# THE HAZARD AND ALARM OF WINDSHEAR

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## Abstract

In this paper, a simplified windshear hazard criterion is developed based on the mechanism of the effects of windshear on aircraft flight and the CAT I worst landing limits specified by FAA. The effects of longitudinal and vertical windshear components on the performance of aircraft are analysed respectively, in the purpose of investigating the hazard of windshear components. After careful study of the correlationship between the hazard criterion and the performance deteriorating parameter J2, the threshold and the principle for the predictive airborne windshear detecting and alerting system are also discussed in detail in the paper.

## I. Introduction

Low-level windshear is the leading cause for the weather related aircraft accidents in the past few decades, and it's called "air killer" by the civil aircraft pilots. A war aimed at conquering the air devil is now spreading all over the world. Up to now, the conclusion comes to be: The best way to cope with windshear is to avoid it if it's possible. Hence, to develop the predictive airborne windshear detecting and alerting system is the key goal of the war. There are two problems here: the first is to detect windshear field; the second is to evaluate the hazard of the detected windshear to the aircraft task if the aircraft penetrates the windshear field. This becomes more and more important as airports become more and more congested. It isn't feasible to abort the task and go around if the detected windshear is slight. So, how to evaluate the hazard of the windshear to aircraft performance and the task, and to represent the hazard degree in the forms of detectable physical parameters is a key problem to be tackled for the design of the predictive airborne windshear system. In this paper, a simplified windshear hazard criterion is developed based on the mechanism of the effects of windshear-on aircraft flight[1] and the CAT I worst landing limits specified by FAA[2]. Also, the principle and the threshold for the predictive airborne windshear detecting and alerting system is discussed in detail in the paper.



## II. The Performance Limits of Aircraft

For ILS CAT II landing, FAA specifies concrete performance limits and the so-called landing windows[3]. Computations show that a slight windshear will cause aircraft dash out of the windows. It's not feasible and practical to evaluate the hazard of windshear according to the landing windows. But if the aircraft is to land safely, the trajectory / performance of aircraft in windshear must meet the lowest limits--the CAT I worst landing limits, see Fig. 1.

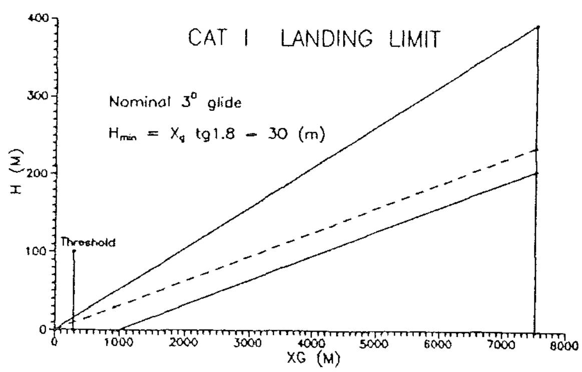



Fig. 1. The CAT I Worst Landing Limits

$$H_{min} = X_g \tan 1.8^\circ - 30. \qquad (X_g > 954 \text{ m}) \qquad (1)$$
$$H_{min} = 0. \qquad (X_g < 954 \text{ m})$$

$$V_a > V_s$$

That is to say that under no circumstances should the aircraft altitude H be lower than Hmin and the relative air speed be less than the stall speed Vs.

## III. Windshear Hazard Criterion

The motion equations of aircraft in windshear field ( 2 Dimension) are formulated in wind-axis as follows[4] :

$$\dot{V} = \frac{T}{m}\cos(\alpha + \delta) - \frac{D}{m} - g\sin\gamma - (\dot{U}_{wx}\cos\gamma - \dot{W}_{wx}\sin\gamma)$$
$$(2)$$
$$\dot{\gamma} = \frac{T}{mV}\sin(\alpha + \delta) + \frac{L}{mV} - \frac{g}{V}\cos\gamma + (\dot{U}_{wx}\sin\gamma + \dot{W}_{wx}\cos\gamma) / V$$

and the supplementary equations are:

$$\dot{X} = V\cos\gamma + Uwg \tag{3}$$

$$\dot{H} = V\sin\gamma - Wwg \tag{4}$$

From (4)

$$\sin\gamma = (\dot{H} + Wwg)/V \tag{5}$$

Substitute (5) into (1), under the assumption $\dot{W}_{wg}\sin\gamma \approx 0.$ $\cos\gamma \approx 1.$

