Effects of Anti-icing Treatment on Lift Degradation during Simulated Take-off

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Effects of Anti-icing Treatment on Lift Degradation during Simulated Take-off

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FOREWORD

This research report is focused on the characteristics of anti-icing fluid flow off from an aircraft wing, which is an important subject in aviation safety. It forms part of the second year studies in the Icewing project initiated by the Finnish Transport Safety Agency, Trafi. In the initiation of the work participated Trafi's Director General of the Civil Aviation Pekka Henttu, Head of Department (Traffic analyses) Heli Koivu, Head of Department (Research and Development) Sami Mynttinen, Chief Adviser (Research and Development) Inkeri Parkkari, and Chief Adviser (Aeronautics) Erkki Soinne, who also supervised the research team.

The research was performed by the team of the Aerodynamics research unit of the Aeronautics research group, first headed by professor Olli Saarela and then by professor Timo Siikonen, at Aalto University at Helsinki in Finland. Following people in the unit participated in the work: MSc Mika Hurme, laboratory engineer MSc Juha Kivekäs, PhD student Airline captain Pekka Koivisto and MSc Antti Rinne.

Helsinki, November 15th 2013

Erkki Soinne

Chief Adviser, Aeronautics
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ABSTRACT

Effects of anti-icing treatment on wing section lift degradation was studied in Aalto University Low Speed Wind Tunnel during winter period 2012-13. Type II and Type IV fluids of one manufacturer were tested. Wind tunnel model used was a three element two dimensional rotating wing section with a chord of 0.65 m. Wind tunnel test section is 2 m x 2 m. Conducted tests consisted of take-off simulations with approximately linear acceleration up to speed of 60 m/s (120 kt). Comparison between one-step and two-step deicing treatment showed no significant differences in fluid flow off properties. Diluted Type IV fluids (25%/75%) appeared to have almost equal aerodynamic effects as neat Type IV during the first 10 s after rotation. Type II fluid had unexpectedly more adverse effect on lift than thicker Type IV fluids. Effect of acceleration time on lift degradation is straightforward by delaying the lift degradation. Also the effect of real cold soaking frost was studied in case of a quite thin frost layer. Aerodynamic effects were significantly less than in case of anti-icing fluids.

NOMENCLATURE

AAT = Aerodynamic Acceptance Test
c = chord
C_L = lift coefficient
CSFF = cold soaked fuel frost, frost on wing surfaces at wing fuel tank area generated by cold fuel
FCOM = Flight Crew Operating Manual
HOT = hold over time, time following an anti-ice treatment within which take-off has to be commenced
k = proportionality coefficient
L = lift force, force perpendicular to the airflow
M_y = ptching moment
n = viscometer rotational speed
OAT = outside air temperature
PEP = Performance Engineer's Program
q = dynamic pressure
RH = Relative Humidity
S = wing reference area
TI = Type I fluid
TII = Type II fluid
TIV = Type IV fluid
TOW = Take-Off Waight
x/c = chordwise relative coordinate, leading edge x/c=0, trailing edge = 1 (or 100 %)
V_1 = decision speed
V_{1sg} = 1 g stalling speed
V_R = rotation speed
V_2 = take-off safety speed
α = angle of attack
α_i = electronically indicated angle of attack
α_m = visually measured angle of attack
$\dot{\gamma}$ = fluid shear rate

1. Introduction

Present Aerodynamic Acceptance Test (AAT) for de/anti-icing fluids is defined in SAE Aerospace Standard AS 5900[1]. SAE AS 5900 is based on research with Type I and Type II fluids not any more on the market. The flight tests and extensive wind tunnel tests that formed the scientific basis of AAT were mainly concentrated on B 737-200 ADV geometry[2]. Since early 1990's when the AAT was completed there have been major changes in the quality of Type II fluids and Type IV fluids have appeared to the market. This however has never lead to updates in the content of AAT.

This report is a documentation of the second part of a two phase wind tunnel research program (Icewing) to examine whether Type IV fluids and wing geometry differing from the B 737 wing leads to different results from the ones AAT (AS 5900) is based on. The present study is motivated by the operative problems and concerns related to the use of Type IV fluids[3]. Icewing research project was funded by Trafi.

The present study is based on wind tunnel tests at Aalto University Low Speed Wind Tunnel carried out during January 3th - April 5th 2013 utilizing a rotational 3 element 2 dimensional wing section model. There were altogether 17 wind tunnel days with more than 30 wind tunnel runs conducted during the test program. The first part of the two phase project is documented in Ref.3 and it concentrated on the fluid flow off process in general during simulated taxi and take-off using a fixed 2 dimensional one element wing section model.

