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패러포일 투하 시스템의 궤적 추종 제어기의 설계

Design of Trajectory Following Controller for Parafoil Airdrop System

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[요 약]

본 논문은 패러포일 투하 시스템을 설계하고 분석하는데 있다. 패러포일 시스템의 6-자유도(6-DOF) 모델을 새우고, 비선형 모델 예측 제어와 PID 제어 방법이 펄럭 편 요각을 제어하기 위해 각각 적용되었다. 펄럭 편 요각의 오버슈트 시간 및 세팅 시간의 결과를 비교하면서 PID제어 방법을 사용하는 것으로부터 펄럭 편 요각이 좀 더 안정화 되는 것을 확인하였다. 그런 다음 MATLAB에 의해 수행된 궤적 추종 효과의 시뮬레이션 결과에 의해 궤적 추종 제어기가 설계되었다. 패러포일 궤적의 측 방향 오차가 그것의 측 방향 편차 제어 방법에 의해 제거 될 수 있었다. 참고로 측 방향 편차는 현재 경로계획의 보간법에 의해 얻어졌다. 그리고 설계된 궤적을 사용하면서, 풍 외란을 추가하는 것으로부터 궤적 추종 시스템이 시뮬레이션 되었다. 시뮬레이션 결과는 풍 외란이 PID로 제어되는 펄럭 편 요각 변화에 의해 제거됨으로써 설계된 궤적에 아주 만족하였다.

[Abstract]

In this paper, parafoil airdrop system has been designed and analyzed. 6-degrees of freedom (6-DOF) model of the parafoil system is set up. Nonlinear model predictive control (NMPC) and Proportion integration differentiation (PID) methods were separately applied to adjust the flap yaw angle. Compared the results of setting time and overshoot time of yaw angle, it is found that the of yaw angle is more stable by using PID method. Then, trajectory following controller was designed based on the simulation results of trajectory following effects, which was carried out by using MATLAB. The lateral offset error of parafoil trajectory can be eliminated by its lateral deviation control. The later offset deviation reference was obtained by the interpolation of the current planning path. Moreover, using the designed trajectory, the trajectory following system was simulated by adding the wind disturbances. It is found that the simulation result is highly agreed with the designed trajectory, which means that wind disturbances have been eliminated with the change of yaw angle controlled by PID method.

Key word : Parafoil airdrop system, 6-DOF, Yaw angle, Trajectory following, Wind disturbances.
색인어 : 패러포일 투하 시스템, 6-자유도, 편 요각, 궤적 추종, 풍 외란

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I. Introduction

Airdrop technology has been wildly applied in civilian and military applications such as airdropping relief supplies to the stricken area and deliver of troops or weapon carrier in modern wars. Parafoil with rectangular planform wings can be kept aloft using ram-air inflated double surface. Thus, parafoil airdrop system (PAS) has been well developed, which is a high-performance gliding airdrop system due to its manipulability, good glide performance, and high reliability [1]. PAS can improve the precision and quality of airdrop capability. It is increasingly used in applications of object delivery and vehicle recovery [2]-[4]. However, there are many complex interferences during the process of actual airdrop, which make the old designed control system can not achieve the desired effects of airdrop. Thus, it is necessary to establish a dynamic simulation model to predict the performance of PAS under different wind conditions. The results of simulation can provide the basis for the selection of control system parameters.

There are a lot of researchers working on developing model parafoil system [2]-[7]. According to the summary of the former work and derivation of Newton and Kirchhoff equation, the two, six, nine, eleven and twelve degree of freedom (DOF) of the parachute and payload system dynamics equation was derived [3]. Xiong *et al.* designed the track trace system by using the traditional proportional differential (PD) controller and the gain regulated fuzzy PD controller for the parafoil system [4]. After the 1990s, PAS adopted multiphase homing trajectory, which includes three steps: close to target segment, energy control, and upwind landing. Although there are many researches have been performed, the collision avoidance has not been discussed yet. Thus, a non-straight counter guard path has been proposed in this paper to study the PAS trajectory for the problem of collision avoidance.

