Wind Tunnel Testing of Ice Roughness Effect on UTM Half Model

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ABSTRACT

Ice accretion effect on the aircraft is a great threat to flight safety. The impact on flight performance is detrimental that it could lead to catastrophic event. This research was carried out to investigate the effect of ice roughness on a three-dimensional (3D) swept wing of the Universiti Teknologi Malaysia (UTM) half model (aircraft) by using a wind tunnel facility. The ice roughness model with different heights was replicated on the leading-edge of the half model swept wing. The test was conducted at the UTM Aerolab Low Speed Tunnel considering low Reynolds number. The UTM half model was configured at three different flap angles to simulate the flight phase of take-off, cruise and landing. The results from the semi-span component balance were analysed and compared with the clean model as baseline. The aerodynamic performance penalty was observed to be substantial. The performance loss was more severed with higher ice roughness height and the finding is in agreement with the published literature for wind tunnel testing of a 3D swept wing.

Keywords: *Ice roughness, swept wing, UTM half model, aerodynamic performance*

1.0 INTRODUCTION

Ice accretion is a weather-related phenomenon which aircrafts experience during operation. There are various situations that ice may accrete on aircraft. Aircraft during ground movement is exposed to potential ice build-up on its critical parts. Improper de-icing procedure and reduce in efficiency or inoperative ice protection system could even make the situation worst. Contaminated wing posed significant risk to aerodynamic penalty. The true aerodynamic performance loss is not a direct parameter for the flight crew to observe during operation. Iced wing can reduce the aircraft climb performance or even loss the controllability as evident from the catastrophic crash of *Comair Flight 3272*into a rural field in Raisinville Township in Monroe County, Detroit, Michigan killing all 29 aboard on January 9, 1997 [1]. Ice roughness is the initial ice accretion [2, 3]; it will further increase in concentration before further pronounce ice shape developed. Ice accretion rate depends on the droplet size of liquid water content, ambient temperature, component size, shape and velocity [4].

Ice roughness on wing leading-edge will appear in three zones [5]. The smooth zone is the ice shape that takes the shape of airfoil leading edge contour and starts from stagnation point. In adjacent, the rough zone is where the ice roughness forms. It is followed by feathering zone further downstream. Ice roughness growth over time will further reduce the smooth zone and extend downstream up to 30 percent of the chord length [6]. In terms of classification of the ice shapes, ice roughness has the most three-dimensional (3D) geometry compares to the other ice shapes and caused the largest range of aerodynamic effect [7]. Ice roughness extracts momentum and reduces boundary-layer health compared to the clean airfoil, causing it to separate early. This causes trailing-edge separation to occur at lower angle of attack than the clean airfoil and resulted in trailing-edge stall. Flight-testing with simulated ice roughness with equivalent grit of sandpaper exhibit the severity of ice roughness can be more than the larger critical ice shapes on some aircraft. Thus, with the finding, ice roughness is also to be considered in aircraft icing certification testing [8].

Three-dimensional iced wing research is still not the main focus of interest for wind tunnel testing unlike the two-dimensional airfoils, particularly taking into account the effect of icing on swept wing [9]. Wind tunnel testing on a modified half-span swept wing of Common Research Model (CRM) and a full model generic transport model had revealed the aerodynamic performance loss with ice model of horn ice shape. Non-icing research on the full-span swept wing with leading edge roughness also found the deterioration of thelift coefficient.This study was conducted with a simulated ice roughness on the leading-edge of the UTM half model with three different roughness heights. The half model was configured at three different flap angles. The aerodynamic performance loss was determined from the ice roughness cases in comparison to the clean model.

2.0 EXPERIMENTAL SET-UP

The wind tunnel testing was conducted at the UTM Aerolab Low Speed Tunnel. A nine percent generic aircraft transport model with a wing profile *NACA 2213* was tested at *Reynolds* number, 0.7 million. The half model system was equipped with moveable control surfaces namely the flap, aileron and elevator. Table 1. shows the specification of the half model and Figure 1. shows the location of the flap on the half model.

