AERODYNAMIC ANALYSIS UNDER INFLUENCE OF HEAVY RAIN

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Abstract

The detrimental effects of meteorological phenomenon such as wind shear, thunderstorm, ice/snow etc, to aviation safety are relatively well known. But aerodynamic influences due to heavy rain are still the on-going research subject. This paper first reviewed some research finding of heavy rain effects on aerodynamic performance degradation. Then a computational method to compute the two-dimensional heavy rain condition is introduced and the effects of droplet cratering, liquid water content, droplet terminal velocity, air density modification are included. It is felt that the quantitative information gained in this work could be useful to the operational airline industry, and greater effort should put in this direction to further improve aviation safety.

1 Introduction

Among numerous factors that influence the aircraft during take-off and landing, these serious factors include crosswind, low level wind shear, heavy rain, runway incursion, runway accumulated water or ice, bird-strike, etc. During these phases of flight, accidents happen most frequently, since at that time the aircraft's velocity and altitude are not enough to safely operate, therefore the pilot operation is in vain to avoid the on coming disaster. More often, it didn't have the time to take any action because the incident was happened so quickly. Due to this reason, we shall pay more attention to how the flight environment can influence aircraft performance during the take-off and landing phase.

Among all the aviation accident or incidents, although the weather hazard factor is not the main cause, but it is the hazard factor that people want to know most about aviation safety. In last twenty years, after put in a great quantity of efforts and resources in studying aviation weather phenomenon, we have begin to understand and grasp the physics of weather, produced operation procedure, even more, to develop several airborne devices and flight plans to avoid/decrease the severe weather damage. But as the air transport increase, the aircraft incident or flight quality degradation still can be heard, representing the most concerned issue of the general public.

Recently, FAA concluded a new plan to ease air traffic congestion, its plan focuses on the four critical problems: arrival and departure rates; en route congestion; the effects of bad weather on airport operations; and severe weather en route [1]. The concern about airport bad weather is with good reasons: among all the contributing factors of aviation accidents, meteorological effect accounts for about ten to fifteen percents of accident causes. Although it is not the most influential factor to cause airliner aircraft to crash, meteorological phenomenon remains the least understood and controllable factor. But gradually, we begin to realize the fundamental physics of such phenomena as low level wind shear, fog, hail, thunderstorm, lightning, tornado, clear air turbulence, etc.

Through the combining efforts in weather forecast, radar technology, data communication, and pilot training awareness, aviation accidents due to these phenomena have decrease drastically in last decade. On the other hand, the adverse efforts of gust wind and heavy rain on aircraft performance and aerodynamic efficiency remain somewhat unclear and even contradictory, and new research results are still reporting from aviation research institutes or universities. The purpose of this paper is first to review the latest findings in this area, and through a new analytical method to compute the aerodynamic degradation effects in heavy rain condition, it is hoped that a general conclusion can be reached. Most important is that these scientific results should pass on to the aviation community, and plays its role at some decisive moments.

2 Heavy Rain Simulation

Generally speaking, the effects of heavy rain on aircraft performance degradation are the tire frictional coefficient, the wing aerodynamic coefficients, and engine thrust level. If the accumulated water on runway is over 3mm thick, then aircraft might encounter the so-called hydroplaning phenomenon during take-off or landing. Hydroplaning is due to the decrease in tire frictional coefficient and air cushion effect on wet runway, and leads to the aircraft sliding motion, thus drastically increase the required field length during take-off/landing. There are 3 different kinds of hydroplaning phenomena: viscous type, dynamic type, and rubber reversion type, all three are relatively well known to the aviation community. According to author's estimation: aircraft tire's frictional coefficient value is about 0.71 on dry runway, and this value can go down to 0.3 (high speed) or 0.4 (low speed) on wet runway. In other words, pilots should always be aware of the potential danger of wet runways on aircraft's take-off / landing- performance.

