A Simple and Safe Takeoff or Landing Procedure with Wing Surface Contaminations

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A pilot attempting an emergency takeoff or landing with wing surface contamination, such as ice, frost, and insect accumulation, has had no reliable method of doing so safely until now Newly developed empirical relationships of drag and lift penalties, derived from wind tunnel experiments on artificially contaminated streamlined bodies and airfoils, were combined with steady state flight equations to suggest safe takeoff or landing procedure modifications Specific results were obtained for a single engine, general aviation aircraft with a NACA 64A215 20 deg flaps wing section that should qualitatively apply to all airplanes in general Similar information was derived for a Boeing 727 transport aircraft Conclusions include the following: 1) In order to maintain a safe stall margin and to climb effectively at takeoff with contaminated wings, the maximum gross weight should be reduced in proportion to the maximum lift loss, and the takeoff and climbout airspeeds should remain unchanged; and 2) to land with a safe stall margin and maintain a safe descent rate, the thrust should be increased, and the landing speed should be increased inversely proportional to the square root of the maximum lift loss of a contaminated wing

Nomenclature

c = chord length of airfoil ft
C_D = drag coefficient
C_f = local friction coefficient
C_L = lift coefficient
k = roughness or protuberance height, mm
l = fuselage length, ft
P = fraction of roughness coverage from the trailing edge
Re = Reynolds number
S = wing area, ft^2
T = thrust lb
V = airspeed ft/s
W = aircraft weight, lb
x = local distance on the flat plate, ft
α = angle of attack
γ = climb angle, deg
ρ_a = air density

Introduction

FOR many years, pilots have known that frost snow or ice on a wing section presents a serious safety hazard during takeoffs and landings In some countries including the United States, regulations do not permit takeoff when frost snow, or ice adheres to transport aircraft On the other hand, there are no regulations governing takeoff and landing in similar conditions for general aviation aircraft. In other countries, dispatch is permitted if in the judgment of the flight crew, the accumulation will not affect the safety of the flight While frost, snow, or ice contamination on a wing section presents serious problems takeoffs and landings have been similarly affected by severe rain according to Haines and Luers[1] and Haines et al [2]

Any airfoil roughness writes Brumby [3] for full wingspan upper surface beginning at the leading edge and extending varying distances aft typically causes a reduction in maximum lift a reduction in the angle of attack at which stall occurs, and a rapid poststall drag increase The effects become more adverse as the size and chordwise extent of the roughness increase They may also be accompanied by a reduction in lift at a given angle of attack and by an increase in the wing parasite drag Controversy concerning per formance degradation caused by frost or snow on the wings may have arisen from tests on military aircraft that showed that frost appeared to cause no takeoff problems According to Langston,[4] the tests were only meant to establish whether or not the particular aircraft would take off at the handbook speeds The reduction of the stall margin was not examined

When an unsafe stall margin exists, a loss of control in flight can occur at the time the engine thrust is reduced, or when the proper takeoff rotation rate is exceeded, or when adequate airspeed is not maintained In examining some National Transportation Safety Board (NTSB) records, it appears that many takeoff accidents result from this loss of aircraft control One example is the Cessna 180 fatal crash that occurred at the Berlin Municipal Airport in New Hampshire in 1977 (Ref 5) The pilot failed to remove the ice and snow and took on two passengers His climb was suc cessful and he accomplished a normal power reduction after 1500 ft from departure He then lost control and crashed Another example is that of a Japan Air Lines McDonnell Douglas DC 8 62F at Anchorage Ala [6] The NTSB report described the conditions as favorable for the accretion of rime icing (or hoar frost) from the time the aircraft approached Anchorage until the crash From the flight recorder data and simulation studies, the NTSB found that the maximum lift coefficient was reduced by $\simeq 15\%$ and the aircraft stalled at an angle of attack 2 deg less than normal This alone may not have prevented continued flight, but the aircraft "may have been rotated to an excessive pitch angle just before it reached takeoff speed and the stall stick shaker did not activate until near impact" [6]

In the even more severe cases there is no stall margin available, and a pilot may be unaware of it until too late Such appears to be the case in the Air Florida Boeing 737 crash in a snowstorm in Washington D C , Jan 13, 1982 (Ref 7) In this case, wing surface contamination was due to snow/ice It is evident that no stall margin existed, because "the aircraft's stall warning stick shaker activated almost immediately after liftoff and continued until impact " The NTSB concluded that the aircraft actually had a lower thrust than the pilot

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> Either [a lower thrust or ice contaminations] alone should not have prevented continued flight [The aircraft should have been able to proceed] immediately after stick shaker activation if appropriate pitch control had been used and maximum available thrust had been added While the flight crew did add appropriate pitch control it did not add thrust in time to prevent impact [7]

Some researchers aware of these performance degradations, have suggested safe takeoff modification procedures According to Ljungstroem,[8] the airlines could realize a substantial savings if it were sufficient to clean only a small part of the wing and control surfaces that is, from the leading edge and 10 20% backwards Weeks[9] had a significantly different approach:

> In the presence of hoar frost contamination some combination of aircraft weight reduction and takeoff speed increase will be necessary in order to maintain the normal safety margins

