International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 1 [January. 2025] PP: 81-87

Synthesizean adaptive control for direct control of g-load factor of small-sized UAV in turbulent wind conditions

Tran Van Cap, Dang Cong Vu*, Ngo Van Tai,Tran Gia Hoanh,
Nguyen Manh Tuong, Nguyen Dong Anh, Phung The Anh, Nguyen Van Long
Air defence-Air force Academy, Viet Nam
**Corresponding author*

Abstract: *In this paper, to ensure the safety of UAV in turbulent wind conditions, the authorsused the adaptive control algorithm with using the Lyapunov method for direct control of g-load factor. Survey results on the computer with UAV hipothetical model show that the application of adaptive control algoritm with using the Lyapunovmethod for direct control of g-load factor are very effective, the angle of attack and g-load factor are much reduced, significantly improving the UAV flight safety.*
Keywords: *Turbulent wind, unmanned aerial vehicle, adaptive control.*

Date of Submission: 09-01-2025 Date of acceptance: 22-01-2025

I. INTRODUCTION

Turbulent wind greatly impacts the motion of small-sized UAV. This factor can lead to dangerous flight modes (flying at close-to-limit angles of attack and/or near the load limit of the aircraft structure), potentially resulting in accidents during low-altitude flights [2]. This significantly limits the safe utilization of UAV in turbulent wind conditions. Therefore, ensuring the flight safety of unmanned aircraft is of paramount importance in turbulent wind conditions. In this paper, the authorsproposes a solution to modify the automatic control algorithm to adjust the lift force. Specifically, considering a UAV flying using a stable altitude control algorithm (using PID - Proportional Integral Derivative), when there is turbulent wind blowing from below, the UAV switches to an adaptive control algorithm (adjusted using the Lyapunov method) controlling the g-load factor. This implies that when there is turbulent wind, the UAV does not maintain altitude but instead maintains the g-load factor within the allowable limits to ensure the UAV flight safety.

II. TURBULENT WIND AND THE EFFECT OF TURBULENT WIND ON UAV VERTICAL MOTION

Turbulent wind can blow in the same direction as or against the aircraft's motion, and it can also blow in the horizontal plane. However, turbulent flows blowing perpendicular to the aircraft's motion and blowing upwards in the vertical plane directly affect the angle of attack and the aircraft's g-load factor. Therefore, this paper focuses on the impact of vertically upward turbulent wind in the vertical plane x_oOy_o. In the general case, the field of vertically upward turbulent wind may vary in space and time, meaning the wind field is non-uniform and non-stationary, $W_y=f(x_o,y_o,t)$. In the scope of this paper, we only consider a stationary wind field, meaning it does not change over time, $W_y=f(x_o,y_o)$. Furthermore, we assume that W_y depends only on the x_o coordinate, i.e., $W_y=f(x_o)$.We consider the following two turbulent wind models:

Staircase turbulent wind model. The staircase model of the vertical turbulent wind field can be represented as follows [2]:

$$W_y = \begin{cases} 0 & khi\ \ x_o < x_o^* \\ W_{yo} & khi\ \ x_o \geq x_o^* \end{cases} \tag{1}$$

With x_o^* is the coordinate of the starting point with turbulentwind, and W_{yo} = *const*is a certain surveyed value of the vertical turbulent wind field. In reality, the turbulent flow cannot abruptly act with the velocity W_{yo}, but the velocity $W_y$changes according to certain rules from the value$W_y=0$ to the value W_{yo}. The author will use the staircase turbulent wind model (1) to assess the reliability of the closed-loop dynamic simulation program.

The turbulent wind model according to European standards. Currently, there are no standards for issuing airworthiness certification for UAVs worldwide, so we will adopt the standards for the Very Light Aircraft (VLA) in Europe, JAR-VLA [3]. The JAR-VLA turbulent wind model:

$$W_y = \frac{W_0}{2}\left(1 - \cos\frac{2\pi\left(x_o - x_o^*\right)}{L}\right) \quad (2)$$

$\left(x_o - x_o^*\right)$ – The flight distance of the aircraft since the occurrence of the turbulent wind, m; W_0 – The amplitude of the turbulent wind, m/s; L – The scale of turbulence, m. The safety of UAV flight depends significantly on the scale of turbulence.