Table 1: Specification of the UTM half model

Parameter	Dimension
Length of fuselage, L (m)	2.362
Wing area, S (m^2)	0.252
Mean aerodynamic chord, MAC (m)	0.339
Half-span, $b/2$ (m)	0.983
Wing volume, V_{wing} (m^3)	0.00072
Fuselage volume, $V_{fuselage}$ (m^3)	0.058

The ice roughness was replicated by using sandpaper with grit sizes of 60, 100 and 150 according to ANSI (American National Standard Institute) standard. Roughness with sandpaper grit equivalence had been used on flight testing and revealed considerably significant effect on the aerodynamic performance. The sandpapers were attached to the leading-edge section of the half model by mounting a backing tape at non-dimensionalized coordinate parallel to the airfoil chordline location, x/c = 0.1 and covering 10% of the surface camber area in chordwise extent at both the top and bottom surface of the wing.

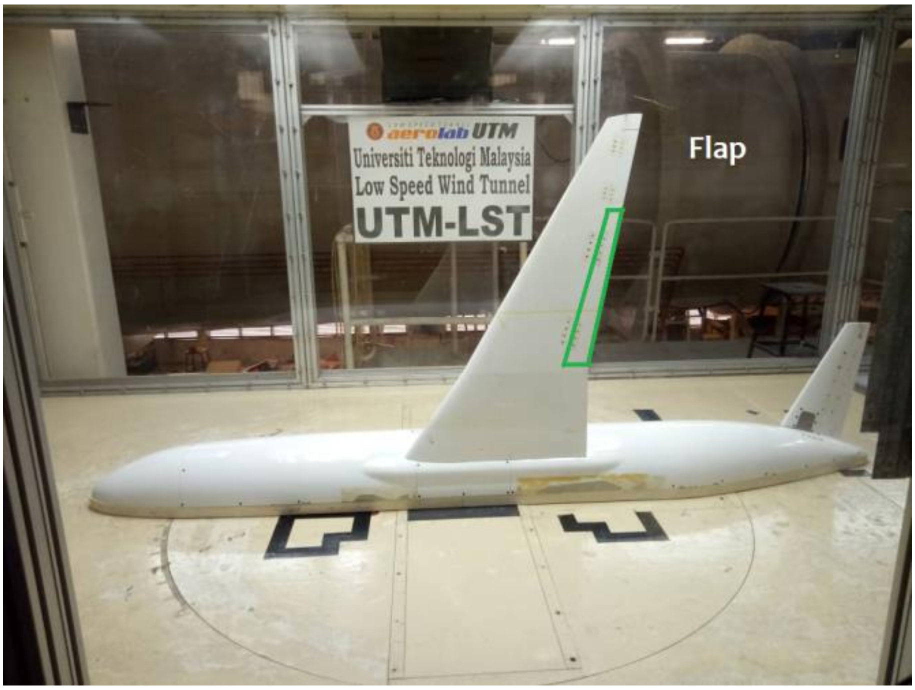


Figure 1: Location of the flap on the UTM half model

Table 2. shows the sandpaper grit dimension and Figure 2. shows the ice roughness model location on leading edge of half model's wing.The aileron and elevator were set at neutral position in this testing. While the plain flap angles were set at 0, 10 and 30 degrees to simulate the flight phase of cruise, take-off and landing positions. The angles of attack were varied between -6 to 20 degrees. UTM LST is equipped with JR3 semi-span component balance for the measurement of force and moment. These measurements were accordingly converted through appropriate means into the lift and drag coefficientsfor analysis.