Finally, Galins and Shirkey's[10] specific recommendation for the Boeing 737 aircraft is:

> When takeoffs are executed during suspected icing conditions or adverse weather conditions sound operational techniques must be exercised Wings should be kept clear of ice and other forms of contamination and rotation rates should not exceed three degrees/second If deemed necessary improved climb performance [that is, 6% takeoff overspeed] may be used for added takeoff speed margins at any flap setting

The following sections will evaluate each of the suggested modified takeoff procedures and, as a result, a new effective takeoff procedure is recommended The most effective landing procedure with wing surface contamination will also be determined. In the first section, an empirical relationship is developed for the lift, drag, and angle of attack penalties that occur on a streamlined body, such as fuselage wings, and tails as a function of the chord Reynold's number the average roughness height to chord ratio and the percent of roughness coverage These results are extended to an aircraft's aerodynamics In the second section, it is shown how a takeoff or landing procedure modification can result in a normal safety margin This is done by requiring a safe stall margin and solving the aircraft equations of motion for a steady climbing or descending flight for each suggested procedure modification

Empirical Relationships for the Drag, Lift, and Angle-of-Attack Penalties

Fuselage Section

To evaluate the minimum drag coefficient of a contaminated streamlined fuselage at takeoff speed we note the fuselage Reynold's number is usually in the tens of millions for a typical general aviation aircraft and higher for transport aircraft It is assumed the fuselage is nearly all friction drag and theoretically represented by a flat plate model For a smooth flat plate, the local friction coefficient from Rubesin and Inouye[11] is correlated as

$$C_{f_s}/2 = 0\ 0131\ Re_x^{-1/7} \quad \text{for } Re_x \geq 10^7 \tag{1}$$

From Young,[12] the correlation of the local friction coefficient over a fully rough flat plate is an approximation of a semilogarithmic power expression with the simpler expression

$$C_{f_R} = 0\ 0139(k/x)^{1/7} \quad \text{for } 4\times 10^{-7} < k/x < 5\times 10^{-4} \tag{2}$$

If P is the fraction of the plate roughened from the trailing ege the relative drag coefficient increase of the plate is modeled by integrating Eqs (1) and (2) in the expression

$$\frac{\Delta C_{D_l}}{C_{D_l}} = \frac{\int_0^{(1-P)\ell} C_{f_s}\,dx + \int_{(1-P)\ell}^{\ell} C_{f_R}\,dx}{\int_0^{\ell} C_{f_s}\,dx} - 1 \tag{3}$$

The result is

$$\frac{\Delta C_{D_l}}{C_{D_l}} = \left[\frac{1\ 06}{2}\left(Re_l \frac{k}{l}\right)^{1/7} - 1\right][1-(1-P)^{6/7}] \tag{4}$$

This equation predicts well Hoerner's[13] very limited data on the minimum fuselage drag due to fully covered roughness Significant frost, rain, and ice roughness is assumed to occur only on one half of the fuselage Thus, Eq (4) is halved to estimate the fuselage drag increment, ΔC_{D_l}, for the given values of k, and P was set to 1 The average roughness height on the fuselage is assumed to be the same as that on the wing It is also assumed the fuselage contributed no lift to the aircraft; thus lift and angle of-attack penalties are inappropriate in this section, but will be important in the following section on aerodynamic wing and tail penalties

Wing and Tail Section

Hoerner's data[13] show a correlation of the airfoil minimum drag coefficient vs the variable k/c for a plain wing section fully roughened at a chord Reynold's number, Re_c in the millions This correlation is the same as that for a flat plate multiplied by a constant The constant is modeled as a function of the airfoil's thickness ratio The data of NACA 64 and 65 series airfoil, typical of most aircraft at the 15% thickness ratio, shows the minimum drag coefficient is nearly all friction drag Hoerner also shows data of the minimum drag coefficients of smooth airfoils to be nearly constant for the Reynold's number from ≃1 to 10 million From a cursory examination of Gregory and O'Reilly [14] Clarius,[15] Ingelman Sanberg et al ,[16] and Abbott and Von Doenhoff[17] data concerning partially or fully roughened plain airfoils, it is observed the drag difference penalty ΔC_{D_c}, tends to be a constant as a function of angle of attack until approaching the roughened airfoil stall angle or at the rapid onset of separation These observations are assumed to apply also to the multielement airfoils partially covered by roughness

The resulting empirical fit of the drag difference to k/c is given by

$$\Delta C_{D_c} = C_{D_R} - C_{D_c} = [a(k/c)^{1/7} - b][1-(1-P)^m] \tag{5}$$

for uniform roughness and for different types of airfoil sections Thus the constants a and b are presented in Table 1 for the data sources, as shown in Fig 1 All data in Fig 1 correspond to an Re_c value of less than 10 million The resulting three curve fits gave the value for m as 0 5 and the constants a and b are treated as a function of the effective thickness ratio assuming even the 20 deg flaps extension will effectively increase the thickness ratio To extend to Re_c greater than 10 million, the coefficient b is made proportional to Re_c to the minus one seventh power, thereby making Eq (5) more similar to Eq (4).