Ⅱ. A model of parafoil airdrop system

Parafoil has three motion states, which are the flap angle free gliding movement without partial, the unilateral partial turning movement, and the bilateral partial deceleration and flare-landing. Thus, a 6-DOF model of PAS with considering the additional mass of parafoil was set up to simulate each motion state, respectively.

To simulate the trajectory of PAS, the following hypotheses have been set up for deriving and establishing the dynamical equations, which are:

(1) Parafoil is a symmetrical design, the canopy has a definite shape after completed opening (except the case of trailing edge lower partial);

(2) Rigid connections are assumed between the lodes and the parafoil;

(3) The ground is assumed as a planar ground;

(4) It is assumed that mass center of PAS is located on the node of connection line.

The dynamic equations are:

$$\frac{dv}{dt} = \frac{f}{m} \tag{1}$$

$$\frac{dIw}{dt} = M \tag{2}$$

where, v is the angular velocity of PAS, f is the force acting on PAS, m is the total quality of the PAS, I is the moment of inertia of PAS, w is the angular velocity of parafoil, M is the resultant moment of PAS.

The simulation model is created by using the software Simulink. As shown in Fig. 1, it illustrates the simulation results of the case of flap without lower partial and the flap take the gliding movement. The position changes of the case of the unilateral partial turning movement is shown in Fig. 2. It is found that there is no deflection during the initial 20s, after that, a 15 ° constant asymmetric deflection quantity is applied. Finally, a turning motion has been confirmed according to Fig. 2 for the case of the unilateral lower partial state.

The results of position changes for the case of glide-the bilateral partial state is shown in Fig. 3 and the profiles of velocity changes are shown in Fig. 4 Similarly, it is found that there is no deflection during the initial 20s, however, flared landing has been found in case of the bilateral partial state according to Fig. 3 after the initial 20s.

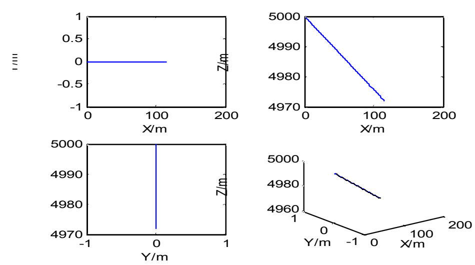

그림 1. 무 하부 적 위치 변화
Fig. 1. No lower partial position change.

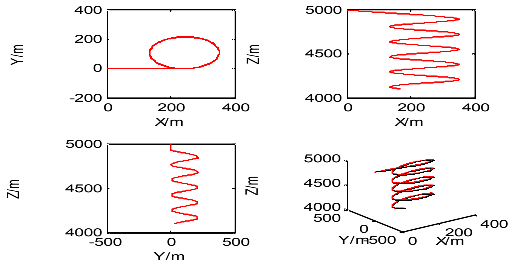

그림 2. 활공-단측 하부 편향 위치 변화

Fig. 2. Position changes of gliding-unilateral partial state.

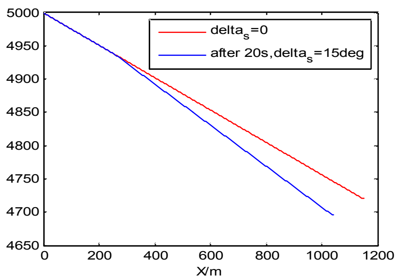

그림 3. 활공-양쌍측 하부 편향 위치 변화

Fig. 3. Position changes of gliding-bilateral partial state.

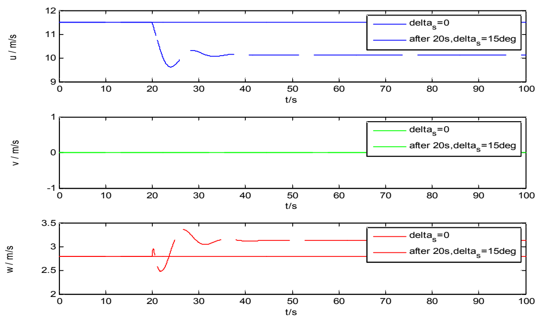

그림 4. 속도 분량(u, v, w)의 변화

Fig. 4. The change of velocity component(u, v, w) .

