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各種惡劣天氣下等效性 F 因子研究

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行政院國家科學委員會補助專題研究計畫 ■ 成 果 報 告
□期中進度報告

各種惡劣天氣下等效性F因子研究

計畫類別：■ 個別型計畫 □ 整合型計畫
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執行單位：淡江大學航空太空工程學系(所)

中 華 民 國 94 年 10 月 30 日

一、中文摘要

為人所週知的，某些天氣現象會對飛行安全造成相當大的危害，例如低空風切、亂流、大雨和飛機積冰等現象。本研究的目的是欲藉由低空風切危害參數F參數為媒介，對在不良天候下飛行的飛機，其性能將會出現何種程度的衰減進行瞭解。

首先，本研究將先建立三維的低空風切風場及三維的F參數，然後將其所計算出來的結果與代表亂流的T參數相加。其次將大雨和積冰情形下使用空氣動力學方程式所解算出的飛機性能衰減量，將其換算成等效的F參數，並將其與前者相加，從而得知在此種天候下飛機性能的總衰減量。在三維F參數的建立上，由於考慮到側風對飛機的影響，將採用二維的F參數加上角動量的影響，做為三維F參數之方程式；而在亂流的部分，則使用自行創造的T參數，其原理為將飛機在風場中所受到的三維加速度和角加速度變化予以非單位參數化。在大雨和飛機積冰的部分，則採用前人所建立的計算流體力學方法解析飛機的空氣動力係數，將其衰減的飛機性能計算出來，並換算出其相對應的F參數值。最後再將飛機可能遭遇的惡劣天氣現象之等效F參數和T參數相加成為FT參數，並應用新發展的FW參數，以求得在同時面對多種惡劣天氣現象下，飛機所受到的影響總合，並進而探討多種惡劣天氣存在時，單獨天氣現象對飛機所造成影響之比重。

台灣位處於世界最大海洋和最大陸塊之交界處，其天氣現象較許多國家更富有變化，近年來亦有多起因惡劣天候所造成之空難事故，故對足以威脅飛行安全之天候現象進行量化性且系統性的研究實有其必要性存在；本研究針對部分對飛機有重大影響惡劣天氣現象進行研究，以期可藉此對我國之飛行安全有所幫助，並能減少國人生命財產損失。

關鍵字：F參數、低空風切、亂流、大雨、積冰、飛機性能、飛行安全

Abstract

It is well known that some meteorological phenomenon will cause sizable danger to aviation safety, for example: low level windshear, turbulence, ice accretion and heavy rain, etc. The purpose of this research is to find out, by using existing low level windshear F-factor as the medium, the degrees of performance degradation for aircraft flying under different adverse weather conditions.

First of all, the study will set up the low level windshear 3-D wind field (including the side wind) and 3-D F-factor, then tally up the result with turbulence T-factor developed by our research group earlier. Secondly, take the aircraft performance amount calculated from heavy rain and ice accretion by using existing CFD techniques; convert it to an equivalent F-factor value. Add it with the previous result would get us the total performance amount under these weather conditions. At the end, tally up the different F-factor and T-factor values from the four adverse weather conditions that the aircraft might face, forming FT-factor

and the newly created FW-factor, which will lead to the total aircraft performance degraded values in various adverse weather conditions. It is believed that the FW-factor represents a measuring weighting parameter for each adverse weather condition, which might co-exist with each other.

Taiwan is located at the intersection of the world's largest ocean and land, which makes its meteorological phenomena full of varieties than that in many countries. In recent years, there are several accidents caused by adverse weather conditions. Therefore, it is necessary to investigate the meteorological phenomena that might be threat to aviation safety. Through the combining efforts in flight dynamics, aerodynamics, performance parameter developments, this study represents a first try in quantifying different adverse weather influences on aircraft performance degradation. It is hoped that the research results will be useful to local aviation safety community and help to eliminate some of the loss in lives and properties.