So far we have considered only partially uniform airfoil roughness The drag of other contaminated airfoils are referenced in Table 1 To consider the drag penalty of a near leading edge roughness on an airfoil, such as rime ice and

Table 1 Summary of coefficients in empirical drag and lift penalties for various airfoils and surface contaminations

Surface contaminations	Airfoil type	C_0	C_1	C_2	C_3	C_4	n	a	b
Upper surface and lower surface covered with roughness: hoarfrost snow adhesion wavy water film	Any plain airfoil	0 85	0 3953	0 6894	0 6297	11141	0 2	See Ref 13	
	Plain NACA 65A215	0 85	0 3953	0 6894	0 6297	11141	0 2	0 10624	0 02206
	Plain NACA 0012	0 85	0 3953	0 6894	0 6297	11141	0 2	0 08912	0 02034
Near leading edge roughness band: rime ice, water film cratering insect accumulation burred paint	Any plain airfoil	0 85	0 3726	0 5184	0 4639	48460	0 5	See Ref 19	
Spanswise protrusion element: glaze ice wire	Any plain airfoil	1 150	0 3726	0 5184	0 4639	48460	0 5	See Refs 20 and 21	
Upper surface and part of lower surface covered with roughness: hoar frost snow adhesion wavy water film	20 deg flaps 0 deg slats NACA 65A215	0 725	0 3016	0 3880	0 3467	1093	0 25	0 1344	0 02595
	20 deg flaps 25 deg slats NACA 65A215	0 68	See Fig 3 dashed lines					0 1344	0 02595
Spanswise protrusion element: glaze ice wire spoiler	20 degflaps NACA 65A215	0.86	Results about same as 0 deg flaps					See data in Ref 15	
	40 deg flaps NACA 65A215	0 98							

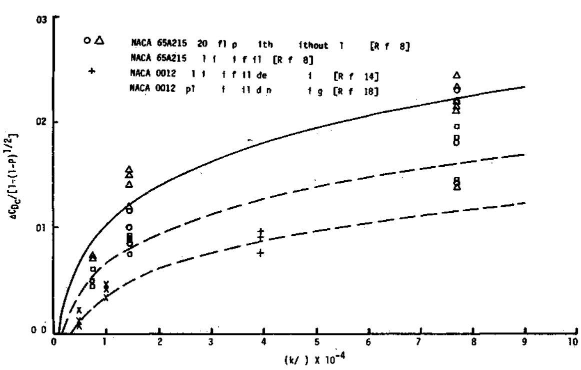

Fig 1 Empirical relationship and wind tunnel data of ΔC_{D_c} for three airfoils as a function of k/c

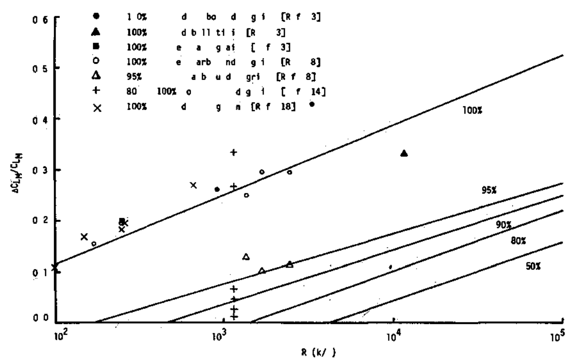

Fig 2 Empirical relationship and wind tunnel data of $\Delta C_{LM}/C_{LM}$ vs $Re_c(k/c)$ for the plain airfoils with uniform roughness

insect accumulation, we refer to Bragg et al [19] For the drag penalty of a spanwise protrusion element on an airfoil such as glaze ice and wires, we refer to Gray[20] and Dietenberger [21] The airfoil drag coefficient beyond the stall angle is given by Schwartzberg.[22]

While wing contamination causes drag penalties on a wing and tail section, the same contamination also causes severe degradation in the lift coefficient When the relative maximum lift loss data by Brumby,[3] Ljungstroem,[8] Abbott and Von Doenhoff,[17] and Gregory and O'Reilly[14] were replotted vs a new variable, $Re_c(k/c)$, on the semi-log scale the scatter due to Re_c variations from 10^6 to 3×10^7 was significantly reduced, and these are shown in Figs 2 4 To include the effects of partial roughness coverage, a relationship similar to Eq (4) was sought The relative maximum lift loss also showed a semi log relationship to the

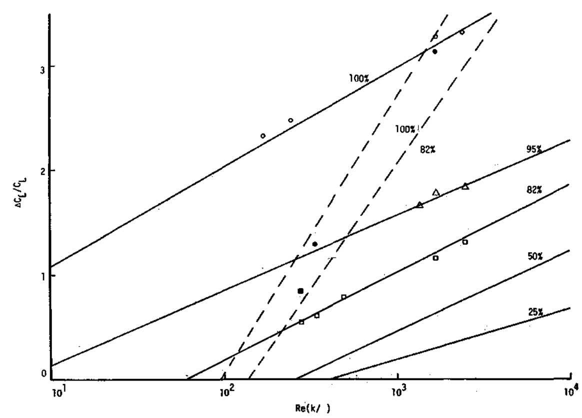

Fig 3 Empirical relationship and wind tunnel data of $\Delta C_{LM}/C_{LM}$ vs $Re_c(k/c)$ for the NACA 65A215 airfoil with 20-deg flaps (Ref 8) The open symbols are without slats and the closed symbols are with 25 deg flaps