Then we have:

$$\frac{g}{V}\dot{H} + \dot{V} = \frac{T}{m}\cos(\alpha+\delta) - \frac{D}{m} - (\dot{U}_{wg} + g\frac{Wwg}{V}) + \frac{g}{V}\dot{H}_{(0)} \tag{6}$$

$$\dot{H} = \dot{H}_{(0)} + \frac{\triangle T}{W}V - (\frac{\dot{U}_{wg}}{g} + \frac{W_{wg}}{V})V - \frac{V}{g}\dot{V} \tag{7}$$

where: $\triangle T$ is the potential thrust margin after the thrust stick is pulled to its maximum position.

Modern civil jet aircraft has a rather long thrust delay Td, usually about 4 to 10 seconds.

Under the worst situation, the energy of the windshear field applied on aircraft is totally used to decrease the aircraft potential energy, i.e. $dV/dt = 0$.

Thus

$$\dot{H} = V(\frac{\triangle T}{W} - F) + \dot{H}_{(0)} \tag{8}$$

Where $F = \frac{\dot{U}_{wg}}{g} + \frac{W_{wg}}{V}$

This is the so-called windshear hazard index factor by Bowles[5].

After integrating (8), we get:

$$H(t) = H_{(0)}t + \int_{Td}^{t}\frac{\triangle T}{W}V\ dt - \int_{0}^{t}FV\ dt \tag{9}$$

We know that windshear stipulates the longitudinal phuigoid oscillation mode of aircraft is the mechanism of windshear hazard to flight. To guarantee the landing safety, the aircraft is not allowed to drop below the CAT I worst landing limits during the half down-oscillation phase of aircraft motion.

The period of the phuigoid mode of aircraft $T_{ph.}$ during approach and landing phase can be approximately written as:

$$T_{ph.} = \frac{\sqrt{2}}{g}\pi V_{ref}$$

where: Vref is the approach reference speed of aircraft (relative to air), usually

$$V_{ref} = 1.3V_s + 10.\ \text{knots}$$

Thus

$$t = \frac{1}{2}\frac{\sqrt{2}}{g}\pi V_{ref} \tag{10}$$

Substitute (1),(10), into (9), then

$$\bar{F} \leqslant \frac{\triangle T}{W}(1. - \frac{\sqrt{2}gTd}{\pi V_{ref}}) + \frac{\sqrt{2}g}{\pi V_{ref}^2}[0.4H_0 + 30. - 0.4747(\frac{V_{ref}}{10.})^2] \tag{11}$$

where $\bar{F}$ is the average of F over distance $\triangle X$.

$$\triangle X \approx V_{ref} * t = \frac{1}{2}\frac{\sqrt{2}}{g}\pi V_{ref}^2 \tag{12}$$

It's easy to see that the larger the potential thrust margin $\triangle T$, the smaller the weight of aircraft, the shorter the engine thrust delay time parameter Td, the higher the initial altitude of aircraft when encountering windshear H0 the stronger the windshear the aircraft can cope with during approach phase. This agrees well with our past knowledge about windshear effects on aircraft flight.

**Example:**

$H_0 = 120$ m  $Td = 6$ s  $V_{ref} = 70$ m/s  $\frac{\triangle T}{W} = 0.15$

We have:

$$\bar{F} \leqslant 0.115$$
$$\triangle X \approx 1110\ (m)$$

This result is rather good as compared to the conclusions about threshold of hazard windshear drawn by Bowles[5].