As AAT forms the reference for analyzing the aerodynamic effects of de/anti-icing fluids the present study applies the methodology adopted in wind tunnel tests performed to compose AS 5900. This means simulated take-off runs in wind tunnel with accelerating airspeeds up to speeds that correspond to a typical airliner rotation speed and sequentially rotating the wing model to an angle of attack representing a lift coefficient typical in an One Engine Out situation at the speed of V_2. The aerodynamic forces were measured throughout the wind tunnel run. In addition video recordings were taken for qualitative analysis.

2. Objectives

The objectives of the present study were to evaluate the effects of Type IV and modern Type II fluids on lift degradation (see chapter 6.) of an airliner during a simulated take-off. The following parameters were studied:

- Take-off sequence parameters: acceleration (time to reach V_R), rotation sequence and angular velocity during rotation
- Fluid type (TII and TIV) and the deicing treatment method (1 step vs. 2 step treatment)
- Dilution of Type IV fluids with water (25 % H_2O)
- Temperature and initial thickness of fluid within limited variation

As there is no possibility for temperature control in Aalto University Low Speed Wind Tunnel the prevailing outside air temperature had to be accepted as a daily changing "fixed" parameter.

In addition to the fluid tests there were two additional tests with real frost on the wing surface to study the effect of frost compared to anti-icing fluids during take-off.

3. Test Arrangements

3.1 Wind Tunnel

Aalto University Low Speed Wind Tunnel is a closed circuit wind tunnel with an octagonal test section with dimensions of 2 m x 2 m and test section length of 4 m. The flow uniformity in the test section is < 0.14 %, and turbulence level <0.1 %.
The massive concrete structures of the wind tunnel ducts are outside the facility building. This makes the tunnel structure during winter time an efficient heat sink and the fan power dissipated during short period take-off run simulation does not increase the test section temperature significantly (< 2 º C). Temperatures in the test section follow roughly the daily outside air temperature (OAT) which during the winter time are suitable for deicing/anti-icing fluid tests (near or below 0 º C). During the tests of this study the wind tunnel air temperature varied between – 9°C and + 3°C.

3.2 Wing Section Model

All tests of the present study were conducted with a two dimensional 3 element rotating model that was mounted to a three component balance to measure the aerodynamic lift, drag and pitching moment. The model was equipped with endplates to minimize the three dimensionality of the flow. Two dimensionality and absence of flow separations were confirmed by tufts. Slats and flaps were adjustable (Fig 2.) and so it was possible to simulate the real operational sequence of extending the flaps and slats just prior to the test. The model was equipped with a glycol coolant tank to simulate the effect of cold fuel in a wing tank of an airliner (Fig 2.).

The wing section model has the geometry of a DLR-F15 (Ref. 4) profile and a chord of 0.65 m. The model span was 1.5 m which implies an area of 0.975 m^2. Anti-ice fluid was applied on the whole upper surface area during the tests (Fig 1.). The model was equipped with two temperature sensors to monitor the coolant tank temperature and the fluid temperature at the 75% chord position. Span wise this sensor was at the centerline of the wing model. The upper side of the model was equipped with thickness measurement point markings in 27 different points (Fig 11.).