variable $Re_c(k/c)$, with the result

$$\frac{\Delta C_{L_m}}{C_{L_m}} = \left[C_1 + (C_2 - C_3 P)\, ln\left(\frac{Re_c(k/c)}{C_4}\right)\right][1-(1-p)^n] \tag{6}$$

where $\Delta C_{L_m}/C_{L_m} > 0\ 0$ The values for the constants C_1 C_2 C_3 C_4, and n are listed in Table 1 The results for the plain airfoils are shown in Fig 2 The data displayed in Fig 3 were not sufficient to determine an empirical relationship for the 20 deg flaps and the 25 deg slats of the NACA 65A215 airfoil, and so the relative maximum lift loss is given by the dashed lines The solid lines represent a fit to open symbol data Lastly, Fig 4 shows the lift loss penalty for localized spanwise disturbances such as roughness bands or glazed ice

In a slightly, but significantly, different manner than Brumby,[3] the relative stall angle loss was simply correlated as

$$\frac{\Delta\alpha_s}{\alpha_s} = C_0 \frac{\Delta C_{L_m}}{C_{L_m}} \tag{7}$$

where the angle of attack is relative to the zero lift line Figure 5 shows the relative stall angle loss vs the relative lift loss All the open symbol data correspond to plain airfoils and C_0 averaged 0 85 for plain airfoils with a relative standard deviation of 0 2 as given by the dashed lines in Fig 5 The values of C_0 are summarized in Table 1 for the different airfoils and roughness types

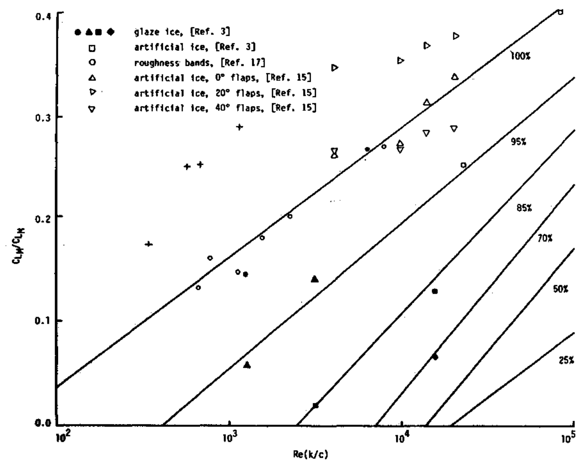

Fig. 4 Empirical relationship and wind tunnel data of $\Delta C_{LM}/C_{LM}$ vs $Re_c(k/c)$ for the plain airfoils with localized spanwise disturbances.

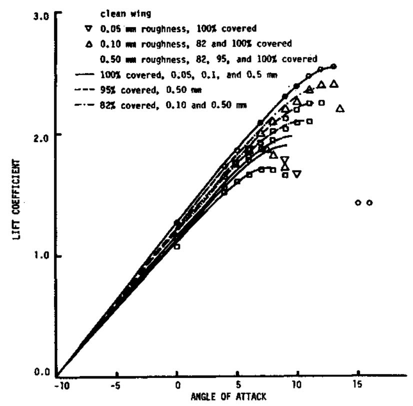

Fig. 6 Empirical curve of lift coefficients vs angle of attack due to upper surface roughness in comparison to Ljungstroem's (Ref.8) wind tunnel data on a NACA 65A215 20-deg flaps, 0-deg slats airfoil at $Re = 2.2 \times 10^6$

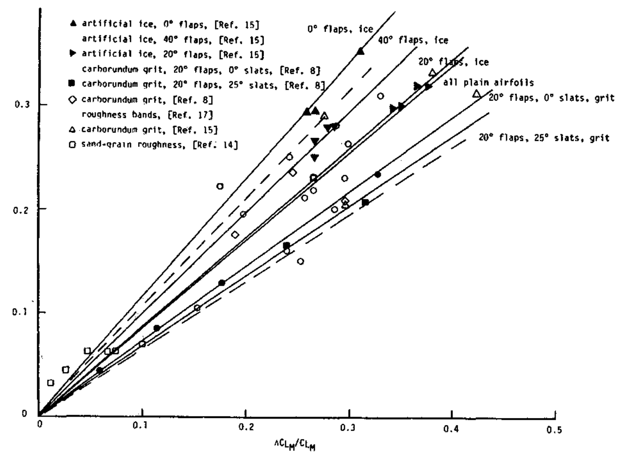

Fig. 5 Empirical relationship and wind tunnel data of $\Delta\alpha_s/\alpha_s$ vs $\Delta C_{LM}/C_{LM}$ for the various airfoils and surface contaminations.