Table 2: Sandpaper grit to roughness height-chord ratio conversion

Ice roughnessmodel	**Grit scale**	**Median diameter(micron)**	**k/c (10^{-3})**
$(k/c)1$	150	93	0.2
$(k/c)2$	100	141	0.4
$(k/c)3$	60	268	0.8

The dynamic pressure correction was done to the component balance results as given in Equation (1) as follows:

$$q_c/q = (1 + \varepsilon_{sb} + \varepsilon_{wb})^2 \qquad (1)$$

Where,

q_c/q is the dynamic pressure ratio
ε_{sb} is the total solid blockage
ε_{wb} is the wake blockage

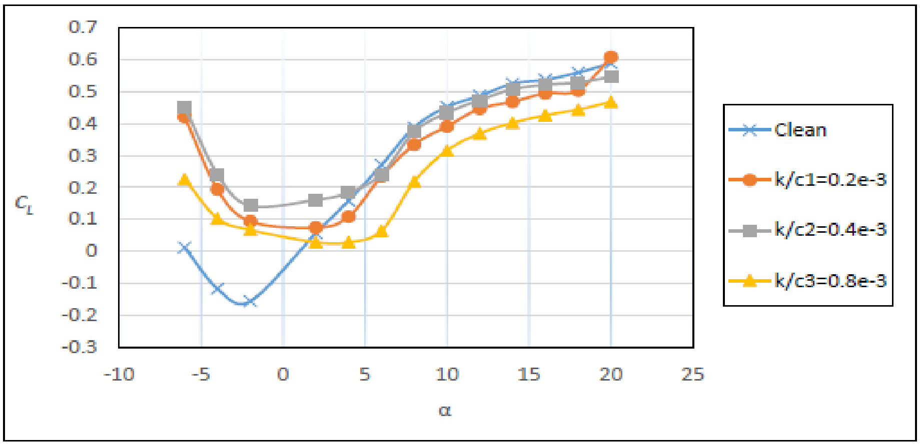
Figure 2:Ice roughness model location on leading-edge of the half model's wing

3.0 RESULTS AND DISCUSSION

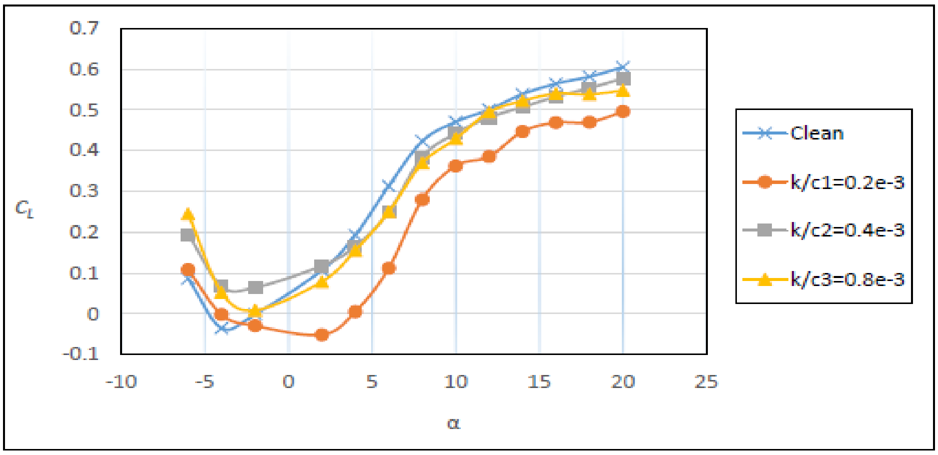
The lift coefficient curve from the UTM half model did not exhibit the true maximum lift coefficient and this finding has been in agreement with the previous past works on the UTM half model by Ujang [10] and Rhubbindran [11]. The surface pressure measurement carried out by Rhubbindran revealed the flow separation occurred at an angle of attack which depicted as the change of gradient of lift coefficient curve from force balance [11]. A similar trend was observed from this work. Thus, the aerodynamic performance loss was based from the same reference stalling angle determined using a similar method.

The aerodynamic performance was based on the liftand drag coefficientsparameters at stalling angle that was compared between the ice roughness and clean models at each flap angle configuration. Figure 3. shows the lift coefficients against angle of attack for the half model flap angle set to 0, 10 and 30 degrees.