Keywords: F-factor, Low Level Windshear, Turbulence, Heavy Rain, Ice Accretion, Aircraft Performance, Aviation Safety

二、計畫緣由與目的

Since aircraft was invented in 1903, aviation accidents have been a critical chapter in the aviation history of mankind. No matter it's by early aircraft manufacturers testing to come up with better aircrafts or the tragedies happened caused by negligence of some trivial matters, accidents seem to pop up one after another since the beginning of flight era.

There are several reasons that could cause accidents, which can mainly put in three categories: human factor, mechanical malfunction and adverse weather condition. Human factor means lack of some steps of operation or not receiving enough flight related information due to negligence or carelessness. Mechanical malfunction generally refers to problems left from maintenance or aircraft designing defects that lead to the flight instability and even accident. Adverse weather condition refers to the severe weather caused by nature, which often caused the degradation of aircraft performance, and result in not being able to fly and eventually crash. The adverse weather factor has the smallest proportionate among the three, but still is the most inevitable and difficult to conquer for mankind.

Adverse weather can influence people's lives as well as aircrafts. When encountering severe weather conditions, people on the ground could evacuate or set up some proper preventing procedures to minimize the live and property damages. However, when a flying aircraft run into severe weathers, there is little chance to escape in the sky. So unless being informed earlier about the adverse weather covered area and tries to avoid it, there is no other ways to go around it. Since World War II, although great improvements in aircraft performance such as speed and range have been achieved, but because the chances of bumping into awful weathers also enhance, so naturally resulting in more aircraft accidents.

In light of the several weather-related flight accidents happened in Taiwan in last few years, this thesis will focus on the study of adverse weather conditions. Also because the varieties of many complicated weather phenomena, the study is only concentrating on four most common and influential weathers, i.e. low level windshear, turbulence, ice accretion, and heavy rain. 1.The cause of low level windshear is the downdraft from thunderstorm or rain cloud that forms close to ground, lowering down the speed and altitude of flights during taking off or landing, and could cause great danger. Comparing with other aviation safety endangering weathers, this phenomenon was not discovered until late 1970s, and is still one of the very perilous weather conditions. 2. Turbulence or gust wind is a wind field generally found in the atmosphere, which has the trait of rapid changes from minute to minute. The danger of turbulence is not about its average wind velocity, but the momentary utmost wind velocity that might cause sudden changes of flight direction, altitude, ride comfort, etc. 3. Other than induce decrease in aerodynamic performance and adds little weight to the aircraft, if the ice freezes on the leading edges of wing and control surfaces, it may cause the aircraft some unstable motion and even out of control. 4. Heavy rain generally refers to the rain shower found in thunderstorm during spring or summer. Besides lowering visualization, it may also change the airfoil upper surface shape by adhering to it and leads to degradation in aerodynamic coefficients.

Since adverse weather conditions can cause brutal damage to flight, so numerous studies have launched by experts, and the F-factor is one of the brainchildren. In 1987, Bowles proposed the idea of utilizing four physical quantities of the aircraft—horizontal and vertical relative winds, aircraft speed, and gravitational acceleration, to come up with the parametric measurement of aircraft performance during wind shear. By using this parameter, aircraft performance declination in a low level wind shear can be clearly shown and easily stated the dangers the aircraft involved at the time. The result is called "windshear hazard factor", the "F-factor". This F-factor is a parameter converted originally from aircraft speed and the ambient wind velocity, used in estimating the lost of aircraft speed and altitude when encountering low level windshear. In this study, the F-factor will be first used as a medium because of its calculable trait in estimating aircraft performance, and merges with the existing T-factor, which estimates the aircraft performance influence by turbulence, and creating a FT-factor. And since the nonlinear character of low level windshear and turbulence wind fields, later a new FW-factor has also been derived. By extending to aerodynamic degradation of heavy rain and ice accretion, these FW or FT-factors are able to give the four adverse weathers mentioned in this study an overall comparison, and in quantifying the endangering degrees to aircraft performance, the aircraft performance decayed in these four adverse weather conditions can be found.

