal will be received in receiver side. Thus, equalization of signal is required in receiver side. For equalization, first we have to compose the replica of the unknown channel. The composition of the replica of the unknown channel can be done by FIR adaptive filter. However, the composition of the replica channel is not sufficient. In order to get reference signal it is required to realize the inverse transfer function of replica Channel. Therefore, the inverse channel is realized after the receiving the distracted signal. This has role of equalizing the received signal. These processes should be implemented in two different stages. One is the feedforward side of the receiver and the other one is the feedback part of the receiver since we have round trip multipath channel in the closed-loop system. After realizing the equalizer, implementation can be done in the closed-loop system. Furthermore, controller can be designed according to plant without considering multipath channel. After designing a controller equalizers and controller are jointed in cascade. Thus, controller and equalizers are jointed in the closed loop system. In Next chapter we will introduce drone and controller design of it.

2. Wireless Telecontrol System

Here, let us define Wireless Tele-Control System as follows. Following figure shows the structure of Tele-Control system[1-3].

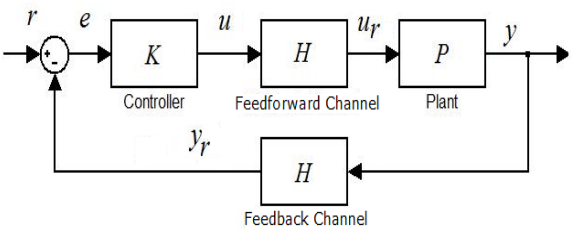

Fig. 1 Tele-Control System

Here H is Multipath channel and u_r, y_r are received input and received output signal, respectively. Through Fig.1, we can get the closed-loop system's transfer function according to following equations.

$$y = PHKe \quad (1)$$

$$e = r - Hy \quad (2)$$

Afterward we get the transfer function between r and y which is complementary sensitivity transfer function as follows.

$$y = \Delta_H PHKr \quad (3)$$

Where, $\Delta_H = \left(1 + PKH^2\right)^{-1}$ stands for sensitivity transfer function which is from r to e.

As we can see in sensitivity function of the closed-loop system, it has been involved with Channel's square. Our proposed method is to reduce the effect of the channel in the sensitivity function. The proposed method has shown in following Fig. 2.

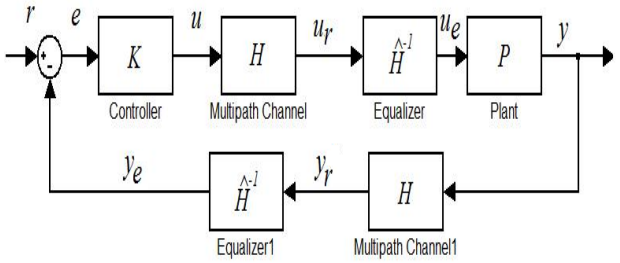

Fig. 2 Configuration of the proposed method

Here, y_e, u_e and $\hat{H}^{-1}$ stand for the equalized input signal, equalized output signal and Equalizer, respectively. $\hat{H}$ itself is the replica channel of H that is estimated with adaptive filter. However, before getting starting the proposed method let us see how we can design a controller for Tele-control system without considering channel equalizer.

For fig.2, we could design a controller according to the explained procedure in the previous chapter.

Therefore, the gain margin of system with multipath channel can be calculated as follows.

$$I + KPH^2 = 0 \quad (4).$$

Here Multipath channel's model can be express as follows. $H(s) = \sum_i \alpha_i e^{-L_i s} I$. Where α is the attenuation factor and L is Time-Delay and i is the number of taps.

Now let us consider the stability condition in SISO. The polar Expression of Multipath channel is:

$$H(j\omega) = \sum_i \alpha_i e^{-jL_i\omega} \Rightarrow H(j\omega) = |H(j\omega)| e^{j\angle H(j\omega)}.$$

Where,

$$|H(j\omega)| = \sqrt{\left(\sum_i \alpha_i \cos(L_i\omega)\right)^2 + \left(\sum_i \alpha_i \sin(L_i\omega)\right)^2}$$ and

$$\angle H(j\omega) = -\tan^{-1}\left[\frac{\sum_i \alpha_i \sin(L_i\omega)}{\sum_i \alpha_i \cos(L_i\omega)}\right].$$

Then we have:

$$K(j\omega)P(j\omega)H(j\omega)H(j\omega) = -1$$

$$|K(j\omega)||P(j\omega)||H(j\omega)|^2 e^{j\left(\angle K(j\omega) + \angle P(j\omega) + \angle H^2(j\omega)\right)}$$

$$= \rho(j\omega) e^{j\theta(j\omega)} = 1e^{j(-180)}.$$

$$\rho(j\omega) = |K(j\omega)||P(j\omega)|\left(\left(\sum_i \alpha_i \cos(L_i\omega)\right)^2 + \left(\sum_i \alpha_i \sin(L_i\omega)\right)^2\right)$$

$$\theta(j\omega) = \angle K(j\omega) + \angle P(j\omega) - 2\tan^{-1}\left[\frac{\sum_i \alpha_i \sin(L_i\omega)}{\sum_i \alpha_i \cos(L_i\omega)}\right]$$