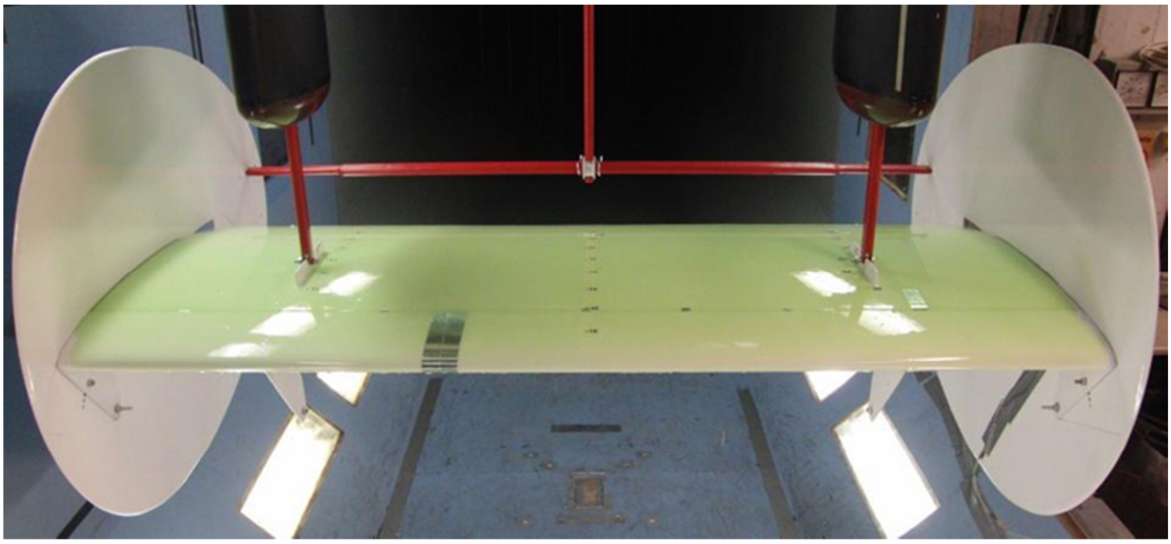

Figure 1. Rotating wing section model in wind tunnel.

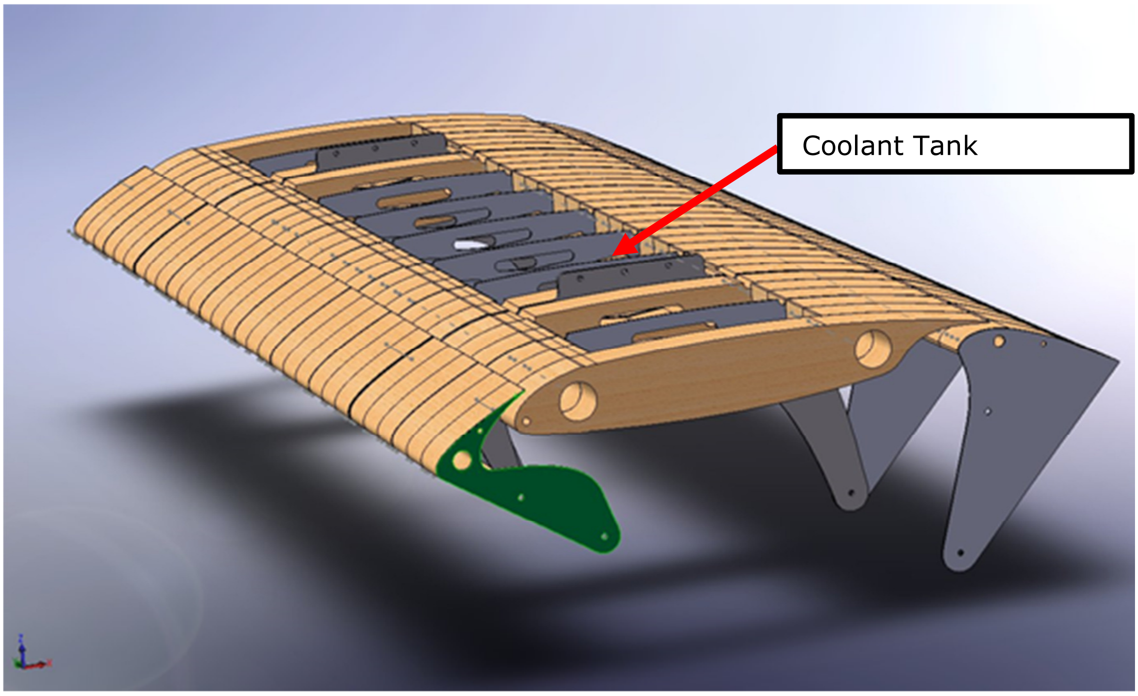

Figure 2. Structure of wing section model

4. Data Acquisition and Assessment of Measurement Accuracy

There is a standard measuring software in the wind tunnel collecting the wind tunnel temperature, airspeed, dynamic pressure, relative humidity, balance forces and moments (lift, drag and pitching moment in this case) and wing angle of attack.

The temperatures of the cooling tank and fluid on the wing were measured separately as the intention was to follow the mean temperatures during each test and not to coordinate it with the measurement sequence in time.

For qualitative analysis of the fluid flow off the test runs were videoed through a Plexiglas window on the roof of the test section. There was no intention to measure the mean thicknesses in time as in the case of fixed model tests reported in Ref 3.