The individual statistic records of aircraft decayed performance caused by these four adverse weathers are obtained from the results of our study group over the years. There are several studies on low level windshear flow pattern and dynamics done by Wan and his co-workers. In 2002, Wan and Huang establish a turbulence wind model, and the T-factor is set up to analyze the aircraft decayed performance and escape strategy in turbulence. In 2003, basing on Computational Fluid Dynamics (CFD), Lee and Wu each developed a method to estimate the aerodynamic degradation effects caused by ice accretion and heavy rain. But these four weather phenomena seldom exist separately by itself. For instance, low level windshear always appears with gust wind, and most likely with heavy rain; and heavy rain will always combine with turbulent gust. In this thesis an attempt has been made to consider all the "real" weathers together and measuring their degrading effects separately.

This F-factor represents a direct measure of the degradation of aircraft performance to gain specific energy due to low level windshear. The 2-D aircraft specific energy E is defined as：

$$E = h + \frac{V^2}{2g} \qquad (1)$$

where h is altitude and V is aircraft velocity. We could use this equation to derive rate of change of specific energy, and combined with appropriate aircraft equations of motion. When considering flight in vertical plane (2-D), the F-factor equation in the aircraft equations of motion and rate of change of specific energy can be accurately approximated by：

$$F = \frac{\dot{W}_x}{g} - \frac{W_h}{V} \qquad (2)$$

where W_x and W_h are the horizontal and vertical wind velocity components respectively. Note that the F-factor combines the effects of the shear ($\dot{W}_x$) and the downdraft ($-W_h$) into a single entity. Positive values of the F-factor are indicative for aircraft performance decreasing situation. It needs to be noted that in the literature, the F-factor is also often defined such that positive values imply an energy loss.

It is assumed that aircraft specific energy equals to

$$E = h + \frac{V^2}{2g} + \frac{I\omega^2}{2mg} \qquad (3)$$

where I is moment of inertia and ω is aircraft angular velocity. In the above equation, $I\omega^2 = I_{xx}\omega_x^2 + I_{yy}\omega_y^2 + I_{zz}\omega_z^2$.

If differentiated with respect to time, it leads to the following result,

$$\dot{E} = \dot{h} + \frac{V}{g}\dot{V} + \frac{I\omega}{mg}\dot{\omega} \qquad (4)$$

The above equations have the similar assumptions as before, and the 2-D F-factor equation can now be rewritten as:

$$F = \frac{T-D}{W} - \frac{\dot{E}}{V} \qquad (5)$$

A comparison of equation (4) and (5) reveals that again the F-factor can be readily interpreted as the loss or gain in available excess thrust-to-weight ratio due to the combined effect of downdraft and horizontal windshear. Note that positive values of the F-factor still indicate aircraft performance decreasing situation. Substitution of equation (4), combined with the use of Cartesian coordinates, allows the F-factor in equation (5) to be conveniently expressed

$$F = \frac{\dot{W}_x}{g} - \frac{W_h}{V} + \left(\frac{I_{xx}P\dot{P}}{mgV} + \frac{I_{yy}Q\dot{Q}}{mgV} + \frac{I_{zz}R\dot{R}}{mgV} \right) \qquad (5)$$

In this study I would implement two wind field factors, namely, the existing low level windshear F-factor; and T-factor developed by our group for turbulence. Now this 3-D F-factor equation can be used in conjunction with the T-factor equation as shown in below.

Earlier Chen and Huang both studied clear air turbulence in their thesis, and established wind field models for aircraft encountering turbulence. They also set up the T-factor that is used to analyze the linear and angular responses of aircraft in clear air turbulence. The following set of turbulence prediction parameters has been proposed to quantify the 3-D wind input severity (T_1), the aircraft linear response (T_2), and aircraft angular response (T_3).

Here we first extend the concepts to include the general turbulence, use T_1 to verify the turbulence intensity, and let T_1 as input to compute the flight path and the responses T_2, T_3.

$$T_1 = \sum_{i=1}^{3} \left| \frac{\dot{W}_i}{g} \right|$$
$$T_2 = \sum_{i=1}^{3} \left| \frac{\dot{V}_i}{g} \right| \qquad (6)$$
$$T_3 = \sum_{i=1}^{3} \left| \frac{\dot{\omega}_i l_i}{g} \right|$$

where $\dot{W}_i$ is wind acceleration, $\dot{V}_i$ is aircraft acceleration, $\dot{\omega}_i$ is the aircraft angular acceleration, and l_i is the characteristic length of Boeing 747-200 aircraft in three directions, which was defined as below:

Pitch: Distance from center of gravity to aerodynamic center of horizontal tail, about 100 feet.