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix}=\sqrt{\frac{2(G_S+G_W)\cos\sigma}{\rho C_L A_S}}\begin{bmatrix} \cos\sigma \\ 0 \\ \sin\sigma \end{bmatrix} \tag{3}$$

$$ctg\sigma=\frac{C_L}{C_D+C_{D_W}A_W/A_S} \tag{4}$$

G_S and G_W are the weight of canopy and recycled materials. C_L and A_S are The characteristic area and resistance of canopy and recycled. σ is orbit inclination. C_L and C_D are Lift and drag

Parafoil system(Including parafoil and load) is represented that: 6-DOF are three inertial position of system center of mass and three euler angles. Added mass is Processed by scalar method. The motion equations of parafoil system as shown as following:

$$\dot{x}=V\cos\gamma\cos\chi \tag{5}$$

$$\dot{y}=V\cos\gamma\sin\chi \tag{6}$$

$$\dot{z}=-V\sin\gamma \tag{7}$$

$$\dot{V}=\frac{-D-Mg\sin\gamma}{M} \tag{8}$$

$$\dot{\chi}=\frac{L\sin\mu+Y\cos\mu}{MV\cos\gamma} \tag{9}$$

$$\dot{\gamma}=\frac{L\cos\mu-Mg\cos\gamma-Y\sin\mu}{MV} \tag{10}$$

$$\dot{\varepsilon}=q-\tan\beta(p\cos\varepsilon+r\sin\varepsilon)+\frac{1}{MV\cos\beta}(-L+Mg\cos\gamma\cos\mu) \tag{11}$$

$$\dot{\beta}=\psi n\varepsilon-r\cos\varepsilon+\frac{g}{V}\cos\gamma\sin\mu+\frac{Y\cos\beta}{MV} \tag{12}$$

$$\dot{\mu}=\frac{1}{\cos\beta}(p\cos\varepsilon+r\sin\varepsilon)-\frac{g}{V}\cos\gamma\cos\mu\tan\beta+\frac{L}{MV}(\tan\gamma\sin\mu+\tan\beta)+\frac{Y}{MV}\tan\gamma\cos\mu\cos\beta \tag{13}$$

$$\dot{p}=\frac{I_{ZZ}\bar{L}+I_{XZ}\bar{N}}{I_{XX}I_{ZZ}-I_{XZ}}+\frac{I_{XZ}(I_{XX}-I_{YY}-I_{ZZ})pq}{I_{XX}I_{ZZ}-I_{XZ}^2}+\frac{[I_{ZZ}(I_{YY}-I_{ZZ})-I_{XZ}^2]qr}{I_{XX}I_{ZZ}-I_{XZ}^2} \tag{14}$$

$$\dot{q}=\frac{1}{I_{rr}}(\bar{M}+(I_{ZZ}-I_{XX})pr-(p^2-r^2)I_{XZ}) \tag{15}$$

$$\dot{r}=\frac{I_{XZ}\bar{L}+I_{XX}\bar{N}}{I_{XX}I_{ZZ}-I_{XZ}^2}+\frac{[I_{XX}(I_{XX}-I_{YY})+I_{XZ}^2]pq}{I_{XX}I_{ZZ}-I_{XZ}^2}-\frac{I_{XZ}(I_{XX}-I_{YY}-I_{ZZ})qr}{I_{XX}I_{ZZ}-I_{XZ}^2} \tag{16}$$

$$\epsilon=\alpha+\theta \tag{17}$$

Where M is the mass of parafoil system. D is the sum of the resistance of parafoil (D_S+D_W), $\bar{L}$ is rolling moment, $\bar{M}$ is pitching moment, $\bar{N}$ is yawing moment. x,y,z are components about displacement of parafoil in geodetic coordinates. V is the parafoil speed in the air-axes system. γ is the flight path tilt angle of parafoil. χ is the flight path azimuth angle of parafoil. ε,β,μ are attitude variables relative to air—axes system. p,q,r are state variables of rotational velocity. $I_{XX},I_{YY},I_{ZZ},I_{XZ}$ are moment of inertia. θ is the setting angle of parafoil coad.