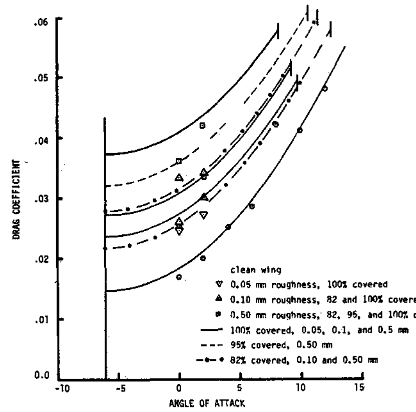

Fig. 7 Empirical curves for drag coefficients vs angle of attack due to upper surface roughness in comparison to Ljungstroem's (Ref. 8) wind tunnel data on a NACA 65A215 20-deg flaps, 0-deg slats airfoil at $Re = 2.2 \times 10^6$

Equations (6) and (7) may be applied directly to the aircraft aerodynamic data for the aircraft flight simulation, because they do not need a correction for the aspect ratio. As a demonstration, the wing section NACA 65A215 with 20-deg flaps, 0-deg slats was considered typical of general aviation aircraft and of some transport aircraft. The curves representing different roughness distributions in Fig. 6 were produced by selecting random points on the clean lift coefficient curve and reducing the lift coefficient using Eq. (6). Simultaneously, the angle of attack was reduced using Eq. (7). To generate the drag coefficient as a function of the angle of attack, a parabolic fit to the clean wing section measured by Clareus[15] for the NACA 65A215 with 20-deg flaps gave the equation

$$C_{D_c} = 0.0146 + 1.066 \times 10^{-4}(\alpha + 5.9)^2 \tag{8}$$

shown by the lower curve in Fig. 7 To this equation, Eq. (5) was added for the ΔC_{D_c} of the different roughness distributions, as indicated by the other curves in Fig. 7 The stall angles are shown by short vertical bars at the end of each curve, indicating the upper limit of Eq. (5).

Aircraft Takeoff and Landing Performance Analysis

Now that we have discussed how the drag and lift coefficient curves were derived, we will now explain how to apply this derivation to the aircraft under the conditions of steady climbing or landing while maintaining a safe stall margin. The equations of motion are utilized to further evaluate the safety of various takeoff and landing modifications.

In order to derive a stall margin for a roughened aircraft that is the same as the margin for takeoff or landing with a clean aircraft, we note that a clean aircraft will takeoff or land with a lift coefficient of a certain percentage less than the maximum clean lift coefficient in order to have an adequate stall margin. Thus, for a roughened aircraft, we must have a lift coefficient at takeoff or landing that is of the same percentage below the maximum roughened lift coefficient to ensure the same stall margin. Consider that the lift coefficients for a roughened aircraft vs angle of attack are calculated by taking the clean aircraft (not the airfoil) lift coefficient at a clean angle of attack and reducing the lift coefficient by the amount.

$$\Delta C_L = (\Delta C_{L_m}/C_{L_m})C_L \tag{9}$$

and simultaneously reducing the angle of attack with respect to zero lift by the amount

$$\Delta\alpha = (\Delta\alpha_s/\alpha_s)\alpha \tag{10}$$

The relative maximum lift loss is obtained from Fig. 3 or Eq. (6), and the relative stall angle loss is obtained from Eq. (7) for a wing section similar to the NACA 65A215 airfoil.

From the lift curve thus generated, we can see that for a roughened aircraft to have a lift coefficient at takeoff or

Table 2 Results of takeoff analysis for a single engine general aviation aircraft[a]

						Galins and Shirkey $W_R = W_C$		Weeks $\gamma_R = \gamma_C$		Dietenberger $V_R = V_C$	
k mm	P	$\Delta C_L/C_L$	$\Delta\alpha/\alpha$	ΔC_D	α_{takeoff} deg	γ_R deg	V_R ft/s	V_R ft/s	$(W_C - W_R)/W_C$	γ_R, deg	$(W_C - W_R)/W_C$
1.0	1 0	0 333	0 241	0 0274	4 69	−0 66	132 6	107 2	0 346	3 26	0 333
0.5	1 0	0 304	0 220	0 0214	4 93	−0 00	129 9	108 4	0 301	3 54	0 304
0 1	1 0	0 237	0 172	0 0096	5 49	1 37	124 1	110 7	0 202	3 98	0 237
1.0	0 95	0 182	0 132	0 0226	5.95	1 05	119 8	105 4	0 224	2 94	0 182
0 5	0 95	0 161	0 116	0 0176	6 13	1 52	118.2	106 4	0 189	3 15	0 161
0 1	0 95	0 111	0 080	0 0078	6 54	2 43	114 9	108 3	0 110	3 51	0 111
Clean wing	1 0	0	0	0	7 475	3 5	108 2	108 2	0	3.5	0

[a] $\gamma_c = 3\ 5$; $W_c = 3100$ lb; $(\rho_a S/2) V_c^2 = 2608\ 2$; $C = 4\ 91$ ft; $l = 25.28$ ft

Table 3 Results of landing analysis for a single engine general aviation aircraft[a]