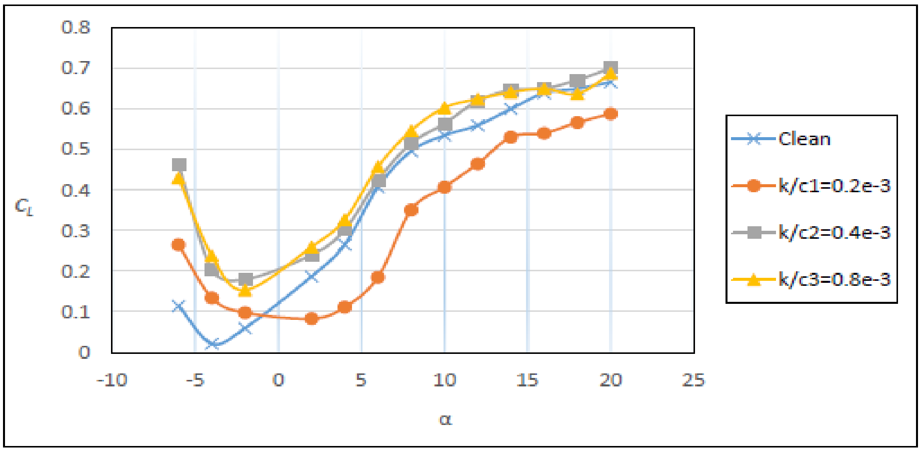
The ice roughness model $(k/c)_3$ recorded the highest lift coefficient loss of about 19% compared to the clean model. It was followed by the ice roughness model $(k/c)_1$ and $(k/c)_2$ with 14% and 9% losses, respectively. However, on full-span swept wing condition at higher *Reynolds* number of 1.7 million, Neely and Corner found out that the carborundum grain roughness of *k/c* approximately half of the $(k/c)_3$ only shall reduce the coefficient of lift at 5% with flap at neutralposition [12]. At a flap angle of 10 degrees, the highest lift coefficient loss was achieved by the ice roughness model $(k/c)_1$ with 34% loss. It was observed that the lift coefficient loss exhibitsan upward trend for the ice roughness $(k/c)_1$ and $(k/c)_2$. While at a flap angle of 30 degrees, only the ice roughness model $(k/c)_1$ resulted inthe aerodynamic penalty with 29% loss but the effect or lossesfrom the ice roughness model $(k/c)_2$ and $(k/c)_3$ tend to be neligible.