Ⅲ. The control of the parafoil

To eliminate the lateral deviation of PAS, unilateral partial is applied to eliminate the lateral deviation of PAS. The nonlinear model predictive control (NMPC) and proportion integration differentiation (PID) methods are applied to adjust the flap yaw angle to stabilize PAS.

3-1 Nonlinear model predictive control (NMPC)

A 6-degree of freedom (6-DOF) model of the parafoil system was set up. Then, NMPC method is applied to adjust the flap yaw angle. The method determined the control input in the form of closed loop by using a limited Taylor series expansion of control vector and output vector. Consider a single input single output nonlinear system, this system is defined as shown in equation (18),

$$\begin{aligned} \dot{x}(t) &= f(x(t)) + g(x(t))u(t) \\ y(t) &= h(x(t)) \end{aligned} \tag{18}$$

$x \in R^n$ is state variables, $u \in R^l$ is control function and $y \in R^l$ is output functions. $f(0)=0$, $h(0)=0$ and $g(0) \neq 0$.

When relation degree of non-linear system is uncertainty, the singular point is used for model predictive control. One case is that the system state variables are in the singular point set , and another case is that the system state variables is outside the singular point set. Moreover, two cases should be considered.

One case is about singular point optimal solutions. The system state variables are within the singular points. The control function u is obtain from solving the following equation.

$$\begin{aligned} &\sum_{i=0}^{\rho+1} k_{i+1}(L_f^i h(x) - w^{[1]}) + \\ &(L_f L_g L_f^{\rho-1} h(x) + L_g L_f^{\rho} h(x))u + \\ &L_g^2 L_f^{\rho-1} h(x) u^2 = 0 \end{aligned} \tag{19}$$

Two solutions were obtains from above equation, these two solutions are both meet the requirements by validated. k is the first line of $M_3^{-1} M_2^T$, and $k_{\rho+2}=1$, ω is angular velocity,.

The second, non-singular point optimal solution, the system state variables are outside the singular points. Control function is

$$u(t) = -[G(x)]^{-1}[kM_\rho + L_f^{\rho} h(x) - w^{[\rho]}(t)] \tag{20}$$

where

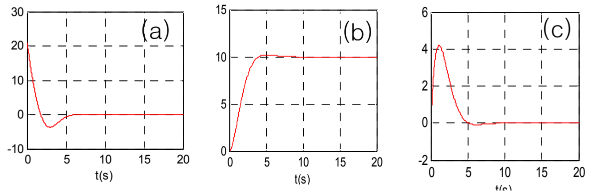

그림 5. 비선형모델 예측 제어 방법을 이용하고 편요각 제어기의 시뮬레이션 결과 (a) 단측 플랩 편요각, (b) 편요각, (c) 요레이트

Fig. 5. The simulation result of yaw controller by nonlinear model predictive control. (a) Unilateral flap yaw angle, (b) Yaw angle and (c) Yaw rate.

$$\begin{aligned} M_\rho = &[(h(x) - w),(L_f^l h(x) - w^{[1]}), \\ &(L_f^2 h(x) - w^{[2]})] \cdots \\ &(L_f^{\rho-1} h(x) - w^{[\rho-1]})] \end{aligned} \tag{21}$$

k is the first line of $T_{rr}^{-1} T_{\rho r}^T$.