Analyzing the influence of turbulent wind on the vertical motion of UAVs. Starting from the system of differential equations describing the vertical motion of UAVs [1]:

$$\begin{cases} m\left(\dfrac{dV_k}{dt}\right) = T\cos\alpha - X_a - G\sin\theta \\ mV_k\dfrac{d\theta}{dt} = T\sin\alpha + Y_a - G\cos\theta \\ J_z\left(\dfrac{d\omega_z}{dt}\right) = \sum M_z \\ \dfrac{dx_0}{dt} = V_k\cos\theta; \quad \dfrac{dy_0}{dt} = V_k\sin\theta; \quad \dfrac{d\vartheta}{dt} = \omega_z; \quad \theta = \vartheta - \alpha \end{cases} \quad (3)$$

The lift force, drag force, and pitching moment are calculated as follows:

$$Y_a = C_{ya}.\frac{\rho V_r^2}{2}.S = (C_{y0} + C_y^{\alpha}.\alpha + C_y^{\delta cl}.\delta_{cl})\frac{\rho V_r^2}{2}.S;$$

$$X_a = C_{xa}.\frac{\rho V_r^2}{2}.S = (C_{x0} + C_{xa}^{\alpha}.\alpha)\frac{\rho V_r^2}{2}.S;$$

$$M_z = m_z.\frac{\rho V_r^2}{2}.S.l_a = (m_{z0} + m_z^{\delta cl}.\delta_{cl} + m_z^{\alpha}.\alpha).\frac{\rho V_r^2}{2}.S.l_a$$

The vertical load factor is calculated as α: $n_y = \dfrac{T\sin\alpha + Y_a}{mg}$.

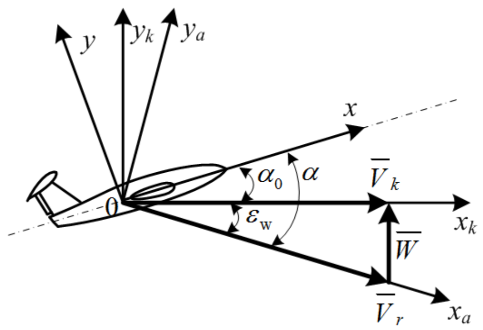

Figure 1. Influence of wind on the angle of attack

Therefore, when there is wind causing changes in the angle of attack α and the airspeed V_r of the UAV, it results in changes in aerodynamic forces X_a, and Y_a and the pitching moment M_z,thus leading to the variation of the UAV's motion parameters.

When there is no turbulent wind, the airspeed vector ($\overline{V}_r$) coincides with the ground velocity vector ($\overline{V}_k$), and the UAV flies at the angle of attack α_0. When there is turbulent wind $\overline{V}_r$, which deviates from $\overline{V}_k$ at an angle ε_w (Figure 1), the magnitude of the airspeed $\overline{V}_r$ and the angle of attack of the UAV are determined by the following expressions:

$V_r = \sqrt{V_k^2 + W^2}$; $\alpha = \alpha_0 + \varepsilon_w$, where $\varepsilon_w = arctg\dfrac{W}{V_k}$

III. CONTROL ALGORITHM

In this paper, considering the UAV is flying steadily with a stable altitude control algorithm, when there is wind turbulence acting vertically from below, the UAV switches to an adaptive control algorithm according to g-load factor to reduce the g-load factor.