(i) Flap angle:0 degree



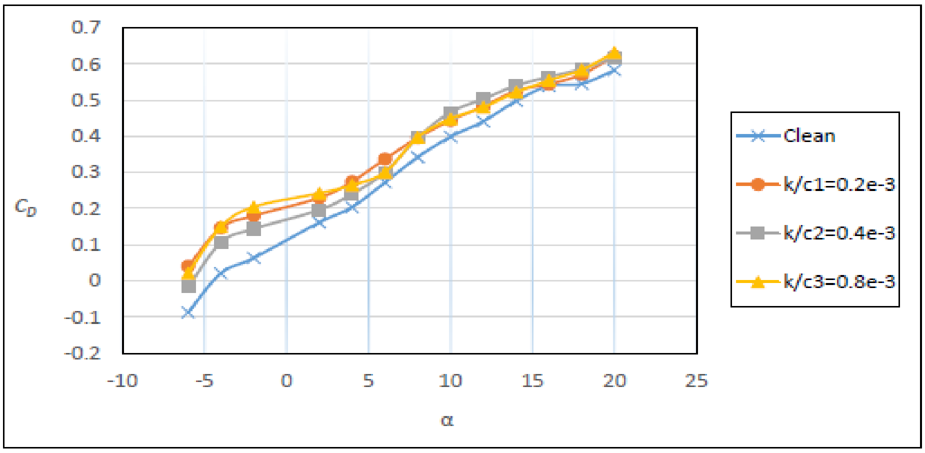
(ii) Flap angle: 10 degree



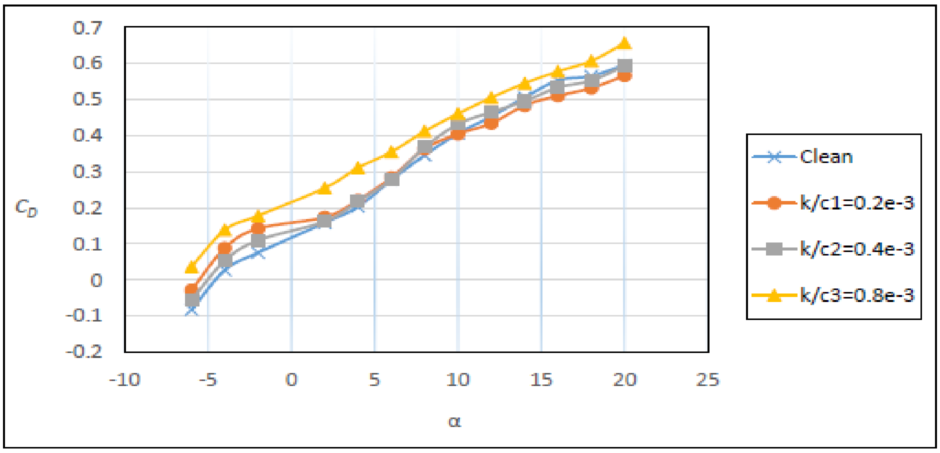
(iii) Flap angle:30 degree

Figure 3: Lift coefficients against the angles of attack at flap angles 0, 10 and 30 degrees

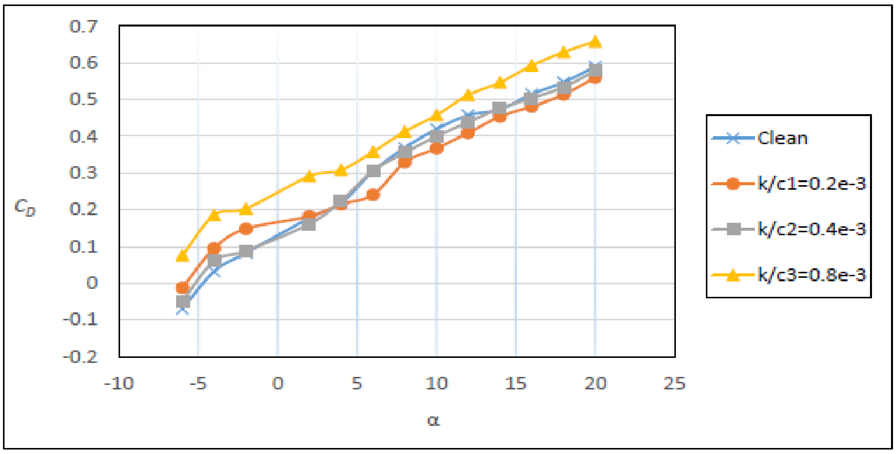
Figure 4 shows the drag coefficient results against the angles of attack for the three flap angle configurations. The ice roughness model $(k/c)_3$ posed the highest drag coefficient rise for the flap angles 0, 10 and 30 degrees with corresponding 24%, 16% and 11% rise, respectively compared to the clean model. The drag coefficient rise exhibited a downtrend for all the ice roughness models as the flap angle increases with the ice roughness $(k/c)_1$ and $(k/c)_2$ showed negligible drag rise at a flap angle of 30 degrees.



(i) Flap angle: 0 degree



(ii) Flap angle:10 degrees



(iii) Flap angle: 30 degrees

Figure 4: Drag coefficientsagainst the angles of attack at flap angles 0, 10 and 30 degrees

Figure 5 shows the summary for the effect of ice roughness on lift coefficient performance. The concentration of the plots shows the stalling angle for the UTM half model was found to be insensitive with the change of flap angles up to 30 degrees. This could be further enhanced with the amplification of the angle of attack resolution. At the clean configuration (flap-up), the ice roughness height played significant role towards the lift coefficient loss. The lift performance loss showed an uptrend at a higher flap angle for the lower ice roughness height. However, as the flap angle increases, the effect of lift coefficient loss was observed to be reduced for the higher ice roughness height. This is in agreement with the findingsbySivells and Spooneron *NACA 65-210* airfoil for the three flap configurations with a leading-edge roughness [13]. The findings could be further understood with a flowfield analysis from the surface pressure measurement or other means.