Roll: Distance between two aerodynamic centers of right and left wing's mean aerodynamic chord, about 83.33 feet.

Yaw: Distance from center of gravity to aerodynamic center of vertical tail, about 100 feet.

The idea of these parameters is that we have to consider the atmospheric turbulence in all three directions, and include its response both in linear and angular motions. But what it matter the most is the force (acceleration) rather than momentum (velocity). Finally, we need to non-dimensional all these physical quantities.

Fig.1 and 2 are the real F-factor illustrations for 1985 Delta Airlines 191 low level windshear related accident. And it is clearly shown that the F-factor value of a real low level windshear will fluctuate with time, which indicates that wind is formed by both the average and gust winds. If the aircraft performance loss from the low level windshear effect shall be quantified, obvious it's not enough either by using the F-factor from low level windshear mean velocity or T-factor from a pure turbulence. Therefore, these two sets of quantified parameters F and T shall combine together, hoping that the new parameter will be physically more complete.

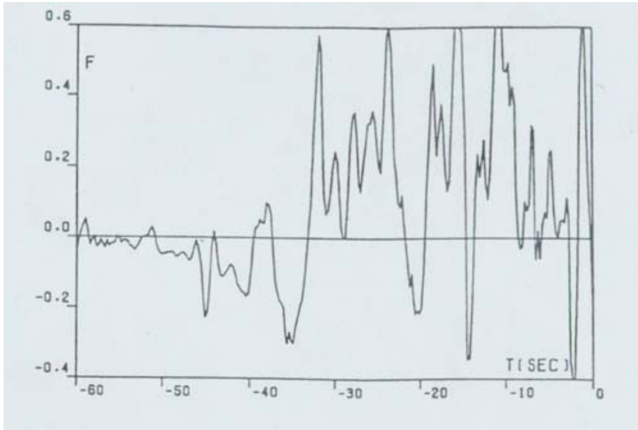

Figure 1 Instantaneous F-factor for Delta flight 191.

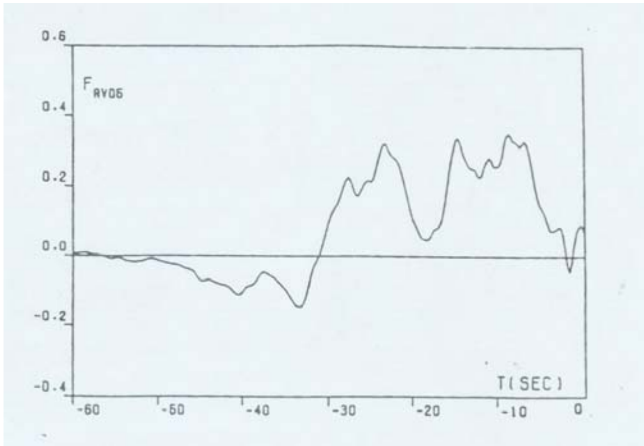

Figure 2 Averaged F-factor for Delta flight 191.

If linearly combine the T-factor with the F-factor and come up with the FT-factor equation:

$$FT = \frac{\dot{W}_x}{g} - \frac{W_h}{V} + \left(\frac{I_{xx} P \dot{P}}{mgV} + \frac{I_{yy} Q \dot{Q}}{mgV} + \frac{I_{zz} R \dot{R}}{mgV} \right) + \left(T_2 + T_3 \right) \tag{7}$$

Here is something that needs special attention: above equation is the conjunction of the T-factor and F-factor, thus include both low level windshear and turbulence impacts to aircraft. However there might be some overlapping on the RHS terms, and here we use mainly as a first try and for later comparison with the FW-factor.