In 1983, The UDRI study [2] analyzed the aerodynamic penalties of heavy rain on landing aircrafts. Torrential rainfall rates of 100, 500, 2000mm/hr were investigated, results show that significant momentum loss was found to occur at moderate and higher rainfall rates. The weight of water film on transport aircraft was found to be only a small fraction of landing weight. Roughness of an airfoil in rain is caused by drop cratering and by waviness to a thin film on the airfoil and fuselage. Both sources of roughness were found to separately produce drag increase of 5 to 10% for a 100mm/hr rain, and increasing to 15 to 25% for a 2000mm/hr rain. In addition, lift decreases of 10% for a 100mm/hr rain to more than 30% for a 2000mm/hr rain were estimated, and stall angle of attack for a roughened (wet) airfoil is from 2 to 6 deg less than that for a clean airfoil. Most importantly, all these events will happen without the notice of pilot or flight warning device.

To further investigate the heavy rain effect, Hansman et.al. [3] conducted experiments on three different airfoils at 1000mm/hr rain rate. They reported that at low angles of attack, the lift degradation in wet conditions varied significantly between the airfoils. The Wortmann airfoil had the greatest lift degradation (~25%) and the NACA 64-210 airfoil had the least (5%). At high angles of attack, the NACA 64-210 and NACA 0012 airfoils were observed to have improved aerodynamic performance in rain conditions due to a reduction of boundary-layer separation. Obviously, heavy rain effects on aircraft differ at different angle of attack.

In the spring of 1989, NASA began to field test the heavy rain effects on transport aircraft. [4] The findings revealed that under a rainfall rate of 100-1000 mm/hr, a reduction in maximum lift of 7-29%, with stall angle of attack decreasing from 1-5 deg, and a drag increase of 2-5% are observed. Evidence also shows that rainfall can affect pitch trim stability of canard-equipped aircraft. More recently, RPI study [5] quantify the behavior of a wing in light to moderate rain and showed that the degradation of aerodynamic performance caused by rain depends on the location of rivulet formation and on the diameter of these rivulets. Drag forces increase with increasing diameter of rivulets, and lift forces decrease with a longer film convection region. Since 1990, there have been at least 10 known incidents where jet aircraft have experienced loss of thrust in one or more turbofan engines while maneuvering in the anvil region near the central core of a thunderstorm [6]. This uncommanded thrust reduction is called engine rollback, and may be associated with ingestion of high mass concentrations of ice particles, snow, and possibly small concentrations of supercooled liquid water in the anvil region.

Research on engine rollback phenomenon is still under investigation. In 1995, J. R. Valentine and R. A. Decker [7] tried to solve the same problem numerically. Two major mechanisms have been hypothesized as contributing to the performance loss: (1) an uneven water film effectively roughens the airfoil surface and (2) splash back droplets from raindrop impacts are accelerated by air flow field, de-energizing the boundary layer and leaving it more susceptible to separation. A Lagrangian particle tracking algorithm for a general body-fitted co-ordinate system has been developed and linked with a thin layer incompressible Navier-Stokes code. Also established the rain model that enter the computational domain from discrete location around boundary, and a splash back model has been proposed. Particles are tracked through the two dimensional, incompressible airflow field around a NACA 64-210 airfoil section.

3 Current Method

Previously, the first author and co-workers have developed a 2-D CFD code [8],[9] consists of a modified Bowyer's grid generator and a Navier-Stokes finite volume flow solver. Bowyer's scheme is a point adding method. It produces the boundary points first, namely, inner boundary and outer boundary points. Then using these points and circle test to generate the initial grids, after that new grids will added to the center of circumscribed circle of triangles that do not conform our specified conditions, and delete the triangles that do not conform the circle criterion. Then find the usable edges outward, and delete the edges and triangles that do not conform our conditions, thus, we can locally regenerate new triangles. The triangles that are produced by circle test must all satisfy one of the following two limitations: 1. All aspect ratios of triangles are smaller than a certain value (i.e. 1.5). 2. All triangle areas are larger than some prescribed small area. Where the prescribed small area is the area of equilateral triangle that is constituted by the small edges.