		$V_R = V_c$		$T_R = T_c$		$\gamma_R = \gamma_c$		$V_{YR} = V_{Yc}$	
k mm	P	γ_R deg	T_R/T_c	γ_R deg	V_R/V_c	V_R/V_c	T_R/T_c	V_R/V_c	T_R/T_c
1 0	1 0	−48 3	−15.8	−7 60	1 22	1 22	2 81	1 22	3 09
0 5	1 0	−46 0	−15 2	−6 95	1 20	1 20	2.52	1 20	2 78
0 1	1 0	−40 5	−13 6	−5 60	1 14	1 15	1.92	1 15	2 12
1 0	0.95	−35 3	−11 5	−5 91	1 10	1 11	2 06	1 11	2.21
0 5	0.95	−33 1	−10 8	−5 45	1 09	1 09	1 86	1 09	1 99
0 1	0 95	−27.5	− 8 9	−4 55	1 06	1 06	1 46	1 06	1 55

[a] $\gamma_c = -3\ 5$; $W_c = 3100$ lb; $(\rho_a S/2) V_c^2 = 2608\ 2$; $C = 4\ 91$ ft; $l = 25\ 28$ ft

landing that will maintain an adequate stall margin, the angle of attack at takeoff or landing is reduced from that of a clean aircraft according to the formula

$$\alpha_R = (1 - \Delta\alpha/\alpha)(\alpha_c - \alpha_0) + \alpha_0 \tag{11}$$

where α_0 is angle of attack at the aircraft's (not the airfoils's) zero lift, and α_c is the clean aircraft angle of attack at takeoff or landing The roughened aircraft drag coefficient, C_{D_R}, is calculated from the clean aircaft drag curve as

$$C_{D_R} = C_{D_c} + \Delta C_{D_c} + \Delta C_{D_l} = C_{D_c} + \Delta C_D \tag{12}$$

where ΔC_{D_l} is the drag increment on the fuselage due to roughness, and ΔC_{D_c} is the drag increment on the wing section due to roughness.

To help evaluate the performance penalties at takeoff or landing, it will be assumed the aircraft flies in a steady, linear, climbing or descending trajectory while airborne We will also be using the following approximated set of steady climbing or descending flight equations in the evaluation of safe takeoff and landing procedures for contaminated air craft:

$$W\cos\gamma = C_L(\rho_a/2)SV^2 \tag{13}$$

and

$$T - W\sin\gamma = C_D(\rho_a/2)SV^2 \tag{14}$$

Before we utilize these assumptions and equations to evaluate safe takeoff and landing procedures for con taminated aircraft, we need to introduce the following data The analysis will consider a single-engine general aviation-type aircraft described by Fink et al[23] The same type of analysis can be done for transport aircrafts, although the numerical values will differ The typical aircraft parameter values for takeoff or landing are given in Tables 2 and 3. For a $\gamma_c = \pm 3\ 5$ deg, steady state climb angle, the necessary angle of attack, $\alpha_c = 7\ 47$, and thrust, $T = 502\ 3$ lb or $T = 123\ 8$ lb, are derived by solving Eqs (13) and (14) using the lift and drag coefficient curves vs angle of attack (see Ref 23) These values also correspond to the maximum lift/drag ratio of 10 and a stall margin of 20% for the lift coefficient For Eq (11) $\alpha_0 = -4\ 06$ Some transport aircraft have similar takeoff or landing performances, except that they have a higher thrust to correspond to a higher weight and speed and have a higher stall margin of $\simeq 40\%$

A severe nocturnal frost layer thickness is about 1 mm, and the average uniform thickness is about 0 5 mm, according to Weeks[9] and Dietenberger[24] Langston[4] has observed a maximum thickness of hoar frost of about 7 mm, which is probably due to freezing drizzles According to Bragg et al[19] the relative roughness height of rime ice is typically $\simeq 0\ 001$ Haines and Luers[1] suggest that a severe rain rate of 500 mm/h may produce a 1 mm roughness, and a heavy rain rate of 100 mm/h may produce a 0 2 mm roughness height on the wing Consequently, the assumed roughness height variations of 0 1 to 1 0 mm are practical values for input into the aerodynamic penalty calculations Table 2 shows the computed values of $\Delta C_L/C_L$ $\Delta\alpha/\alpha$ ΔC_D, and α_R at takeoff or landing for the different roughness heights 0.1, 0 5, and 1 0 mm and for the P values 1 0 and 0 95 on the NACA 65A215 wing section with 20 deg flaps

Takeoff Performance Evaluation

During the ground takeoff run, it is assumed the value of the thrust force is much larger than that of the increased drag force due to roughness, so that the extra runway length covered before takeoff is negligible Assume that, for any flight at takeoff, the thrust, air density and wing area are constants The lift and drag coefficients will differ according to the existence of roughness on the wings and fuselage Let the subscript R stand for rough aircraft surface and the subscript c stand for clean aircraft surface Under these conditions Eqs (13) and (14) are rewritten removing the thrust, density and wing area parameters as

$$\frac{W_R\cos\gamma_R}{W_c\cos\gamma_c} = \frac{C_{L_R}V_R^2}{C_{L_c}V_c^2} = \left(1 - \frac{\Delta C_{L_c}}{C_{L_c}}\right)\frac{V_R{}^2}{V_c{}^2} \tag{15}$$

and

$$T = W_R \sin\gamma_R + C_{D_R}\left(\frac{\rho_a S}{2}\right)V_R^2 = W_c \sin\gamma_c + C_{D_c}\left(\frac{\rho_a S}{2}\right)V_c^2 \qquad (16)$$