## IV. The Effectiveness of the Hazard Criterion

A good windshear hazard criterion must describe the flight performance deterioration degree due to windshear, and must be robust to changes in windshear model, aircraft type, aircraft control manner and aircraft initial altitude, etc.[10] According to [6], we introduce the improved flight performance deterioration parameter J2:

$$J2 = \int_0^t[AD]\frac{\triangle H}{\triangle H_{max}}\ dt \tag{13}$$

Where:

$$\triangle H = H_{ref} - H$$
$$\triangle H_{max} = H_{ref} - H_{min}$$
$$AD = \sqrt{P_1(\frac{\gamma_{a0} - \gamma_a}{0.7^\circ})^2 + P_2(\frac{V_{ref} - V}{V_{ref} - V_s})^2}$$

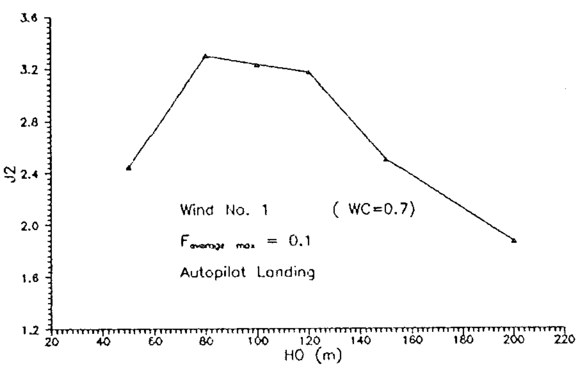
$$P_1 = \begin{cases} 1 & \gamma_a < \gamma_{a0} \\ 0 & \gamma_a \geqslant \gamma_{a0} \end{cases}$$

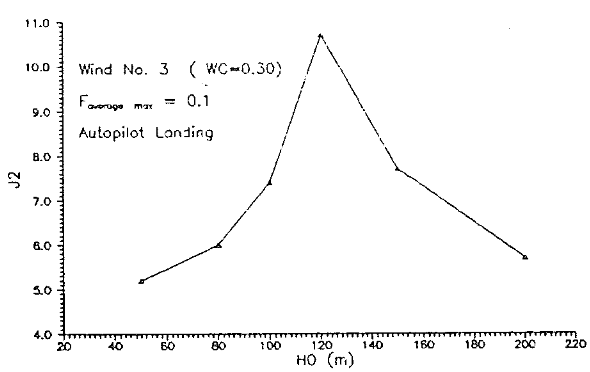
$$P_2 = \begin{cases} 1 & V < V_{ref} \\ 0 & V \geqslant V_{ref} \end{cases}$$

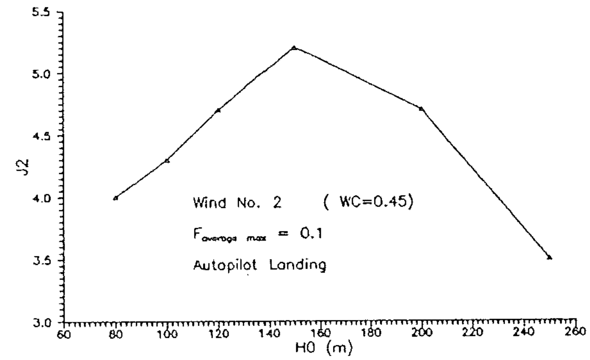
Where $\gamma_e$ is the true glide angle in ground based axis,
$H_{ref}$ is the nomial height of aircraft at time t.

We see from (13) that [AD] can be much larger if the derivation of height from the nominal path $\triangle H$ is not so large as compared to the maximum allowable derivation $\triangle H_{max}$ . As time goes, the height of aircraft becomes lower and lower, the derivation $\triangle H$ becomes larger and larger, and $\triangle H_{max}$ becomes smaller and smaller. This makes [AD] smaller and smaller in order to keep the performance deterioration parameter from diverging.

Simulations of Airbus 300A aircraft encountering windshear field during approach and landing are made for fixed stick situation and autopilot landing situation. The windshear models are No. 1, 2, 3 respectively taken from [8] recommended by FAA for pilot training, as well as the microburst model by Miele[9]. Computation results are given in Fig 2.