Equation (7) can be analyzed as follows:

1. $\frac{\dot{W}_x}{g} - \frac{W_h}{V}$ is an element in the original 2-D F-factor calculation.
2. $\left(\frac{I_{xx} P \dot{P}}{mgV} + \frac{I_{yy} Q \dot{Q}}{mgV} + \frac{I_{zz} R \dot{R}}{mgV} \right)$ is the item that mainly represents the changes of pitching , rolling, and yawing moments after the aircraft being influenced by the wind field velocity.
3. Parameter T_2 represents the aircraft acceleration in longitudinal, lateral, and vertical directions.
4. Parameter T_3 represents the aircraft angular acceleration in pitching, rolling, and yawing directions.

So what we did is first modify the original 2-D F-factor by including the rotational kinetic energy part, then directly adds the aircraft responses in linear and angular directions due to turbulence.

In last section we simply adds 3-D F-factor and the T_2 , T_3 parts of turbulence T-factor together, to come up with FT-factor, but this might exaggerate the degraded value of aircraft performance loss in bad weather. The reason is although different in expressions, but physically there might be some repetitions in F-factor and T_2 (aircraft linear response), T_3 (aircraft angular response) equations. So if the wind field is in the most extreme situation then the resulting FT-factor may larger than expected, representing a somewhat unreal aircraft performance loss in severe windshear/turbulence condition. To compensate this, better expression is also needed.

Most recently, we try to get back to the original assumption and definition of F-factor equation,

$$F = \frac{\dot{W}_x}{g} - \frac{W_h}{V} = \frac{T - D}{W} - \frac{\dot{E}}{V}$$

In here we learn that F-factor equation can be expressed in two forms, and the second type is adopted here. As before, assuming 3-D aircraft specific energy is equal to the summation of potential energy, linear kinetic energy and rotating kinetic energy. Then this aircraft specific energy will be:

$$E = h + \frac{V^2}{2g} + \frac{I\omega^2}{2mg}$$

Again if differentiated with respected to time, it leads to the following result,

$$\dot{E} = \dot{h} + \frac{V}{g}\dot{V} + \frac{I\omega}{mg}\dot{\omega}$$

Comparison of the above reveals that the

F-factor can be writing as

$$F = \frac{T-D}{W} - \frac{1}{V}\left(\dot{h} + \frac{V}{g}\dot{V} + \frac{I\omega}{mg}\dot{\omega}\right) \quad (8)$$

Reorganizing a new expression can be achieved:

$$FW = \frac{T-D}{W} - \frac{W_h}{V} - \frac{\dot{V}}{g} - \frac{I_{xx}p\,\dot{p}}{mgV} - \frac{I_{yy}q\,\dot{q}}{mgV} - \frac{I_{zz}r\,\dot{r}}{mgV} \quad (9)$$

Where W is weight, T is thrust, D is drag, W_h is vertical wind velocity, and V is aircraft velocity. To distinguish the difference, this new expression is named FW-factor. As in FT-factor, this FW-factor also includes the linear and angular responses of aircraft under a 3-D wind field, but mean velocity of low level winshear and fluctuated velocity of turbulence are considered at the same time. Also, the non-dimensional excess thrust is also included. Compared with FT-factor, it is believed that the new FW-factor is physically more meaningful and can represent a true degree of aircraft performance degradation in four kinds of bad weathers considered in this thesis.

The calculation methods and related formula mentioned in this chapter were set up by Lee and Wu in 2003, aiming to solve for the aircraft performance loss in ice accretion and heavy rain conditions. Through the existing rate of climb vs. F-factor plot under heavy rain condition, we can implement their aerodynamic performance degradation results, then the equivalent F-factor of aircraft performance degradation under ice accretion and heavy rain conditions can be estimated. Their CFD numerical techniques will be discussed briefly as follows:

This research use CFD program code consists of a modified Bowyer's grid generator and a Navier-Stokes finite volume flow solver. Bowyer's scheme is a Delanuey-type unstructured grid concept, and the modifications made including: 1. boundary vertex check to distinguish point in or out of the circle in the "circle test" criterion, 2. Laplacian smoothing to further improve the quality of triangles by adjusting the "spring constant" in each of the triangle branch, 3. addition of local point for those convex region in order to overcome the inherent nature of Delanuey-type unstructured grid generator.