Equations (15) and (16) relate parameters for steady state climbing with a roughened aircraft to those for a steady state climb with a clean aircraft Considering the known clean aircraft takeoff parameters W_c γ_c, C_{L_c} C_{D_c} V_c, and the roughened aircraft lift and drag curves, which are derived by modifying the clean aircraft curves via Eqs (9-12) there remain three unknowns, W_R V_R and γ_R, in the two equations

Galins and Shirkey's[10] suggestion for a transport as applied to general aviation implied the roughened aircraft weight to be the same as the clean aircraft weight, $W_R = W_C$ Equations (15) and (16) are solved for the climb angle γ_R and the takeoff speed V_R that sustain a steady climbing flight with an adequate stall margin The results in Table 2 show that for roughness in which the lift loss is $\Delta C_L / C_L > 0$ 3 the climb angle becomes negative and the takeoff speed is 120% that of the clean aircraft To climb at all for $\Delta C_L / C_L > 0$ 3, the stall margin will have to be reduced to an unsafe level A thrust that decreases slightly with an increase in takeoff speed only makes the situation worse

Week's[9] suggestion implies that the climb angle remains same $\gamma_R = \gamma_c$ and that Eqs (15) and (16) be solved for the V_R and the relative reduced takeoff weight $(W_c - W_R)/W_c$ that sustain a steady climbing flight with an adequate stall margin The favorable results in Table 2 show that for different roughness conditions, V_R deviates from V_c by about ±3%, and the relative reduction in the aircraft weight shows somewhat the same trends as $\Delta C_L / C_L$ Ljungstroem's suggestion of only partially cleaning the wings will result in an unsafe takeoff if the aircraft is at the maximum clean gross weight as is obvious from Table 2

The final option is to maintain the same takeoff speed $V_R = V_c$, and solve for γ_R and $(W_c - W_R)/W_c$ from Eqs (15) and (16) in order to sustain a steady climbing flight with an adequate stall margin The results in Table 2 indicate that γ_R deviates not more than 0 5 deg from γ_c and the required relative aircraft weight reduction, $(W_c - W_R)/W_c$, is practically the same as the relative lift loss $\Delta C_L / C_L$ This means the maximum gross weight of the roughened aircraft can be approximated as

$$W_{R\max} \simeq (1 - \Delta C_L / C_L)\, W_{c\max} \qquad (17)$$

This takeoff procedure does not have to use the aircraft's equations of motion and is related to partial removal of roughness through the relative lift loss term $\Delta C_L / C_L$ Of course while setting $V_R = V_c$ and maintaining constant airspeed during climbout the angle of attack will naturally be at the reduced value for a safe margin above stall Although one of the purposes of a safe stall margin is to tolerate small wing roughness it is rather obvious the typical roughness thickness due to frost ice, or rain reported here and elsewhere can bring the stall margin below a safe level (at least for the general aviation aircraft examined) when fully loaded

Similar conclusions apply to the transport aircraft For example if a transport such as a Boeing 727 has a typical takeoff speed of 265 ft/s and a wing chord length of 16 4 ft then a roughness height of 1 mm gives $Re_c(k/c) = 1714$ or $\Delta C_L / C_L = 0$ 32 according to Fig 3 for a fully covered wing This result assumes the data in Fig 3 can be extended to a transport such as a Boeing 727 even though the airfoil section may be different and the Re_c is much higher If the transport aircraft is to maintain the climbout performance, that is retain the climb angle and its usual 40% stall margin then Eq (17) applies in requiring a 32% reduction in maximum gross weight On the other hand Galins and Shirkey's[10] recommendation of a 6% takeoff overspeed for $W_R = W_c$ would result in an 11% reduction in the lift coefficient according to Eq (16) This is equivalent to a 19% stall margin of the lift coefficient of the roughened wing A drag increment of about 27% is expected after substituting $Re_c(k/c) = 1714$ into Eq (4) and dividing it in half If a transport, such a Boeing 727 has a clean climbout angle of 3 5 deg and a clean lift to drag ratio of 10 0, then a solution of Eqs (15) and (16) gives $\gamma_R = 1$ 08 deg for $W_R = W_c$ As a result the roughened aircraft is barely climbing and about a 26% increase in the takeoff thrust is necessary to maintain the normal climb angle Thus it is evident that only a 1 mm roughness height on the wings may require a transport aircraft pilot to initiate procedure modifications over and above Boeing's recommended 6% overspeed

Landing Performance Evaluation

Assume that for any flight landing, the weight, the air density and the wing area are constants The lift and drag coefficients will differ according to the existence of roughness on the wings and fuselage Under these conditions, Eqs (13) and (14) are rewritten as

$$\frac{\cos\gamma_R}{\cos\gamma_c} = \frac{C_{L_R}}{C_{L_c}} \frac{V_R^2}{V_c^2} \qquad (18)$$

and

$$\frac{T_R}{T_c} = \frac{\sin\gamma_R + C_{D_R}\left(\frac{\rho_a S}{2}\right)V_R{}^2/W_c}{\sin\gamma_c + C_{D_c}\left(\frac{\rho_a S}{2}\right)V_c{}^2/W_c} \qquad (19)$$