The effect of different de/anti-icing treatments on the take-off performance is evaluated by measuring the lift coefficient degradation ΔC_L due to the treatment. This means sequential C_L - measurements of the clean wing and wing with fluid applied on the upper surface. As the result is a difference of two lift coefficients at the same angle of attack the repeatability of tests is more relevant than the absolute accuracy. There is a detailed description of lift coefficient degradation repeatability in Chapter 7.2.9.

Due to some elasticity of the model suspension setup the angle of attack α indicated electronically differed from the actual visually measured α. While the indicated angles of attack had an average coefficient of variation (standard deviation divided by mean value) per measurement of $1.13\ 10^{-14}$ %, the visually measured angles of attack deviated considerably from the indicated ones. This deviation was detected to be in linear dependence with the indicated angles of attack. A simple correction formula for the indicated angle of attack were developed assuming that the error due to elasticity is proportional to the pitching moment of the model. Using this formula the corrected lift coefficients were calculated assuming linear dependency between the lift coefficient and the angle of attack (see Chapter 7.2.9 and Appendix).

The initial mean thicknesses of fluid layers were measured directly from the batchers used to apply the fluid and via point wise measurements of film thickness using an Elcometer type of thickness gauge. After subtracting the off dripped fluid before the test from the applied amount the two methods gave an initial thickness that agreed within 5%.

The maximum effect of mass of the applied fluid on the measured lift values were less than 0.1 % of lift force.

5. The Rheological Properties of the Anti-icing Fluids

In the present study only one manufacturer supplied their Type IV and II fluids for the tests. These two fluids represent then in this study the behavior of Type IV and Type II anti-icing fluids. The viscosities of the fluid batches used to the tests were determined with a Brookfield LV viscometer (spindle no LV2). The viscosity variation of Type IV fluid with shear rate (or in this case the viscometer rotational speed *n*) is shown in Fig. 3. The viscometer rotational speed *n* can be converted to shear rate $\dot{\gamma}$ using a recursive method of ref 6. Then the horizontal scale will be modified but the basic behavior is similar to Fig. 3, which shows the typical non-Newtonian behavior of Type IV fluid: the viscosity reduces with the shear rate of the fluid (shear thinning). This means for an anti-ice fluid that the increasing aerodynamic shear stress due to outer airflow will enhance the fluid flow off from the wing.

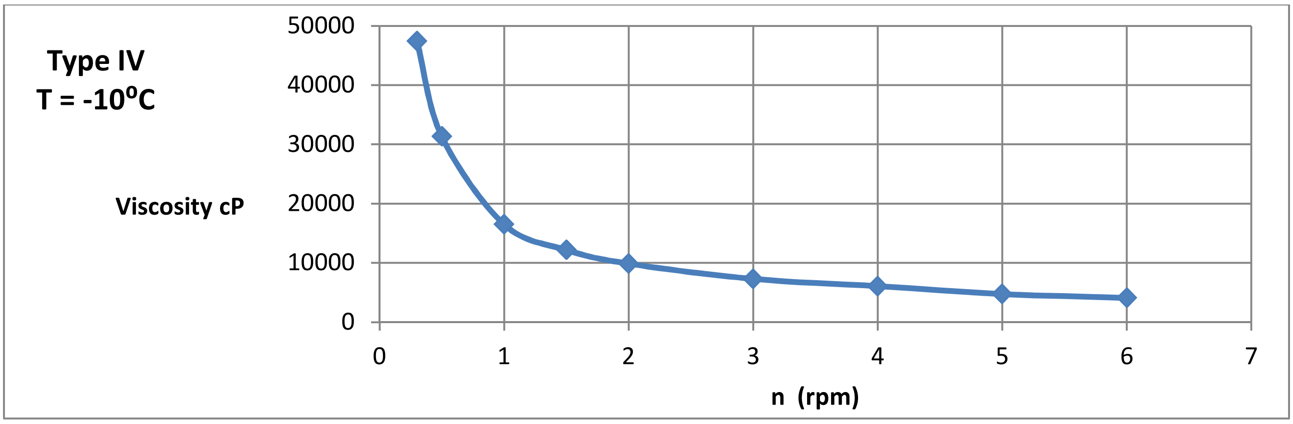

Figure 3. Viscosity variation of Type IV fluid with rotational speed of Brookfield LV viscometer (spindle no LV 2).

The variation of viscosity with temperature for the selected fluid can be seen in Fig. 4 for two distinct shear rates (=n in this case). The variation of viscosity with temperature is quite modest in the range of temperatures prevailing during the tests of present study.