This Bowyer scheme grid generation has been modified and used extensively by first author, the modifications are: 1. Boundary vertex check to distinguish points inside or outside of the "circle". 2. Laplacian smoothing in order to improve the quality of triangles by adjusting the "spring constant" in each of the triangle branch. 3. Local refinement by adding points or regenerating grids within a locally confined region. 4. Addition of local point for those convex region in order to overcome the inherent nature of Delaurey-type unstructured grid generator. Due to the enhancement of PC performance in recent years, the aspect ratio limitation is defined as AR $\leqq$ 1.4 except for those smallest area triangles. Aspect ratio is shown in Fig. 1.

The flow solver is the Roe's scheme on the classical Navier-Stokes equation, with no heat flux considered. This governing equation is finite volume form is

$$\frac{\partial}{\partial_t}\int\oint_{\Omega} Q d\Omega + \oint_s \overline{F_I} \bullet \hat{n} dS = \oint_s \overline{F_V} \bullet \hat{n} dS \qquad (1)$$

This equation is further discretized in finite volume form and applied to every triangular grid. To increase the convergence rate, the 4th order Runge-Kutta time stepping is also implemented.

When the aircraft suffering heavy rain in the air, the aircraft performance will be lose greatly. According to this phenomenon, we need to understand what happened to the whole airplane, then, we should simulate this hazard factor on the airfoil directly. First, when the rainfall rate increase the air density will also increase. In experimental simulations, 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. The relation between rainfall rate (R, mm/h) to LWC (g/m3) is determined as (Dunham 1987)[11].

$$LWC = 0.054R^{0.84} \qquad (2)$$

We find the air density plus LWC will become our new air density for the heavy rain case. Secondly, the downward rainfall will change the angle of attack, and it is entirely determined by the raindrop terminal velocity. The terminal velocity of raindrop is a function of droplet size and altitude and has been established by Markowitz[12]. Because our simulation is in take-off or landing phases, so at low altitude the droplet velocities are assumed to be terminal velocity,

$$V_T\,(m/s) = 9.58\left\{1 - \exp\left[-\left(\frac{D\,(mm)}{1.77}\right)^{1.147}\right]\right\} \qquad (3)$$

For large droplet size, for instance D=6mm, the terminal velocity is 9.4 m/s. Thus, we can use combination of vertical and horizontal momentum vector to estimate the decrease value of angle of attack. In addition, a database of the water-film location on the airfoil or wings has been established. Using this database, we can easily find the water-film location on airfoil, and choose water-film as needed, then combining the LWC and AOA changed by heavy rain momentum. So we can easily simulate the aircraft performance loss in heavy rain situation. Finally, the flow solver should be modified to simulate our heavy rain case. The modifications are as follow:

1. A droplet trajectory algorithm is implemented in both the horizontal direction (flight speed transform into total droplet mass in the horizontal control volume) and the vertical direction (torrential rainfall rate transform into total droplet mass in the vertical control volume), and the summation of the two will account for the droplet mass accumulated on the airfoil upper surface, i.e. the water layer thickness on the wing surface.
2. The “ cratering effect “ on this water layer is artificially simulated through the re-generation of surface grids. These upper surface grids are now moved to the top of water layer surface, and finer but irregular triangular grids are intentionally created to closely resemble the surface roughness in this cratering layer.
3. The velocity and air density and air density should include the influences of torrential rainfall induced vertical velocity and mass flow rate.

4 Results and Discussion

The idea of solving heavy rain effects has recently being proposed by the authors, and some preliminary works have been done and results seem encouraging. The quality of computational grids that generated by our code is good, which can solve the flow and converge at precise value. Moreover, the tendency of Cl and Cd coefficients are similar to Fig.2 and Fig.3 of Ref. [7], which is also for NACA 64-210 airfoil. Our Cl and Cd coefficients have some difference with Ref. [7]. Besides the difference in grid resolution, one of the reason is that our airfoil at Reynolds number of 9×10^6 and the Ref. [7] at Reynolds number of 3.4×10^6.