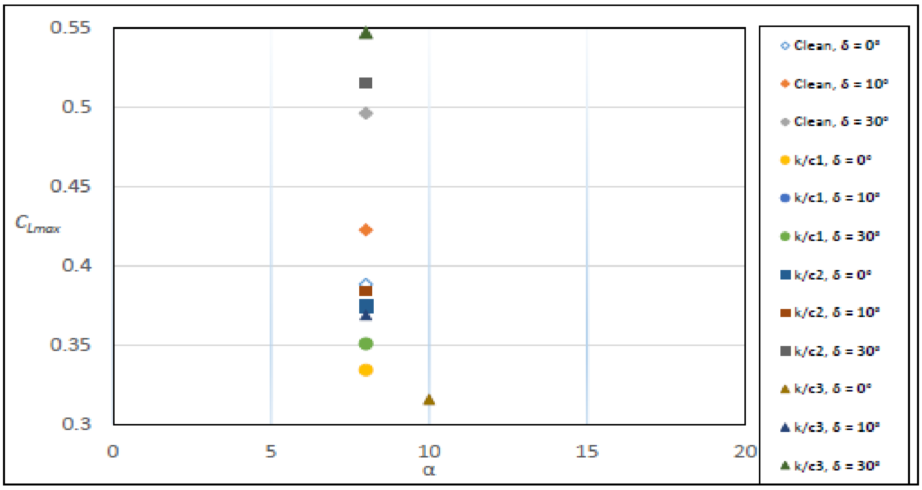


Figure 5:Summary of the lift coefficients at stalling angle against the angles of attack

The summary for the effect of ice roughness on the drag coefficient performance is shown in Figure 6. Overall, the drag coefficient uptrend remained similar for all the three flap angles. The severity of the drag coefficient rise penalty was in accordance to the ice roughness model height. In terms of the overall aerodynamic performance loss (the summation of percentage for lift coefficient loss and drag coefficient rise compares to the clean model), the worst performer was the ice roughness model $(k/c)_3$ at flap angle of 0 degree. Thus, it suggests the effect of ice roughness is more critical at the clean configuration without augmentation of the high lift device.

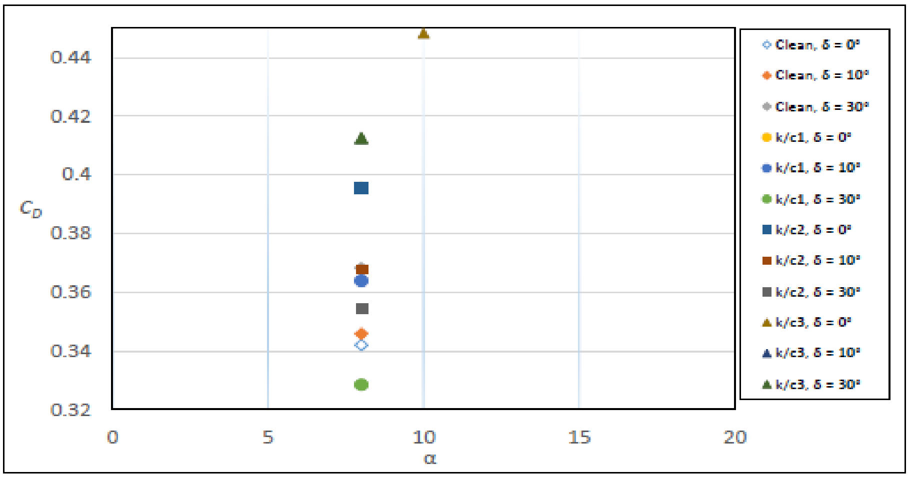


Figure 6: Summary of the drag coefficients at stalling angle against the angles of attack

4.0 CONCLUSION

The wind tunnel testing was conducted to assess the aerodynamic performance loss to half model due to ice roughness effect. The results from component balance shows the effect of ice roughness caused significant penalty to aerodynamic performance. The most severe performance loss was achieved at clean configuration with the highest ice roughness model height. Thus, aircraft at flap-up configuration is exposed to higher risk of detrimental aerodynamic performance loss with initial ice accretion shape of the ice roughness.

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