Stable altitude control algorithm. In the absence of turbulent wind, the UAV is stabilized, and the parameters of the UAV's dynamics model change slightly,the authors employs a Proportional Integral Derivative (PID) control algorithm.

$$U_1 = K_p.\left(H_{th} - H_{ct}\right) + K_d.\left(\dot{H}_{th} - \dot{H}_{ct}\right) + K_i\int_0^t\left(H_{th} - H_{ct}\right).dt + \delta_{cbb} + k_{oz}.\omega_z \quad (4)$$

δ_{cbb} - the equilibrium value of the altitude deviation angle when flying level; k_{oz} – vertical damping factor; ω_z– the angular velocity of the UAV around the OZ axis; H_{th}– the actual altitude of the UAV during flight; H_{ct} –the altitude according to the program.

The coefficients K_p, K_d, K_i – correspond to the proportional gain, derivative gain, and integral gain of the PID controller, respectively. The coefficients K_p, K_d, K_i ,and k_{oz} are selected using the Simulink Response Optimization tool in Simulink.

The adaptive control algorithm adjusts with using the Lyapunov method for direct control according to g-load factor. To synthesize the adaptive controller, the linearization of the system of differential equations governing the vertical motion of the UAV is performed. When linearizing, only short-cycle motions (angular motions) are considered, neglecting the changes in speed and flight altitude and ignoring the lift component of the elevator. We obtain the system of differential equations based on the deviation:

$$\begin{cases} \Delta\dot{\alpha} = -a_4.\Delta\alpha + \Delta\omega_z \\ \Delta\dot{\omega}_z = -a_2.\Delta\alpha - a_1.\Delta\omega_z - a_3.\Delta\delta_y \end{cases} \quad (5)$$

Since the g-load factor is related to the angle of attack $\Delta n_y = \frac{V.a_4}{g}\Delta\alpha$, it can be expressed as:

$$\begin{cases} \Delta\dot{n}_y = -a_4.\Delta n_y + \frac{V.a_4}{g}.\Delta\omega_z \\ \Delta\dot{\omega}_z = -\frac{g.a_2}{V.a_4}.\Delta n_y - a_1.\Delta\omega_z - a_3.\Delta\delta_y \end{cases} \quad (6)$$

When there is no turbulent wind and the UAV is flying stably, we will have the standard model written in the form of state equations:

$$\dot{X}_M = A_M.X_M + B_M.Y \quad (7)$$

In which: Y - the control signal of the UAV when flying steadily,

$$A_M = \begin{pmatrix} -a_4 & \frac{V.a_4}{g} \\ \frac{-a_2.g}{V.a_4} & -a_1 \end{pmatrix}, \qquad B_M = \begin{pmatrix} 0 \\ -a_3 \end{pmatrix}$$

a_1, a_2, a_3, a_4 – the dynamic coefficients [1];

The coefficient of drag: $a_1 = -\frac{m_z^{\omega_z}.q}{V.J_z}.S.b_a^2,(1/s)$

The coefficient of static stability: $a_2 = -\frac{m_z^{\alpha}.q}{J_z}.S.b_a,(1/s^2)$

The coefficient of aerodynamic effectiveness of the elevator: $a_3 = -\frac{m_z^{\delta_y}.q}{J_z}.S.b_a,(1/s^2)$

The coefficient of aerodynamic lift due to the angle of attack: $a_4 = \left(\frac{C_y^{a}.q.S+T}{m.V}\right),(1/s)$

To enable the system to automatically adapt to the effects of turbulent wind on the surface of the UAV, we need to synthesize the adaptive algorithm and the control structure to achieve the control objective, which is:

$$\lim_{t\to\infty} E(t)=0 \tag{8}$$

With: $E(t)=X(t)-X_M(t)$ - error vector.

$X(t)=(x_1;x_2)=(\Delta n_y;\Delta\omega_z)$ - The vector represents the deviation between the actual g-load factor and the deviation of the actual angular velocity of the UAV during flight.