It is very important to choose our simulation model. Since 1980s, the papers studying about heavy rain effect on airplane were very few. The reason is it’s rather difficult to simulate heavy rain on airfoil, and it needs to investigate the possible properties change when heavy rain happened. These possible properties include density, velocity, pressure, sonic speed, droplets impact angle, rain model, etc, so we must consider all these factors. The airfoil sections chose by most researchers were NACA4412, NACA64-210, NACA0012, etc. According to the usefulness we choose clean NACA64-210, NACA64-210 with flap and NACA4412 as our simulation models, as shown in Fig.4. Also shown in Fig.5 and 6 are the NACA 64-210 airfoil combined with flap, and it seem have good grid resolution and flow pattern.

Table 1 is the seven cases considered in this work, including two high lift devise cases. Fig.7 and Fig.9 are the relationships about lift coefficient vs. angle of attacks, we can see clearly that when the angle of attack equals to zero, the lift coefficient in rain condition is slightly larger than the no rain condition. This is because that the water film forms at airfoil upper surface lead to a more camber airfoil surface and re-smooth again at zero angle of attack, thus the lift coefficient will increase. When the angle of attack increases, the water film gathered on airfoil surface become thicker and rougher, so the lift coefficient decrease. Yet, the stall angle of attack will decreased by water film and flow field. It is because the raindrops has downward terminal velocity, and brings surrounding airflow with it, so the angle of attack will decrease by this airflow. Fig.8 and Fig.10 are the drag coefficients vs. angle of attacks. Compared with no rain condition, when the angle of attack increase the drag will increase more in rain condition.

Finally, all aerodynamic performance results of the seven cases are summed up in Table 2, and it seems that while high speed cruise (case 3) and small LWC cases have little lift/drag degradation effect in rain condition, it is the high lift device configuration that suffer the least in stall angle of attack under heavy rain. Also shown in Fig.11 to Fig.14 are the causes of some of the lift and drag coefficients degradation, while velocity and density modifications account for about one to twelve percent, obviously it is the water film shape (or cratering effect) that influence the most in aerodynamic efficiency.

5 Conclusion

Currently, we can get satisfactory results of aerodynamic performance loss when encountering heavy rain, but we can conclude in several aspects:

1. The aerodynamic degradation effect is mainly due to water film and the cratering effects.
2. The rain penalty is less severe for cruising speed, low liquid water content situation, and in stall angle of attack decrease.
3. A better rain model can be established. According to this rain model we can simulate any airfoil section in rain conditions.
4. We should develop the three dimensional wing models to tally with the real situation.
5. In order to get high turn-around results, we shall construct PC Cluster system to enhance our computational efficiency and save computer time.
6. When heavy rain condition happens, it is often accompany the gust wind. So we can add the gust wind hazardous factors to our simulation, this will more closely represent the real conditions.

Although the heavy rain is not the main hazard factor for weather, but still the aircraft performance loss caused by it is very astonishing in very short period. In the future, we plan to investigate the local real cases under the heavy rain and compare with our simulation. If the results are in agreement, then we can offer our technology to the pilot of airline company, Aviation Safety Council, research center of FAA, etc. to prevent future incident or accident to happen under the adverse effects of heavy rain.

Acknowledgment

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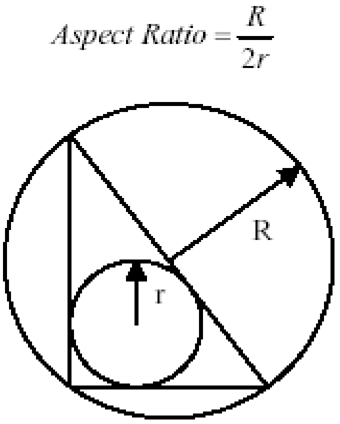

Fig. 1 Definition of aspect ratio.