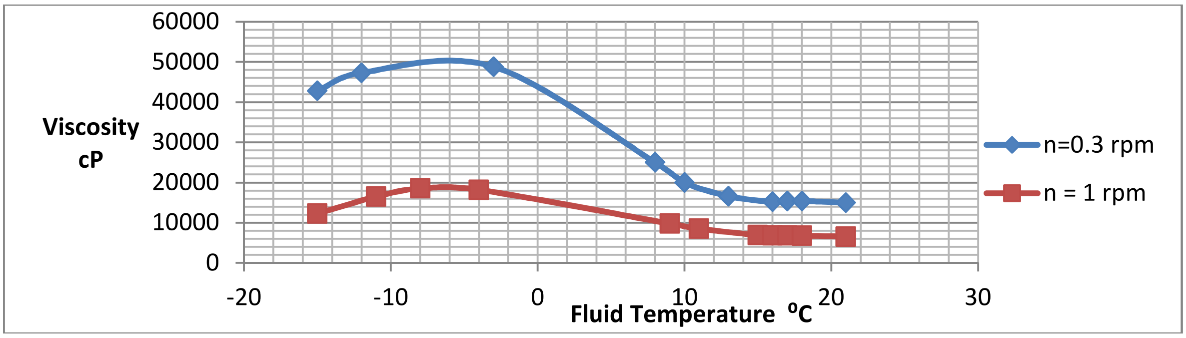

Figure 4. Viscosity variation of Type IV fluid with temperature for two viscometer rotational speeds.

The corresponding rheological properties for the Type II fluid are presented in Fig. 5 and 6.

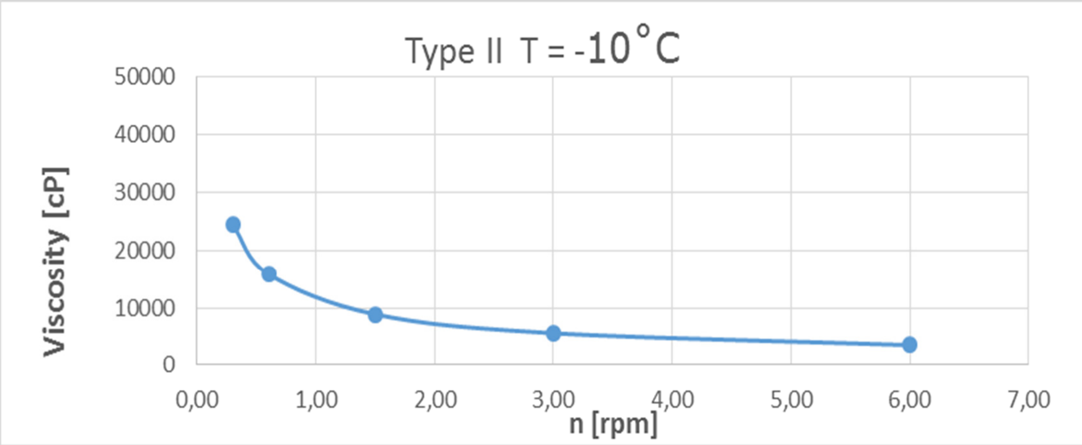

Figure 5. Viscosity variation of Type II fluid with rotational speed of Brookfield LV viscometer (spindle no LV 2).