$X_M(t)=(x_{M1};x_{M2})=(\Delta n_{yM};\Delta\omega_{zM})$ - The vector represents the deviation between the actual g-load factor and the deviation of the actual angular velocity of the UAV during stable and no-wind flight.

$$E(t)=\left(e_1;e_2\right)=(x_1-x_{M1};x_2-x_{M2})=\left(\Delta n_y-\Delta n_{yM};\Delta\omega_z-\Delta\omega_{zM}\right) \tag{9}$$

To achieve the control objective (8), in this paper, the method of positive definite predefined objective function adjustment is used (Lyapunov tuning method).

The choice of control signal [4]:

$$U_2=\overline{K}^{Y}(t).\overline{K}^{X}(t).X(t)+\overline{K}^{Y}(t).Y(t) \tag{10}$$

In which: $\overline{K}^{Y}(t),\overline{K}^{X}(t)$ - parameters needing adjustment.

Given that $\overline{K}^{X}(t)=(k_1,k_2)$,we can write:

$$U_2=\overline{K}^{Y}(t)\left[k_1(t).x_1(t)+k_2(t).x_2(t)+Y(t)\right] \tag{11}$$

Synthesizing the adaptive algorithm using the Lyapunov function, employing a positive definite function (Lyapunov function) in the following form:

$$V(E)=0.5E^THE+0.5\left[\frac{(\overline{K}^{X})^2}{\gamma_1}+\frac{(\overline{K}^{Y})^{-2}}{\gamma_2}\right] \tag{12}$$

To achieve asymptotic stability and accomplish the control objective $E(t)\to 0$ the Lyapunov function must have the property $\frac{dV}{dt}<0$. By differentiating the Lyapunov function with respect to time, we can derive the adaptive algorithm as follows [4]:

$$\begin{aligned}\dot{\overline{K}}^{X}&=-\gamma_1 B_M^T HEX^T\\ \dot{\overline{K}}^{Y}&=-\overline{K}^{Y}\gamma_2 B_M^T HE(Y+\overline{K}^{X}X)^T(\overline{K}^{Y})^T\overline{K}^{Y}\end{aligned} \tag{13}$$

Or:

$$\begin{aligned}\dot{k}_1(t)&=-\gamma_1 B_M^T HEx_1(t)\\ \dot{k}_2(t)&=-\gamma_1 B_M^T HEx_2(t)\\ \dot{\overline{K}}^{Y}&=-\gamma_2 B_M^T HE(Y+k_1x_1+k_2x_2)(\overline{K}^{Y})^3\end{aligned} \tag{14}$$

In which: the coefficient $\gamma_1>0$ and $\gamma_2>0$

The matrix H must satisfy: $H=H^T>0$. Based on the known matrix A_M, solving the Lyapunov equation for the standard model will find the matrix H.

$$HA_M+A_M^TH=-Q \tag{15}$$

The optional matrix Q satisfies the condition $Q=Q^T>0$.

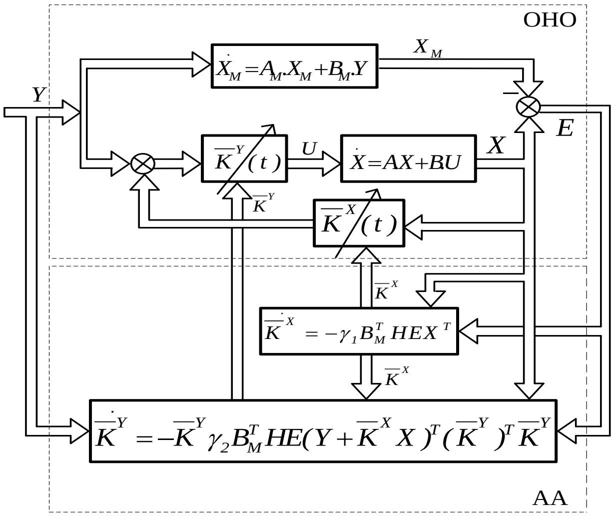

Figure 2. Structure diagram of the adaptive system using the Lyapunov function

IV. SIMULATION RESULTS

Perform simulations and examine the longitudinal motion of the UAV hipothetical modelon a computer using the Simulink tool. Some parameters of the UAV hipothetical model are as follows:

- Length: *2707 mm*; Mass: *56.3 Kg*;
- Wing area: *1.05* m^2;
- Wingspan: *3000 mm*;
- Mean aerodynamic chord: *350 mm*;
- Cruise speed:*40 m/s*.
- Moment of inertia: *31.3* $Kg.m^2$
- $m_z^{d_c} = -2.2136$ *(1/rad);* $m_z^{v_z} = -16.0505$; $m_z^{a} = -1.4515$ *(1/rad);*
- $C_y^{a} = 5.913$ *(1/rad);* $C_y^{dc} = 0.61264$ *(1/rad);* $C_y^{wz} = 28.4219$ *(1/rad).*

Verify the reliability of the program: To fully assess the program's reliability quantitatively, we need to conduct test flights. Here, we only analyze qualitatively the UAV's response to external disturbances, such as stair-step turbulent wind with amplitude. The theoretical calculation will yield the initial value of the angle of attack $\Delta\alpha_r = arctg(W_{y0}/V_k) \approx W_{y0}/V_k = 0.125(rad) \approx 7^o$

The response of the UAV using the altitude stabilization control yields the following results:

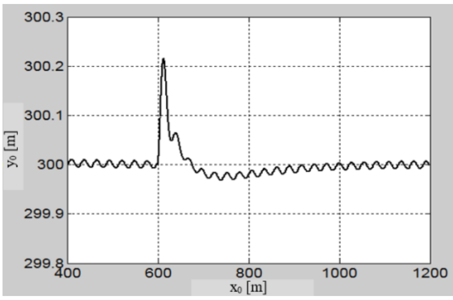

Figure 3. Trajectory of the UAV when subjected to staircase wind with amplitude W_{y0}=5m/s

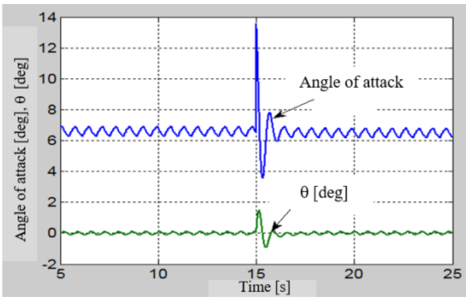

Figure 4. Angle of attack and trajectory inclination when there is a stair-step wind of amplitude W_{y0}=5m/s

Figures 3 and 4 demonstrate that the theoretical calculations align perfectly with the UAV's response. When the turbulent wind occurs, the angle of attack increases with an initial deviation of about 7^0, then gradually approaches 0 due to the stability of the closed-loop control system. After a few short oscillation cycles of the angle of attack, the algorithm maintains the preset altitude before the onset of the disturbance, resulting in the trajectory inclination and altitude deviation gradually approaching 0.

The response of the UAV when using the adaptive control system for g-load factor:

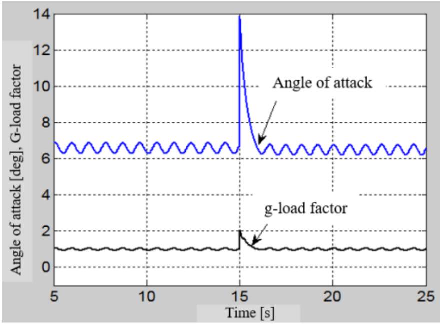

Figure 5. G-load factor and angle of attack in the influence of stair-step wind

Figure 5 shows that when the thermal updraft affects the angle of attack, the number of iterations increases to around 7^0. However, due to the stability of the closed-loop control system, this number gradually approaches 0. The increased angle of attack results in an increased g-load factor. The action of the adaptive control algorithm according tog-load factor subsequently reduces the g-load factor, and after a few oscillations, the g-load factor returns to the desired value of 1 (which is the value during level flight), ensuring the stability of the program.