Considering the known clean aircraft landing parameters T_c W_c V_c γ_c C_{L_c} C_{D_c} and the roughened aircraft lift and drag curves, which are derived by modifying the clean aircraft curves via Eqs (9 12) there remain three unknowns, T_R V_R and γ_R, for the two equations A clean climb angle of −3 5 deg an airspeed of 108 2 ft/s, and an aircraft weight of 3100 lb result in computed values of $\Delta C_L / C_L$ $\Delta\alpha/\alpha$, ΔC_D and α_R for the landing case, similar to those shown in Table 2 One difference is that by solving Eq (14), the clean aircraft thrust is now 123 8 lb which is about four times less than the takeoff thrust

Table 3 summarizes four modified landing procedures The first two assume no change in airspeed and no change in thrust, respectively The third and fourth procedures are two different ways of specifying the descending angle one involving no change in descending angle and the other no change in the sink rate In the first case, where $V_R = V_c$, the modified landing procedure that would maintain a safe stall margin with roughened aircraft gives values of the climb angle of −27.5 to −48 3 deg and negative thrust Since the thrust is negative and the climb angle is at least −25 deg it would be impossible to maintain a safe stall margin under any circumstances.

The next modified landing procedure shown in Table 3 is that of $T_R = T_c$ The increase in airspeed varied from 6% to 22% as required to maintain a steady descending flight for a roughened aircraft with a safe stall margin The descending angle is still too large because it will result in an increase in the sink rate of 38% to 150% of that of the clean aircraft sink rate Furthermore sufficient thrust is available to possibly arrest such a sink rate

The third modified landing procedure is to maintain the glide slope or $\gamma_R = \gamma_c$ In order to maintain a steady descending flight for the assumed roughened aircraft with a safe stall margin the increase in airspeed varied from 6% to 22% and the increase in thrust varied from 46% to 181% The required thrust is well under the 300% limit, and the increase in the sink rate varied from 6% to 22% for the various roughnesses shown in Table 3 This landing procedure would be feasible if the aircraft could tolerate a higher sink rate

However, the best modified landing procedure would maintain the same sink rate as the clean aircraft, or $V_{y_R} = V_{y_c}$ Thus, the glide slope would decrease for the roughened air craft as the increase in airspeed varied from 6% to 22% to maintain a safe stall margin At the same time, the increase in thrust varied only from 55% to 209%, as shown in Table 3

In summary, aircrafts, in general to maintain a safe stall margin due to aircraft roughness, must have a relative landing speed V_R / V_c, as calculated from Eq (18) with $\cos\gamma_R \simeq \cos\gamma_c$ In addition, sufficient thrust must be applied to maintain a safe sink rate Thus, an effective combination of pitch and thrust controls must be applied to maintain V_R and V_{y_c} during a steady state landing

Conclusion

A simple and safe takeoff or landing method with wing roughness or protuberances has involved combining the computation of aerodynamic penalties with the steady flight equations The empirical relationships for the drag lift, and angle of attack penalties for different airfoil types and surface contaminations are summarized in Table 1 and Eq (5 7) Their use in constructing the lift and drag coefficient vs the angle of attack was explained in the first section The relative maximum lift loss has a semi-log relationship with the variable $Re_c(k/c)$ for the different airfoil types and surface contaminations This has allowed us to select typical values for k and to choose the NACA 65A215 20 deg flaps airfoil with uniform roughness as a demonstration case with results that should qualitatively apply to all airplanes in general

In order to maintain a safe stall margin with wing con tamination, the lift coefficient during takeoff or landing is equal to the clean aircraft coefficient reduced by the relative maximum lift loss due to contamination. This implies that the angle of attack at takeoff or landing is equal to the clean aircraft angle of attack reduced by the relative stall angle loss due to contamination This alone is not enough to insure a safe takeoff or landing, as there are various ways of maintaining a safe stall margin due to wing roughness or protuberances using the steady climbing or descending flight equations

Consequently, for a safe takeoff it is recommended that the maximum gross weight be reduced by the same amount as the relative maximum lift coefficient loss, which can be as high as 33%. The increase in takeoff speed to maintain a safe stall margin (rather than reducing the gross weight) was found to be ineffective in cases of serious wing contamination On the other hand it is not practical to reduce the maximum gross weight when landing. Fortunately, with wing con tamination, a safe stall margin and a safe sink rate are maintained by increasing the landing speed and by increasing the thrust This is true even when entering a heavy rain or an icing environment in which aerodynamic penalties are an ticipated by increasing the landing speed

The takeoff and landing performance analysis can be applied to most airplanes provided the relative maximum lift loss and the relative stall angle reduction can be related properly to (k/c) P and Re_c of a particular aircraft Ob viously, a wind tunnel and a flight test program would need to be conducted to verify the takeoff or landing procedure modifications before even considering operational ap plication

It must be pointed out that, in mose cases, the preventive procedures, such as ice and frost removal or avoidance, and heavy rain avoidance, are the more sane and convenient ones to follow, as the takeoff and landing accidents testify Thus operationally, this paper is directed to emergency flight conditions that are likely to occur either with a system failure or in a military environment

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