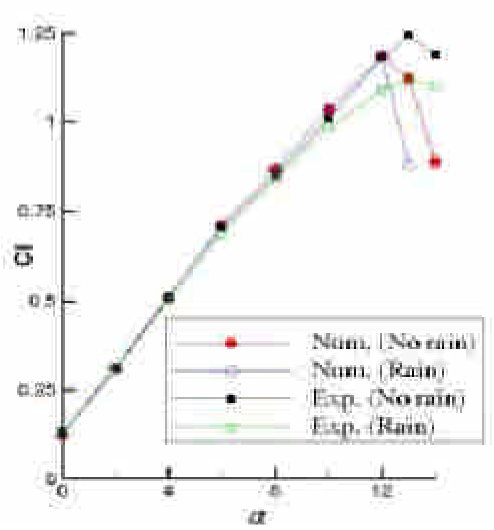

Fig. 2 C_l coefficients vs. angle of attack Ref.[7]

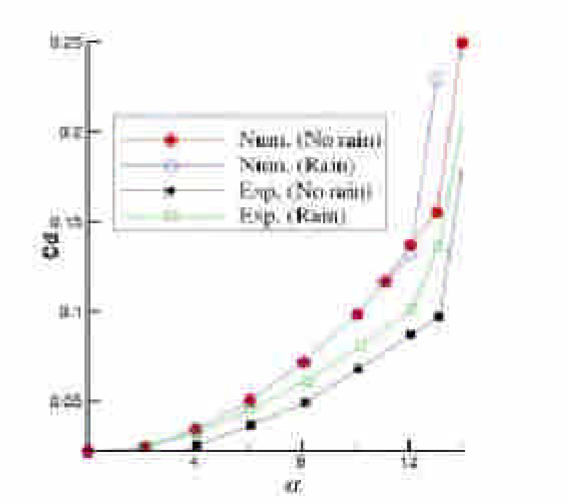

Fig. 3 C_d coefficients vs. angle of attack Ref.[7]

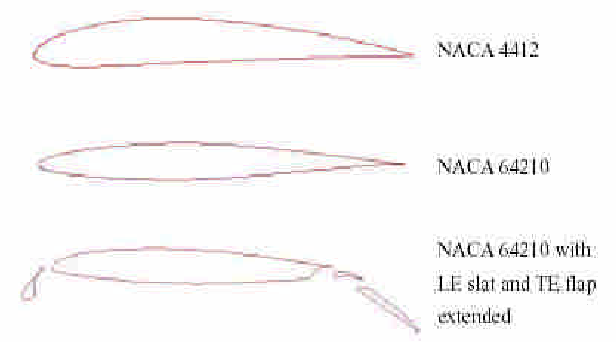

Fig. 4 Profile of airfoil models

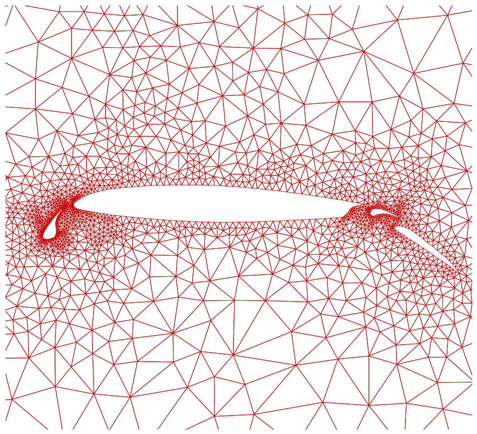

Fig. 5 NACA64210 with flap close grids

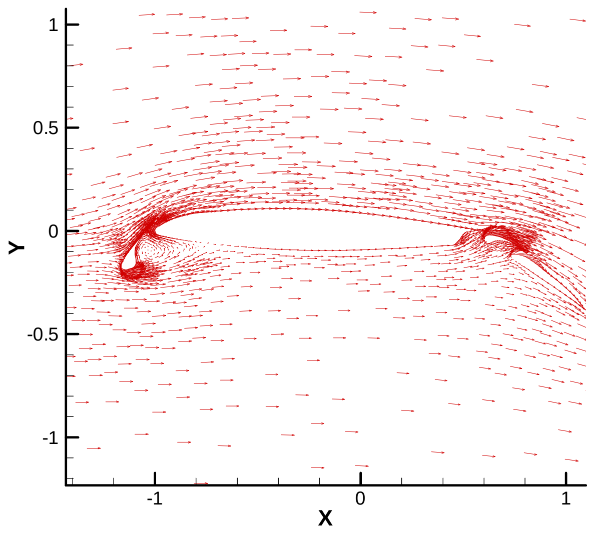

Fig. 6 NACA 64210 high lift device velocity profile at α=0°

Case	Airfoil Model	Mach Number	LWC (g/m^3)
1	NACA64-210	0.2	30
2	NACA64-210	0.2	3.23
3	NACA64-210	0.8	30
4	NACA4412	0.2	30
5	NACA4412	0.2	3.23
6	NACA64-210 with high-lift device	0.2	30
7	NACA64-210 with high-lift device	0.2	3.23