*The survey of the influence of the turbulence scale (L) on the flight safety of small-sized UAV using the altitude stabilization control algorithm:*The turbulent wind model used for the survey is the European standard wind model with a wind amplitude of $W_0=7.62$ *m/s.*

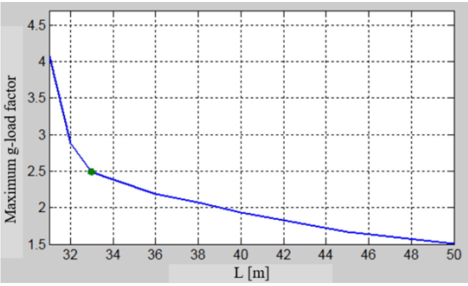

Figure 6. The maximum g-load factoraccording to the turbulence scale

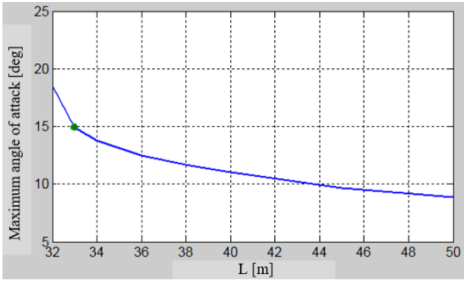

Figure 7. The maximum angle of attackaccording to the turbulence scale

Figures 6 and 7 show that the maximum angle of attack and maximum g-load factor of the UAV vary with the turbulence scale (*L*). Therefore, flight safety (defined as the angle of attack not exceeding 15^0, the g-load factor not exceeding 3 and not less than -1) depends on the turbulence scale. From the results in Figures 6 and 7, it can be observed that, with the altitude stabilization control algorithm, the UAV ensures safety when the turbulence scale$L>33m$. We will choose the turbulence scale $L=33m$ (corresponding to a maximum angle of attack of about 15^0, the threshold for unsafe flight of the UAV) for further investigation.

The survey with the European standard wind model with a turbulence scale L=33m, wind amplitude $W_0=7.62$ *m/s, and wind time t=15s (corresponding to* $x_0=600m$*).*

Results when using the altitude stabilization control:

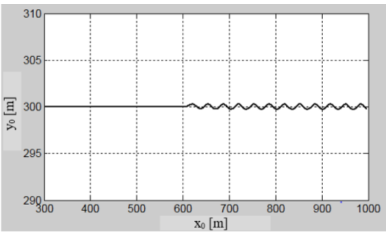

Figure 8. Trajectory of the UAV

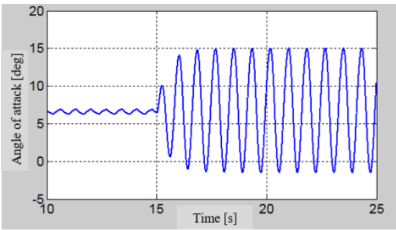

Figure 9. Angle of attack of the UAV

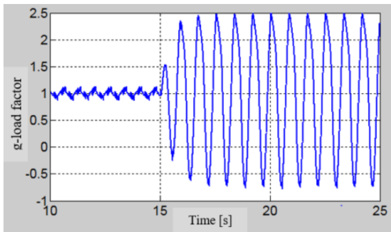

Figure 10. G-load factorof the UAV

Figures 8, 9, and 10 show that when using altitude stabilization control, the trajectory of the UAV is maintained. However, with a turbulence scale *L=33m*, angle of attack of approximately $15^0$and g-load factor about 2.5, it may lead to an unsafe flight for the UAV.