The crossover frequency can be obtained by solving the following equation.

$$\angle K(j\omega_{ph}) + \angle P(j\omega_{ph}) - 2\tan^{-1}\left[\frac{\sum_i \alpha_i \sin(L_i\omega_{ph})}{\sum_i \alpha_i \cos(L_i\omega_{ph})}\right] = -180^\circ$$

Afterward, gain margin will be obtained and eventually controller can be designed. However, the stability point of view, it is very stiff problem to satisfy the small gain theorem which is shown as below.

$$\left|P(j\omega)H^2(j\omega)K(j\omega)\right| < 1 \quad (5)$$

$$\rightarrow |K(j\omega)| < \frac{1}{|P(j\omega)||H^2(j\omega)|}$$

$$= |K(j\omega)| < \frac{1}{|P(j\omega)|\left(\left(\sum_i \alpha_i \cos(L_i\omega)\right)^2 + \left(\sum_i \alpha_i \sin(L_i\omega)\right)^2\right)} \quad for\ \forall\omega.$$

As well small gain theorem ca be applied in MIMO system.

$$\bar{\sigma}\left(K(j\omega)H(j\omega)P(j\omega)H(j\omega)\right) < 1 \quad (6)$$

Which $\bar{\sigma}(.)$ indicates the maximum singular value.

As it can be seen in equation (5) and (6), it is stiff problem to maintain the small gain theorem due to the existence of multipath channel. Thus, it is required to reduce the effect of multipath channel in sensitivity transfer function. In the next chapter proposed method, characteristic of multipath channel and Multipath channel canceller are introduced.

3. Reduction of Multipath Channel Effects in Control System

As we have discussed previously, existence of the multipath channel make the systemunstable and it is very hard to determine the PID parameter that satisfies the small gain theorem which has been mentioned in Equation (5). Therefore, somehow the multipath channel should be eliminated in order to get rid of the instability. Thus, equalizer is required in the receiver side of the plant for the feedforward multipath channel and another equalizer is required in the controller side for feedback multipath channel. By implementation of the equalizer we can reduce the effect of the multipath channel. However, before equalizing the received signal estimation of multipath channel is required [4]. Estimation of multipath channel can be done by adaptive filter. After reconstructing the replica of multipath channel, inversion of the replica channel should be implemented in cascade to vanish the multipath channel. In following figure the process of the proposed system is indicated in detail (*di* and *de* stand for internal and external disturbances, respectivley).

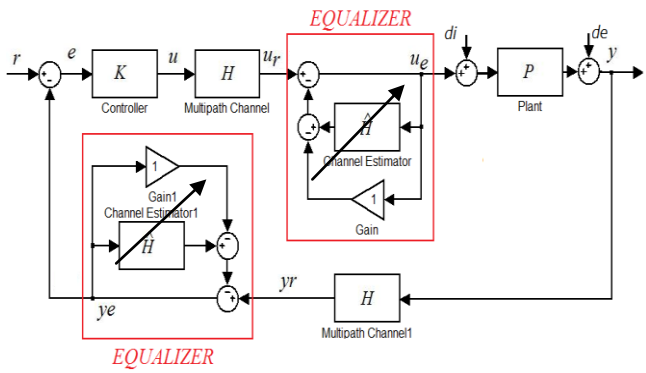

Fig. 3. Configuration of the proposed method in detail considering disturbances

$$y = KH\hat{H}^{-1}Pe \tag{7}$$

$$e = r - H\hat{H}^{-1}y \tag{8}$$

Afterward, we have as follows.

$$y = \frac{PH\hat{H}^{-1}K}{1+PK\left(H\hat{H}^{-1}\right)^2}r \tag{9}$$

That $\dfrac{1}{1+PK\left(H\hat{H}^{-1}\right)^2}$ is the sensitivity function of the proposed method.

If and only if $\hat{H} = H$, then we obtain the conventional feedback control system. However, this does not happen since replica channel cannot realize the exact characteristic of multipath channel. Nevertheless, we can reduce the effect of multipath channel. Thus, the closed-loop system stabilized by this method.

4. Simulation and Results

In order to evaluate the perforamnce and stability of the proposed method considering disturbances, we have simulated for a system that requries wirelss Tele-Control system. The plant is set to be a Drone. We aim to control the attitude of drone which consist of roll, pitch and yaw. Drone is considered to be MIMO 6 dimentional plant matrix with 3 inputs and outputs, respectivley. As we disscused, in the case of wirless In this condition we can consider that in the closed-loop system channels both forward and feedback contain same charecteristic. In the result, in order to see the charachtresitc and influences in control system we simulat the step response of the closed-loop system with equzlier considering the internal and external disturbances. Internal disturbances considered to be gaussian noise and external disturbances is set to be step input and vice versa. Following shows the condition and 3 cases of simulation.