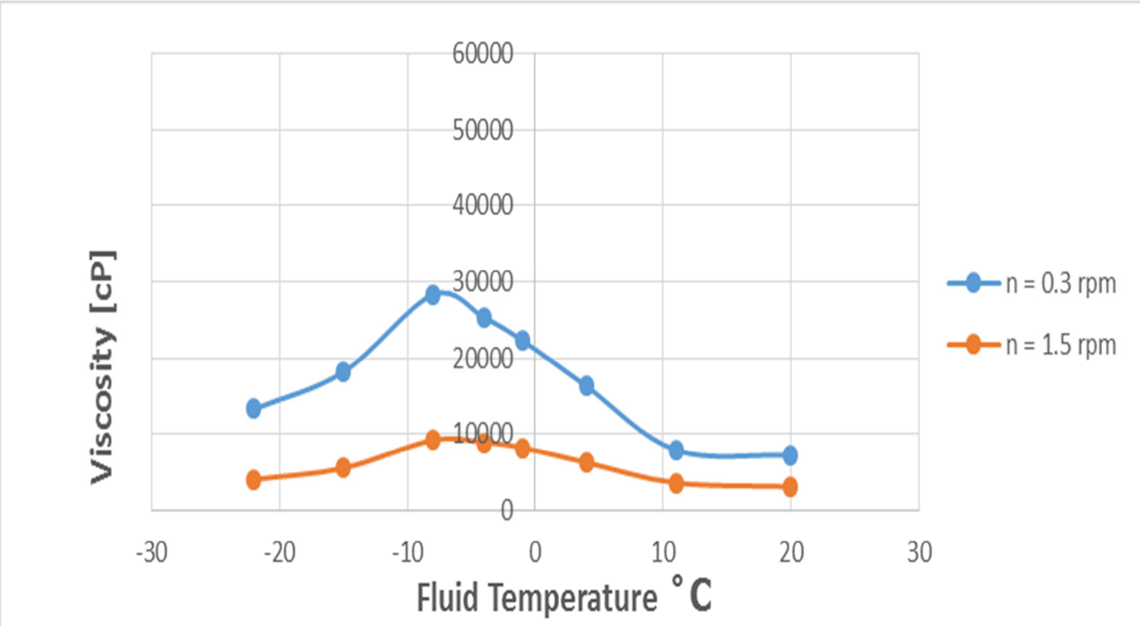

Figure 6. Viscosity variation of Type II fluid with temperature for two viscometer rotational speeds.

6. Measurement Program

6.1 Lift Degradation as a Take-off Performance Criterion

The objective of a take-off simulation test is to simulate the One Engine Inoperative (OEI) situation where the airliner is flying at the speed of V_2 after lift-off up to the so called "cleaning altitude" at which the flaps and slats are retracted (>400 ft above ground level as per EASA CS 25.121[7] see figure 7).

As the transient phase of fluid flow off is well before reaching the cleaning altitude the relevant phases of flight considering anti-icing fluid effects are take-off roll and initial climb at speed V_2.

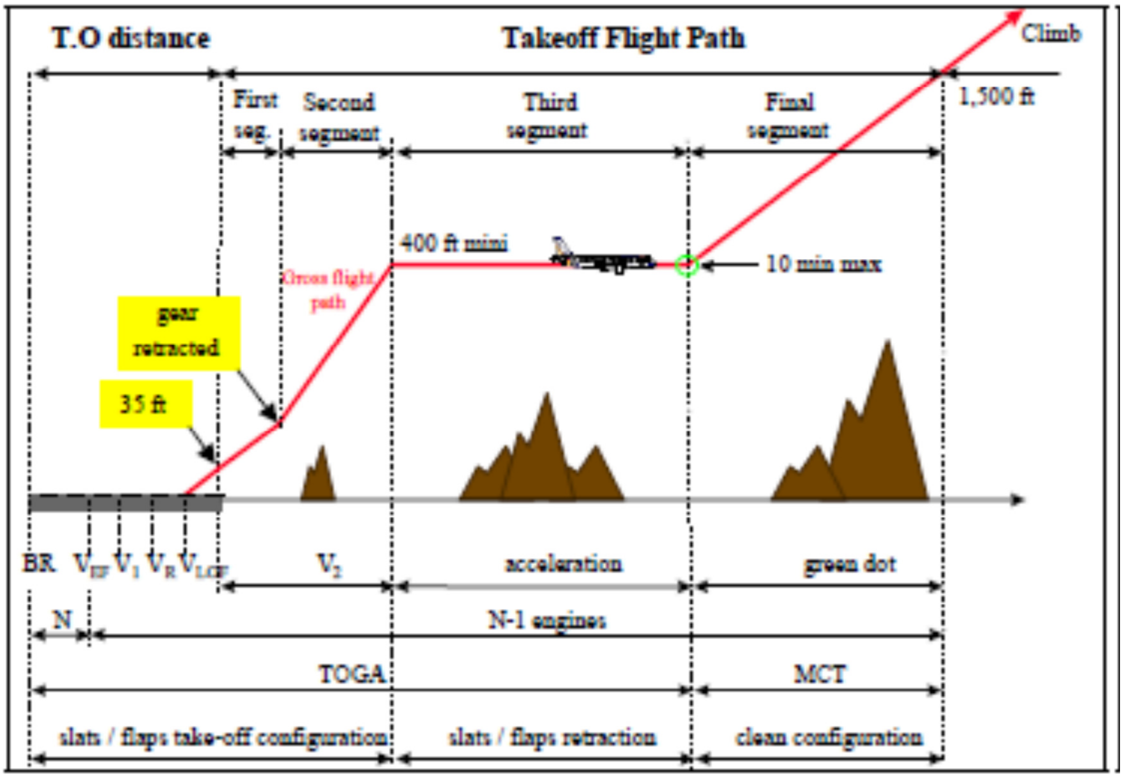

Figure 7. Take-off flight path as per EASA CS 25.121

While developing the Aerodynamic Acceptance Test, Hill and Zierten[8] evaluated five specific take-off performance criteria following FAR 25 requirements:

- Adequate margin between 1 g stall speed (V_{s1g}) and take-off safety speed V_2
- Adequate margin between minimum unstick and lift-off speed
- Adequate aft body-runway clearance during take-off
- Adequate take-off acceleration and climb capabilities
- Adequate maneuver capability to stall warning

Hill and Zierten determined that the most critical of these five criteria was maintaining adequate margin between the 1 g stall speed and V_2. To insure a safe operation when the fluids are used they selected a criteria requiring a V_2 that is at least 1.1 V_{s1g} compared to FAR 25 requirement of 1.13 V_{s1g}. Therefore in the case of V_2 limited take-off, the margin to stall is reduced from 13% to 10 %. This implies an acceptable lift loss of 5.24 %. The algebraic analysis behind this reasoning is presented in Ref 2.

Why the reduction in stall speed margin described above has been accepted by the community responsible for Aerodynamic Acceptance Test (SAE, AEA, Boeing, FAA etc.) has never been reasoned in any publication. Contrary to this at least one operator (SAS) applied take-off weight limitations for their DC-9 and MD-80 fleet[9] to maintain a stall margin originally defined in certification standard (then FAR 25)

Considering the conditions often prevailing after anti-icing treatment such as poor visibility and gusty winds it is particularly questionable to reduce the stall margins without any adjustments in take-off speeds or maximum take-off weights.

It should be noted that the 5.24% lift loss refers to the maximum lift coefficient for a three dimensional aircraft or wind tunnel model whereas the present study considers a two dimensional wing section at a C_L corresponding to V_2. However the analysis of Zierten and Hill showed for the B 737 an almost equal lift loss for these two. The three dimensional lift loss at maximum lift coefficient was 1.04 times the lift loss of two dimensional wing model at $\alpha=8^\circ$ (corresponding approximately speed of V_2).

Analyzing the correlation between the three dimensional wing maximum lift degradation and the two dimensional lift degradation at an angle of attack corresponding to speed V_2 due to fluid application is considered to be beyond the scope of the present study. Therefore the acceptable lift loss due to the fluids is considered to be 5.24% at the selected angle of attack representing V_2 (see 6.2).

6.2 Defining Wing Section Configuration and Take-off Sequence

A take-off sequence (engine failure at speed V_1) of an airliner consists of (see Fig. 7.):

- Acceleration from stand still to the rotation speed (V_R) with a constant pitch attitude during ground roll
- After reaching V_R the pitch attitude is increased to a lift off attitude (normally a predetermined constant value e.g. 15°)
- Once airborne the airspeed is accelerated to V_2 where it remains until reaching the cleaning altitude

To simulate in a wind tunnel the speed sequence in detail, as given above is too complicated a task. A generally adopted simplification among the AAT –research tests documented[2] is to accelerate the speed from wind tunnel idle speed as linearly as possible to V_2 and then rotate the wing section to a predetermined angle of attack and keep it there for a predetermined time – e.g. 30 s.

Simulating the take-off sequence described above in terms of flow conditions around the wing, a lift coefficient time history is assumed. The only unclassified source for C_L history during take-off known by author is the Airbus performance software PEP[10]. A graphical presentation of C_L time history for an Airbus 321 calculated by PEP, is presented is figure 8. The prominent C_L peak between V_R and V_2 is probably due to the short period of increased load factor during rotation (curved motion).

During the ground roll the lift coefficient C_L has a constant value of 0.75 regardless of weight or other aircraft dependent variables according to PEP. This is due to the constant pitch attitude and angle of attack. However to determine C_L–values during climb at V_2 calls for a more rigorous analysis.

The wing section model DLR F-15 is considered as a generic example of an airliner wing profile utilized by Airbus Industries though it is not identical to any particular wing section of any Airbus type. For this reason Airbus 321 is used only as a reference type in the following.