Results when using adaptive control to regulate g-load factor:

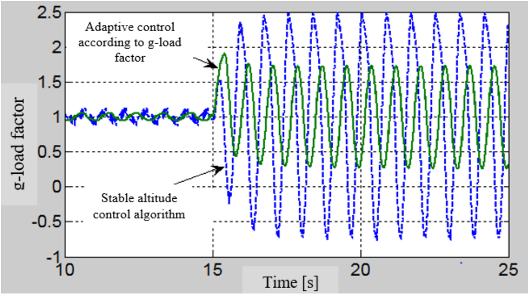

Figure 11. G-load factor of the UAV

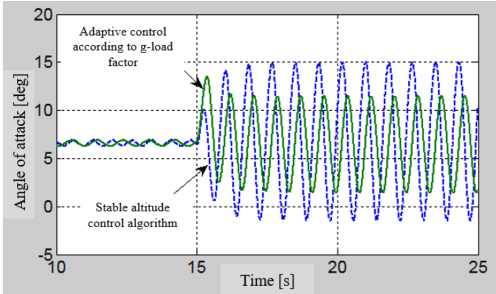

Figure 12. Angle of attack of the UAV

Figures 11 and 12 show that under windy conditions, if switching to adaptive control algorithm according to g-load factor, the g-load factor and angle of attack decrease significantly (g-load factor decreases to 1.9 - corresponding to a 24% reduction; angle of attack decreases to 13^0 - corresponding to a 13% reduction). Therefore, these results will ensure an improvement in the flight safety of the UAV when encountering turbulent wind conditions.

The surveywith usingthe adaptive control algorithm according to g-load factor and the European standard wind model with a wind amplitude W_0=7.62 m/s, wind time t=15s (corresponding to x_o=600m) and a turbulence scale less than 33m.

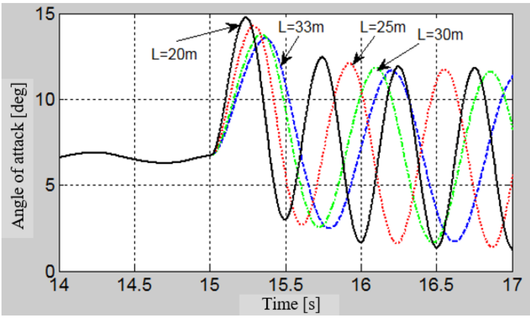

Figure 13. Angle of attack of the UAV

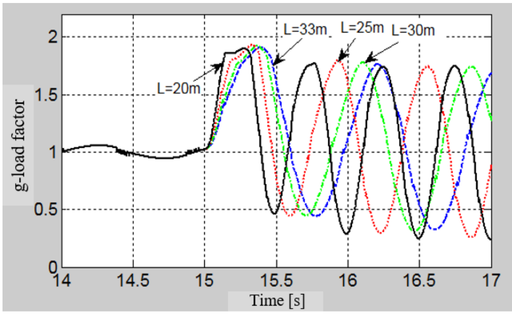

Figure 14. G-load factor of the UAV

Figures 13 and 14 show that when using the adaptive control algorithm according tog-load factor, the UAV still maintains safe flight (with the angle of attack and g-load factor within the permissible limits) in turbulent wind conditions where the turbulence scale decreases to approximately 20m. Therefore, the use of the adaptive control algorithm according to g-load factor will expand the use of small-sized UAVin turbulent wind conditions.

V. CONCLUSION

Therefore, by changing the automatic control algorithm (switching from altitude control to adaptive control algorithm according to g-load factor), a significant reduction in g-load factor can be achieved, enhancing the safety of small-sized UAVin turbulent wind conditions and increasing the lifespan of the UAV. At the same time, it expands the use of small-sized UAVin turbulent wind conditions.

REFERENCES

[1]. А.А. Красовский. Ю.А. Вавилов. А.И. Сучков, "*Системы автоматического управления летательных аппаратов*", М.1986.
[2]. Ю.П. Доброленский, "*Динамика полета в неспокойной атмосфере*", М. 1969, Изд. Машиностроение.
[3]. JAR-VLA: Joint Airworthiness Requirements For Very Light Aeroplanes, 1990.
[4]. Пупков К.А., Егупов Н.Д., и др "*Методы робастного, нейрон-нечеткого и адаптивного управления*"(том 3)-М.: Изд. МГТУ, 2002 г - 743с.