$$T_{\rho r} = \begin{bmatrix} T_{(1,\rho+1)} & \cdots & T_{(1,l+1)} \\ \vdots & \ddots & \vdots \\ T_{(\rho,\rho+1)} & \cdots & T_{(\rho,l+1)} \end{bmatrix} \tag{22}$$

$$T_{rr} \begin{bmatrix} T_{(\rho+1,\rho+1)} & \cdots & T_{(\rho+1,l+1)} \\ \vdots & \ddots & \vdots \\ T_{(l+1,\rho+1)} & \cdots & T_{(l+1,l+1)} \end{bmatrix} \tag{23}$$

where

$$T_{(i,j)} = \frac{T^{i+j-1}}{(i-1)!(j-1)!(i+j-1)} \tag{24}$$

Taylor expansion order of the system output function is set as 3. Model predictive time domain T is 3s. coefficient k_1 is 1.6667, coefficient k_2 is 2.0. In MATLAB/simulation, RK4 solver iterative calculation methord is adopted, simulation step t is set as 0.002s. The simulation results are as follows in Fig. 5.

It is found that yaw controller has good tracking performance as shown in Fig. 5. Experiment result indicate that: This method can adapt to pathological conditions (not completely control or default control). The best control result is obtained by properly select Taylor expansion of the controller. The design of model predictive controller has good tracking effect. But the simulation of yaw controller have overshoot phenomenon in the process of mediation.

3-2 Proportion Integration Differentiation(PID) control

Yaw controller of parafoil system is designed by PID method. The simulation model is set up and the yaw angle control is shown as follow in Fig. 6. The relationship of input error e(t) and the output control $u(t)$ is as shown as shown in (23).

$$u(t)=K_Pe+K_I\int edt+K_De \tag{23}$$

K_P is proportionality coefficient. K_I is integral coefficient. K_D is differential coefficient.

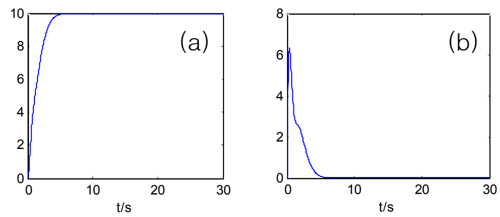

그림 6. PID 제어 방법을 이용하고 요우 제어기의 시뮬레이션 결과 (a) 편요각의 조절 과정 (b) 조절 과정 중에서는 요 레니트의 변화.
Fig. 6. The simulation result of yaw controller by proportion integration differentiation control (a) Yaw angle regulating process and (b) The change of yaw rate in regulating process.

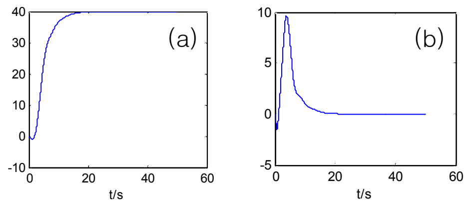

그림 7. 피드백 량의 외 순환(유도루프) (a) 옆으로 미끄럼 Y의 조절 과정 (b) 조절 과정에서는 속도 분량 V의 변화.
Fig. 7. Feedback quantity of the outer loop (guidance loop). (a) Sideslip Y of regulating process and (b) The change of velocity component V in regulating process.

The simulation as shown in Fig. 5(b) and Fig. 6(a), yaw settling time is 4s when the yaw is controled by use NMPC method. And settling time is 5s when the yaw is controled by use PID control method, settling time of NMPC less than the PID control 1s. In Fig. 5(b), overshoot can be seen by use NMPC method, In Fig. 6(a), yaw regulating process have no overshoot by use PID control method. The stability of parafoil is very import. Too much regulating variable may be lead to unfavorable factors of parafoil such as out of control. So, in this paper, PID method is selected. Above content is inner loop control of parafoil system.

The cornering Y need to be controlled in outer loop (guidance loop)of control. Cornering Y and velocity component v are feedback quantity. The cornering Y and velocity component v of the outer loop are shown as follow in Fig. 7.