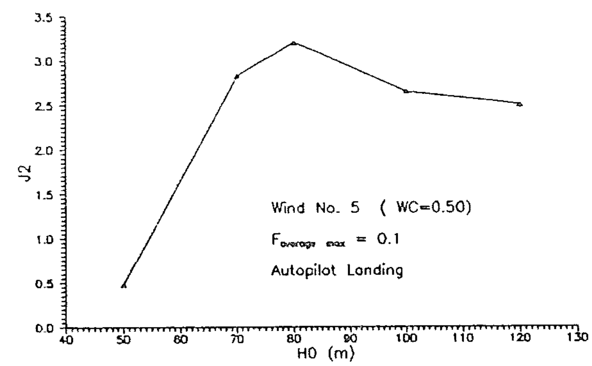




Fig 2.

It can be readily drawn from Fig 2. that there are two critical heights H1 and H2. The fight is safe when the initial height is high ( H0 > H1 ) or the initial height is very small ( H0 < H2 ). The windshear poses more threat to aircraft flight when the initail height is between the two critical heights. This conclusion seems unreasonable ! But careful examination into the question gives some explanation.

When H0 is high, the aircraft possesses higher potential energy, and the aircrfat engines can deliver more energy to aircraft to cope with the windshear devil, hence the flight is safe.

When H0 is very small ( H0 < H2), the aircraft will land before the windshear gains enough energy to jeopardize the flight, since the effect of windshear on flight is a time integrated process.

Since the airborne radar or infrared windshear detecting system can only detect longitudinal or vertical windshear component, it's necessary to study the differences and relationships between the horizontal and vertical windshear toaircrfat performance deterioration parameter J2.

Fig 3. shows the computation results for stick fixed and autopilot situations respectively.