Table 1 Rain simulation in different cases

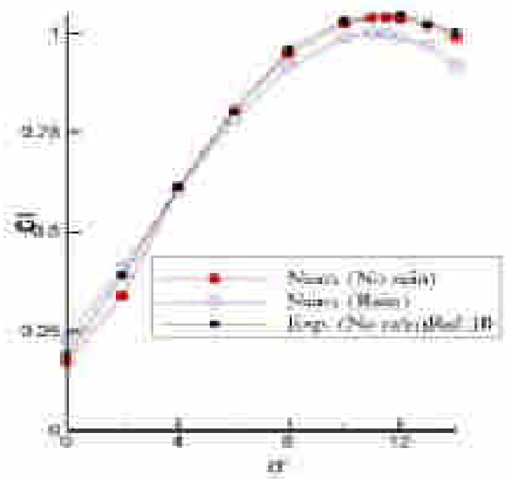

Fig. 7 C_l coefficients vs. angle of attack (NACA62-210)

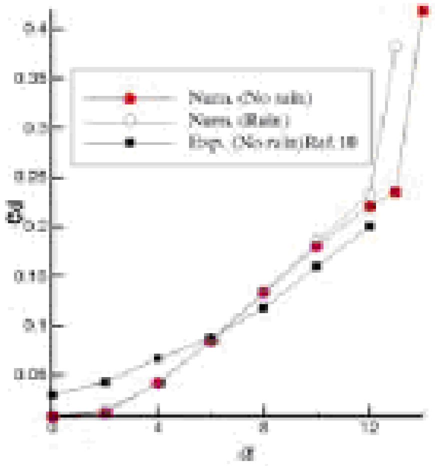

Fig. 8 C_d coefficients vs. angle of attack (NACA64-210)

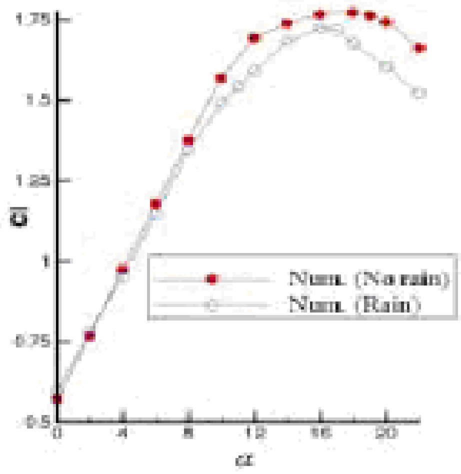

Fig. 9 C_l coefficients vs.angle of attack (NACA4412)

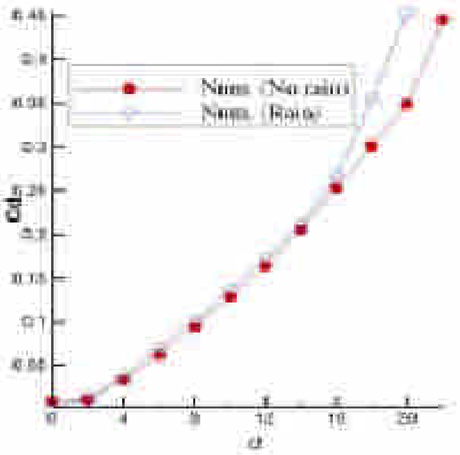

Fig. 10 C_d coefficients vs. angle of attack (NACA4412)