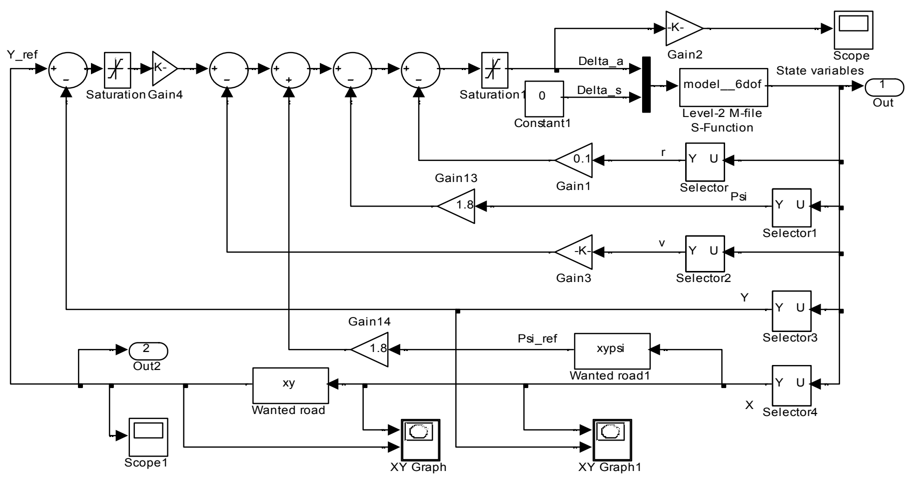

그림 8. 궤적 추종 시뮬레이션
Fig. 8. Trajectory following simulation.

Ⅳ. Trajectory following tracker of parafoil system

4-1 Design method of trajectory following tracker

In this paper, PID control method is selected to design of a trajectory following tracker of parafoil. The later offset deviation reference was obtained by the interpolation of the current planning path. Moreover, using the designed trajectory, the trajectory following system was simulated by adding the wind disturbances. The trajectory following simulation are shown as followed in Fig. 8. canopy area $S_p = 21\,m^2$, setting angle $\Phi = 0.1745(10^\circ)$, $S_w = 0.5\,m^2$, aspect ratio $AR = 2.333$, parafoil quality: $m_p = 13\,kg$, sling length $L_w = 0.5\,m$, resistance characteristics area airdrop quality $m_b = 135\,kg$, span $b = 7\,m$, length of chord $c = 3\,m$. $k = 0.1$ in gain1, $k = 57.3$ in gain 2, $k = 0.05$ in gain 3, $k = 0.04$ in gain 4, $k = 1.8$ in gain 13, $k = 1.8$ in gain 14.

The trajectory following path is realized by controlling the internal loop and external loop. Internal loop including the control of the yaw angular velocity control and yaw angle control. Outer loop including lateral velocity and lateral displacement. The differential value of lateral displacement of given path and parafoil actually lateral displacement are controlled. Interpolated the parafoil forward displacement of the current time at a predetermined planning path. The reference of lateral displacement is obtained. The lateral displacement is feedbacked to control the lateral displacement deviation. Selector, selector 1, selector 2 and selector 3 are signal selector. Feedback signal are choosed from state variable signal. S function model_6dof is parafoil model. S function xy is lateral displacement of the reference of given function. S function xypsi is reference side slip angle. Saturation is limited scope of asymmetric flap deflection quantity.

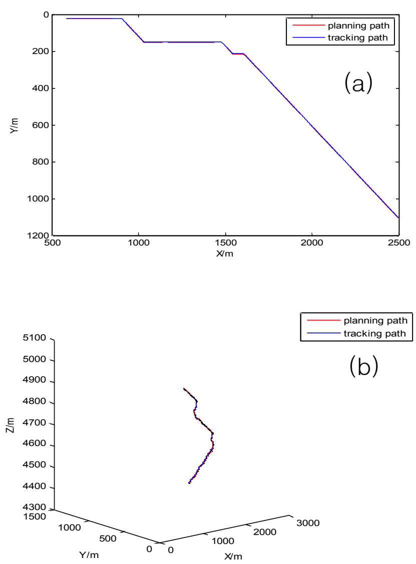

그림 9. 계획한 비 평직 노선의 추종 효과 (a) 2차원 평면에서 추종 효과 (b) 3차원 공간에서 추종 효과

Fig. 9. Tracking effect of planned the track of non straight line. (a) The tracking effect of two-dimensional plane and (b) The tracking effect of three-dimensional plane.