The new triangles generated by circle test should tally with two limitation conditions:

1. The aspect ratio of all triangles must less than 1.45.

2. The area of all triangles should great than the definition of minimum area.

Where aspect ratio equal to $R/_{2r}$, R is the radius of circumscribe circle, and r is the radius of inner circle. The definition of smallest area means in any given triangular boundary, we choose the smallest boundary constitute the right triangular area. Owing to our triangular unstructured grids, we choose finite volume form to solve Navier-Stokes equation. The solver is the classical Roe's average scheme on the Navier-Stokes equation, and then Runge-Kutta fourth order method is implemented to accelerate convergence rate.

Finite volume form can easily use on arbitrary sharp grids, so this research use finite volume form to solve triangular unstructured grids. All triangles must tally with mass, momentum, and energy conservations, then save conservative variable average values in interior of triangles. Because our unstructured grids are triangles, so when solving the numerical flux or conservative variable, we should transfer Cartesian coordinate into normal and shear coordinates. Finally, the conservative variable values that stored in interior of triangles should transfer into each node.

Around computation region's boundary, a virtual grid layer must be added to deal with boundary condition. It can be divided into two parts, inner boundary and outer boundary. When solving the outer boundary problems, the chose of outer boundary must be large enough. For the time being the outer boundary condition can view as infinity.

For ice accretion flow analysis, we select a control volume composed of product of velocity and time (X-direction), and twice the airfoil thickness (Y-direction). For our unstructured grids, a physical quantity transformation to Cartesian coordinate is necessary, so that U, V components of velocity field in each control volume can be derived. First we uniformly cut the Y-direction into N segments, and then select each grid point location (X, Y) and U, V components inside a certain control volume. By analogy, we can find the U, V velocity components of every segmented point in the control volume. Fig. 3 shows the flow field linear analysis results of a NACA 0012 airfoil.

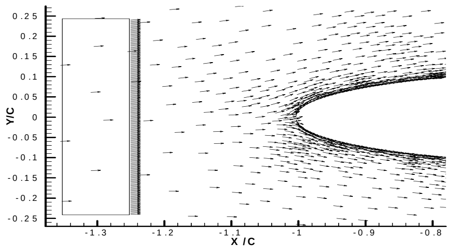

Figure 3 Flow field linear analysis in control volume (NACA 0012 M = 0.3, α= 4°).

First, when the rainfall rate remaining increase, the air density will also increase. Generally rainfall's intensity is measured in terms of the Liquid Water Content (LWC) of the air or the mass of the water per unit volume of air. According to the equation developed by Dunham in 1987, the relation between rainfall rate (R, mm/h) and LWC (g/m^3) is

$$LWC = 0.054R^{0.84} \qquad (10)$$

We found the air density added with this

LWC will become our new density in the air when suffering the heavy rain.

$$\rho_r = \rho_{air} / \{ 1 - (LWC / \rho_{water}) \} \quad (11)$$

Secondly, the downward rainfall changes the angle of attack, and we should know what the terminal velocity of a raindrop is. The terminal velocity of a raindrop can be expressed as a function of droplet size & altitude and has been established by Markowitz.

$$V_T(m/s) = 9.58\left\{1-\exp\left[-\left(\frac{D(mm)}{1.77}\right)^{1.147}\right]\right\} \quad (12)$$

Therefore, we could combine the vertical velocity from heavy rain and the horizontal cruise velocity to obtain new velocity vector with a small angle, thus this decreased value of angle of attack could be estimated.

Most important is the effect done by this new airfoil upper surface shape that formed by heavy rain's water layer, and the cratering effect impacted by large droplets. Obviously the original aerodynamic property will degrade by this new airfoil shape. Finally we could establish the database about water-film formed on airfoil. According to this database, we can find the water-film location on airfoil upper surface, and then combined the new density and angle of attack changed by downfall heavy rain momentum. Through the same numerical schemes we now can easily simulate the aircraft performance degradation under the heavy rain condition.