Case	Mach Number	LWC (g/m^3)	Max. $\Delta C_l / C_l$	Max. $\Delta C_d / C_d$	$\Delta\alpha_{C_{l\max}}$
1	0.2	30	7.3%	38%	0.6
2	0.2	3.23	2.7%	2%	0.2
3	0.8	30	0.5%	0.01%	0
4	0.2	30	6%	23%	2
5	0.2	3.23	2.8%	3.7%	0.5
6	0.2	30	18%	2%	—
7	0.2	3.23	3%	0.01%	—

Table 2 Reduction in maximum aerodynamic performance and angle of attack at stall due to rain condition in each case

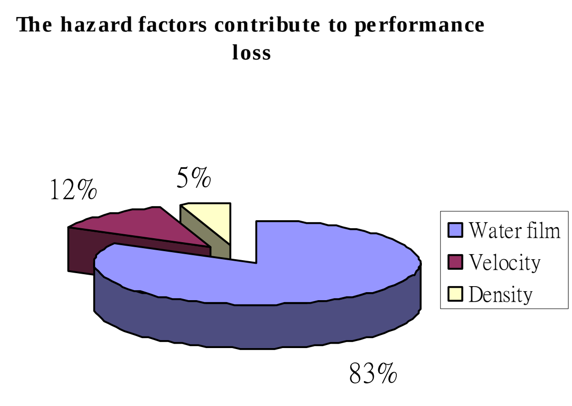

Fig. 11 The hazard factors contribute to decrease of lift coefficient for case 1

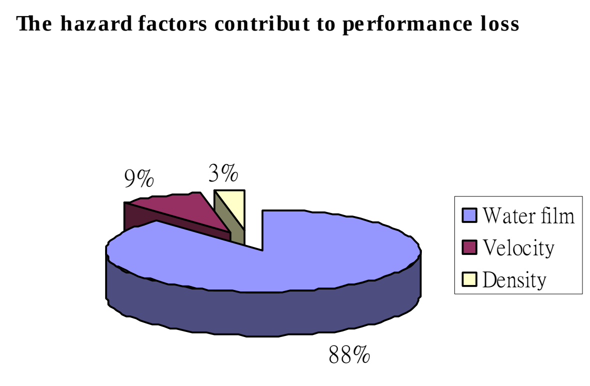

Fig. 12 The hazard factors contribute to increase of drag coefficient for case 1

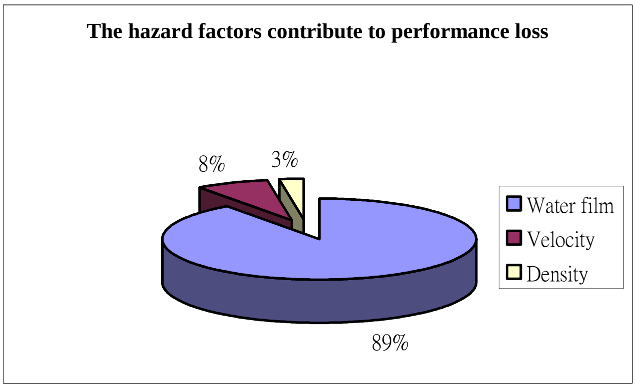

Fig. 13 The hazard factors contribute to decrease of lift coefficient for case 6

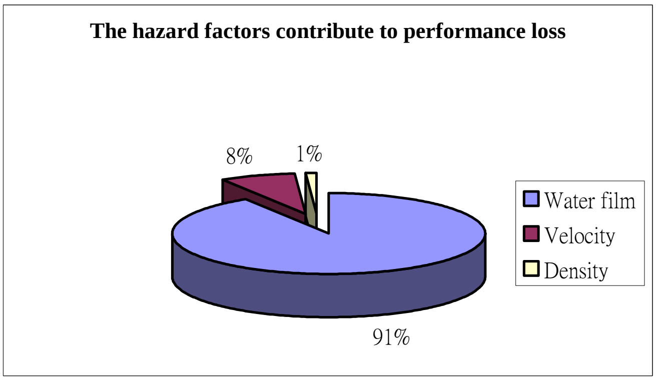

Fig. 14 The hazard factors contribute to increase of drag coefficient for case 6