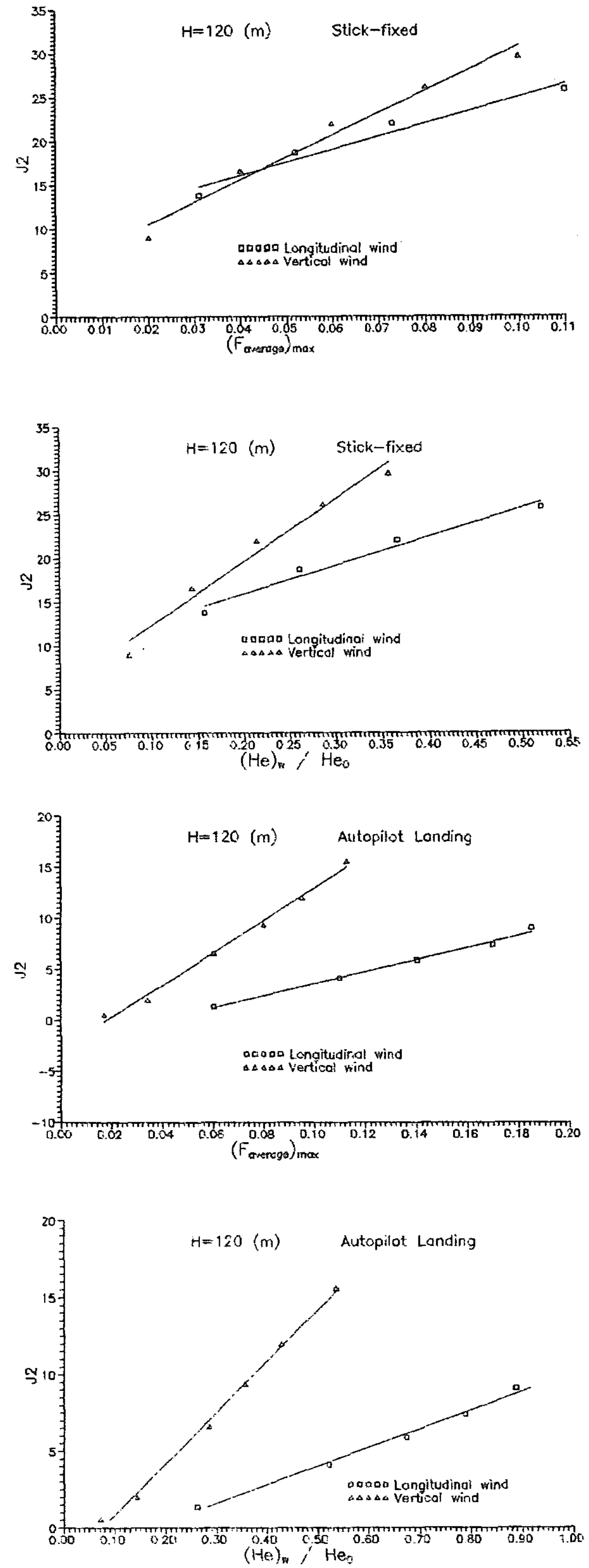



Fig 3

In Fig 3, $(He)_w$ is the total energy height loss that the windshear field will impact on aircraft on it's nominal glide path.
$(He)_0$ is the initial energy height of aircraft when it meets the windshear field.

$$He_0 = H_0 + \frac{V^2}{2g}$$

It's easy to find the fact from Fig 3 that under the same energy height loss situations, the flight situation is worse for vertical windshear than horizontal windshear. This hints that the energy height loss only isn't a good discriminant for judging the risk of windshear.

We see that for both situations, the vertical windshear poses much more risk as compared to the horizontal windshear with the same intensity $\bar{F}$.
and

$$\frac{\partial J2}{\partial \bar{F}_v} > \frac{\partial J2}{\partial \bar{F}_H} \qquad (14)$$

This suggests the following expression:

$$J2 = J2_0 + k\,\bar{F}_H + \bar{F}_v, \quad k < 1 \qquad (15)$$

where

$\bar{F}_H$, $\bar{F}_V$ are average horizontal and vertical windshear intensity over a certain distance.

From (13), we find that J2 is approximately determined by DF, where

$$DF = -\Delta\gamma - \frac{\Delta V}{(V_{ref} - V_r)}\,\frac{0.7}{57.3} \qquad (16)$$

Since vertical windshear has much effect on $\Delta\gamma$, and horizontal on $\Delta V$, a bold assumption is made as follows:

$$\Delta\gamma \approx -\frac{W_{wg}}{V} + 2g\int_0^{Td}\frac{\Delta V}{V^2}\,dt$$
$$\Delta V \approx -\dot{U}_{wg}\,t \qquad (17)$$

i.e.

$$DF = \frac{W_{wg}}{V} + \left(\frac{gTd}{V}\right)^2 \frac{\dot{U}_{wg}}{g} \qquad (18)$$

Thus, average over the distance $\Delta X$, we get:

$$\overline{DF} = \bar{F}_v + K\,\bar{F}_H \qquad (19)$$

$$K = \left(\frac{gTd}{V}\right)^2 \qquad (20)$$

Fig 4. gives the hazard map for Airbus-300A aircraft autopilot landing situation.

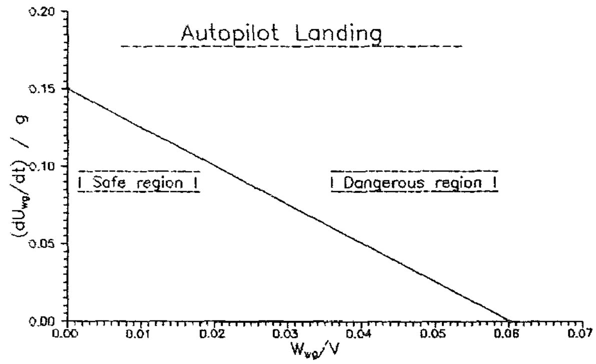



**Fig 4**

Fig 5 shows the correlationship of the hazard criterion $\overline{DF}$ and the performance deterioration parameter J2.