三、結果與討論

The estimation method and figure of the equivalent F-factors of every single adverse weather condition have been thoroughly discussed in the earlier sections. They will be gathered in Table 1, which shows the F-factor, T-factor, FT-factor, or FW-factor of every adverse weather conditions.

In the table 1, one find out that the equivalent F-factor of heavy rain and ice accretion is about 25~30% of low level windshear F-factor. The result implies that low level windshear has more influence on aircraft performance than heavy rain or ice accretion does. And the T-factor that represents turbulence has more influence on aircraft performance than low level windshear does to it. But while considering the effects of adverse weather condition to aircraft performances, the time scale has to be considered, that is to say the duration has to be judged. As to the duration of the previous four adverse weather conditions, from the longest to the shortest are ice accretion, low level windshear, heavy rain, and turbulence. Even though from the figure, it seems turbulence has the most effect on aircraft performance, but the timeframe is shorter and it could only create damage in that short period. As to heavy rain and ice accretion, even though the equivalent F-factor is smaller, but the time duration is longer, therefore the time that will influence aircraft performance will also be longer. So the danger could be even more serious than what it involves in turbulence. But looking from a different angle, it also means that the danger can be avoided if precautionary steps are taken in the earlier stage.

Also, one can tell that along these five adverse weather conditions in the list, which are all considered as compound adverse weather conditions, the sum of FT-factor value appears to be larger. When analyzing each adverse weather individually, one can find that whenever there's heavy rain or ice accretion involves, its equivalent F-factor will only be 10~15% of FT-factor. It shows that if the influencing timeframe is the same, wind will have more direct degrading effect toward aircraft performance, and it will reflected on larger F-factor or T-factor value. At this time, heavy rain and ice accretion will be like the last straw that hammers the camel, making the already declined aircraft performance even worse. As to the FW-factor value, it is the most sensible parameter developed in this work, ranging from 25% to 50 % of FT-factor value.

At last, what makes people fear the most is that the influence of heavy rain and ice accretion toward aircraft is not direct. So when confronting with compound adverse weather conditions, the pilot will often only notice the effect from low level windshear and turbulence wind, but the influence from heavy rain or ice accretion are often ignored or underestimated. This might lead to the case that the pilots wrongly judge the circumstance and believe that the aircraft is still in manageable situation, but eventually crashes.

	Adverse Weather Conditions		F-factor	T-factor	FT-factor	FW-factor
Case1	Low Level Windshear	Steady	-0.058~0.65	N/A	N/A	0.27~0.91
		Unsteady	-0.042~0.62	N/A	N/A	0.2847~1.05
Case2	Turbulence		N/A	0.0735~1.164*[1]	N/A	0.24~0.45
Case3	Heavy Rain		0.15	N/A	N/A	0.15
Case4	Ice Accretion		0.14~0.15	N/A	N/A	0.14~0.15
Case5	Low Level Windshear*[2] and Turbulence		-0.92~2.64	0.09~9.025*[3]	-0.552~11.17	0.11~1.32
Case6	Low Level Windshear*[2] and Heavy Rain		0.108~0.77*[4]	N/A	N/A	0.4347~1.2
Case7	Turbulence and Heavy Rain		0.15	0.0735~1.164*[5]	0.2235~1.314	0.39~0.6
Case8	Turbulence and Ice		0.14~0.15	0.0735~	0.2135~1.31	0.38~0.6

	Accretion		1.164*5	4	
Case9	Low Level Windshear*2, Turbulence and Heavy Rain	-0.77~2.79*6	0.09~9.025*3	-0.402~11.32	0.26~1.47

Table 1 F-factor, T-factor,

*1 T-factor equal to T2+T3, T2:0.045~1.145, T3:0.018~7.92.

*2 The wind field use unsteady low level windshear.

*3T-factor equal to T2+T3, T2:0.045~1.145, T3:0.018~7.92.

*4F-factor equal to low level windshear+ heavy rain, low level windshear:-0.042~0.62, heavy rain: 0.15.

*5T-factor equal to T2+T3, T2:0.015~0.375, T3:0.006~1.01.

*6F-factor equal to low level windshear+ heavy rain, low level windshear:-0.92~2.64, heavy rain: 0.15.

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