Non straight line which had planned joined into tracker controller. The tracking effect has been shown as follow in the Fig. 9[8]-[9], tracking effect is good.

4-2 Anti-interference of trajectory following tracker

In Fig. 10, the constant lateral winds are joined in the following tracker. In Fig. 9(a) and Fig. 10(b), if lateral wind disturbances did not appeared, cornering trajectory did not appeared. The planning path is tracked with no tracking error. When lateral wind is about 10 m/s, the error be up to 13 m. Trajectory tracking path is better by use following tracker. In the path following of slope, the wind disturbances joined or not joined all have tracking error.

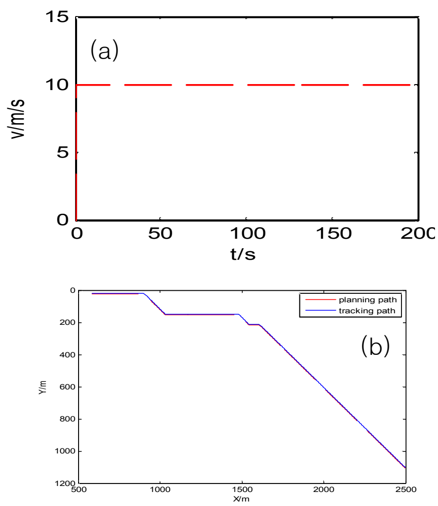

그림 10. 추종기에서는 상치 측 방향 풍이 추가함 (a) 상치 측 방형 풍 외람 (10 m/s), (b) 측 방형 풍 (10 m/s)의 경로추종 효과

Fig. 10. Constant lateral winds joined the following tracker controller. (a) Constant value of lateral wind disturbances (10 m/s) and (b) Path tracking effect by lateral wind (10 m/s).

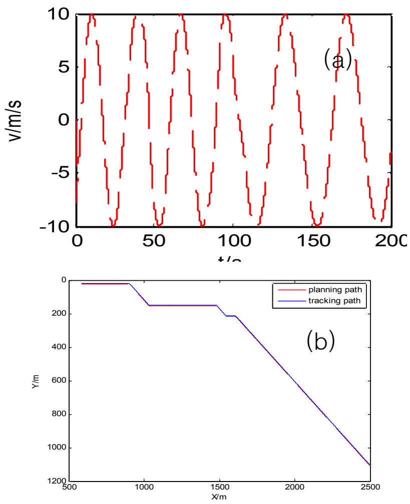

그림 11. 추종기에서는 변속 측 방향 풍이 추가한 후에 경우 (a) 변속 측 방향 풍 (b) 추종 효과

Fig 11. In such a case that variable speed of lateral winds joined the following tracker. (a) Variable speed of lateral winds and (b) Tracking effect.

In Fig 11, the variable speed lateral winds are joined in the following tracker. It can be shown that tracking trajectory slightly fluctuated nearby desired trajectory, and tracking effect is good.

Ⅳ. Conclusions

Parafoil system had been set up by use 6-DOF model. 6-DOF model can be good for stability of parafoil system. The yaw regulating process has overshoot by use NMPC method. Yaw regulating process has no overshoot by use PID control method. The stability of parafoil is very import. Too much regulating variable may be lead to unfavorable factors of parafoil such as out of control. So, PID method is selected to controled the trajectory following controller. Above content is inner loop control of parafoil system. The lateral offset error of parafoil trajectory can be eliminated by its lateral deviation control. The later offset deviation reference was obtained by the interpolation of the current planning path. Moreover, using the designed trajectory, the trajectory following system was simulated by adding the wind disturbances. It is found that the simulation result is highly agreed with the designed trajectory, which means that wind disturbances have been eliminated with the change of yaw angle controlled. When lateral wind is about 10 m/s, the error be up to 13 m. Trajectory tracking path is better by use following tracker. In the path following of slope, the wind disturbances joined or not joined all have tracking error.

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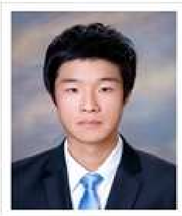

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