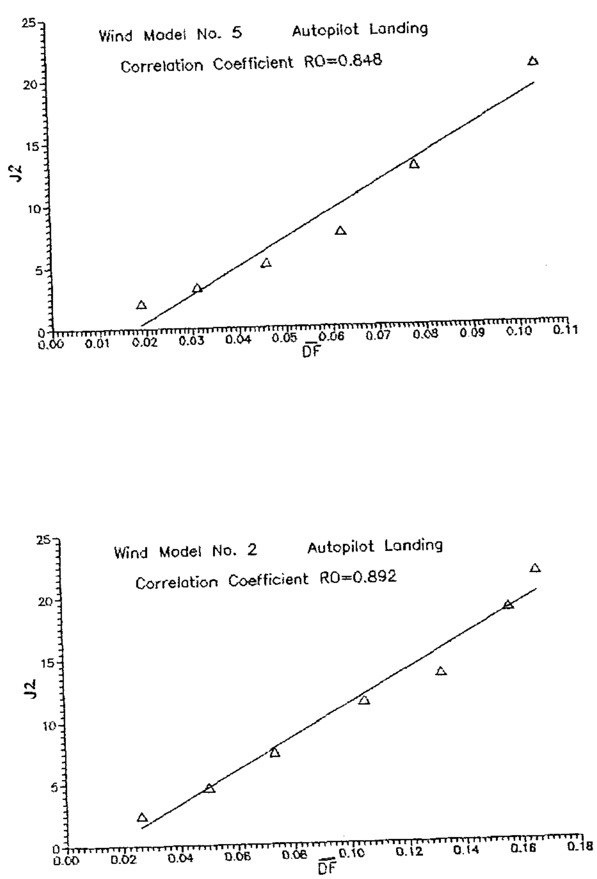



**Fig 5.**

From [6], we know that for the most hazardous windshear--microburst, the vertical velocity Wwg can be represented by the following expression:

$$W_{wg} = (SF)\left(\frac{\partial U_{wg}}{\partial X} + \frac{U_{wg}}{R}\right) \qquad (21)$$

$$SF = 27. - 0.341H + 0.00403H^2 \qquad (22)$$

where R is the radius of the point concerned from the core of the microburst.

Since neither the infrared or radar system can not measure R accurately, we consider the most dangerous situation of penetrating th e micro-burst through the core. Thus,

$$W_{wg} = (SF)\ 2.\ \frac{\partial U_{wg}}{\partial X} \qquad (23)$$

Thus from (11),(12),(19),(20),(22),(23), we get the windshear hazrad criterion for the predictive airborne winsdshear detecting and alerting system:

$$\frac{\Delta U_{wg}}{\Delta X} \leqslant \frac{\frac{\Delta T}{W}\left(1. - \frac{\sqrt{2}\, gTd}{\pi V_{ref}}\right) + Q}{K\frac{V_{ref}}{g} + \frac{2(SF)}{V_{ref}}} \qquad (24)$$

$$Q = \frac{\sqrt{2}\, g}{\pi V_{ref}^2}\left[0.4H_0 + 30. - 0.4747\left(\frac{V_{ref}}{10.}\right)^2\right] \qquad (25)$$

## V. Summary

Several conclusions ca

paper:

1. There are two critical heights between which the windshear poses hazard to flight safety.
2. Vertical windshear poses much more danger to flight as compared to the same intensity horontal windshear.
3. The threshold of hazard windshear is a function of

4. The correlation between the hazard criterion developed in this paper DF and the performance deterioration oarameter J2 is rather good.

There are still a long way to go before we can conquer the 'air killer ', some tasks are still on our agenda:

1. Develop windshear hazard criterion directly using dBZ for radar detecting system.
2. Develop windshear hazard criterion directly using the temperature drop for infrared system.
3. Study the correlationship between the criterion and the performance deterioration parameter J2, by using much authentic and real windshear model TASS we already established
4. Study the errors dissemination to determine the accuracy of the detecting system.

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