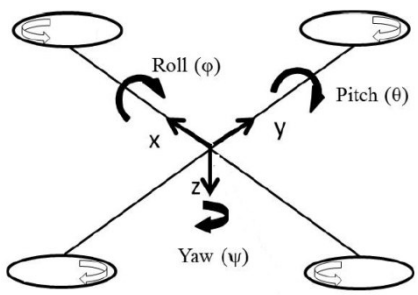

Fig.4 Attitude control of Drone

Doyle Expression of the simplified atitude dynamics of Drone:

$$P(s) = \left[\begin{array}{cccccc|ccc} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 5.1282 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 7.4074 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 7.4074 \\ \hline 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{array}\right]$$

・Controller of attitude:

$$K(s) = K_P\left(1+\frac{1}{T_i s}+\frac{T_d s}{as+1}\right)I_{3\times3}$$
$$= 0.005\left(20+\frac{0.01}{s}+\frac{2s}{0.01s+1}\right)I_{3\times3}$$

・Channel Specification (with 10 taps M=10):

$$H(s) = \sum_{i=1}^{M}\alpha_i e^{-sL_i}$$

Where, attenuated and time delay factor are indicated below.

$$\alpha_i = rand(i)e^{\frac{-0.1i}{M}}, \quad \tau_i = 0.5i \times sort(|rand(i)|)$$

(i=1 to 10).

Case 1 :

・Step response of the close-loop whithout *di* and *de*.

Case2 :

・Step response of the close-loop whithout *di* and with *de* : unit step

Case 3 :

・Step response of the close-loop *di* : Gaussian Noise and with *de* unit step

For Gaussian Noise we have set Mean Value to 0 and varaince to 0.1.

Results

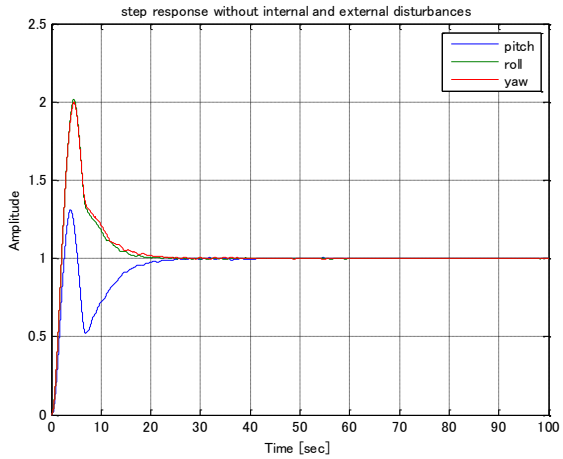

Fig.5 Step response without disturbances

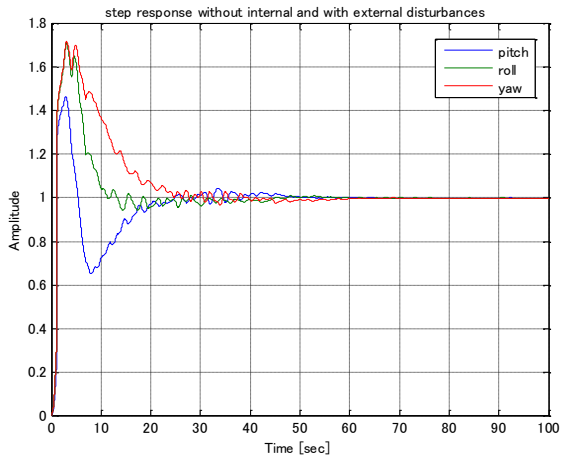

Fig.6 Step response without *di* and with *de*

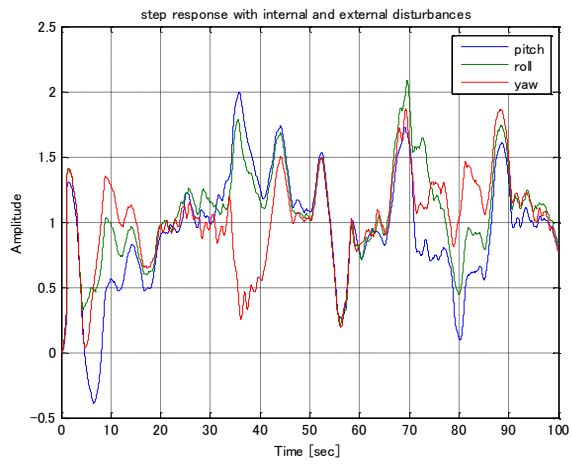

Fig.7 Step response with *di* and with *de*

As it is clear in Fig. 5 step response for wirelss tele control system is stable due to utilization of equalizer in receiver sides of controller and plant. Fig. 6 shows the step response with external disturbances. In this result as it is clear even thought there are harmonical fluctuation on curves, however, the behavior of output are not influnced. Finally for Fig. 7 shows the step response of closed-loop system with intenal and external disturbances. As it is obvious system is stable however, performance is degraded and not suitable for actual cases.

5. Conclusion

In this research we disscused about wireless tele-control system and implemented eqaulizers for feedforward and feedback channel. Moreover, we analyzed the stability and performances of the-closed-loop system with internasl and external disturbances disturbances. As a result we could confirm the stability even when system contain disturbances. However, for internal disturbances the performance of the closed-loop is degraded. Therefore, as a future work we are going to enhance the performances of the closed-loop system for internal disturbances.

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