Analysis of fluid effects on the aerodynamic performance presented above was based on a V_2 limited take-off situation. A review of V_2 speeds for two different take-off configurations and take-off weights of Airbus 321 is presented in Table 1 (speed data for calculations taken from A321 FCOM, Ref 13).

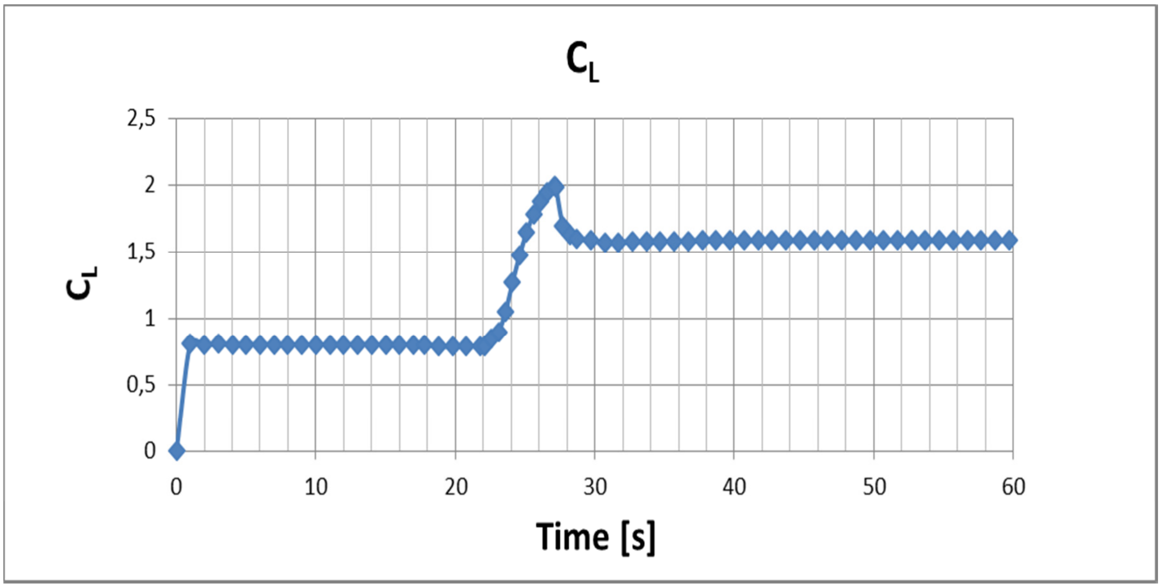

Figure 8. Time history of C_L calculated by PEP performance software. Parameters: TOW 66tn, configuration Slats 18°/Flaps 10°.

Table 1. Lift coefficients for different TOW values and take-off configurations on Airbus 321. Speeds taken from Airbus 321 FCOM (Ref 13).

TOW = 60 tn	TOW = 60 tn	TOW = 90 tn	TOE = 90 tn
Slats 18°/Flaps 10°	Slats 22°/Flaps 14°	Slats 18°/Flaps 10°	Slats 22°/Flaps 14°
V_{s1g} = 116 kt	V_{s1g} =108 kt	V_{s1g} = 141 kt	V_{s1g} = 131.5 kt
V_2 = 131 kt	V_2 = 122 kt	V_2 = 159 kt	V_2 = 149 kt
C_L =1.56 @ V_2	C_L = 1.8 @ V_2	C_L = 1.59 @ V_2	C_L = 1.8 @ V_2

According to Fig. 8 there should be approximately a difference of ΔC_L = 0.7 – 0.8 in C_L between ground roll and initial climb at V_2. Corresponding angles of attack are α = 0 at ground roll and α = 9° at V_2 when slats are deflected 22° and flaps 14° (according to PEP). These figures are not intended to be strict numerical objectives but merely as approximate guidelines for a realistic simulation.

The DLR F-15 wing section model was tested with several different slat and flap configurations to find a satisfactory combination of angle of attack and lift coefficient both during ground roll and at speed V_2, which in this case was limited by the maximum wind tunnel speed of 60 m/s (120 kt). An additional challenge in finding the best flap slat configuration was the tendency of the gap between wing and flap to be clogged by the fluid. After a set of extensive tests the best configuration appeared to be slats deflected 11°, and flaps 12°which gave the following combinations of angle of attack and lift coefficient (see also Fig. 9):

- Ground roll (acceleration to 60 m/s) α = 1° and C_L = 0.5
- Speed 60 m/s (V_2) wing section rotated α = 7.5° and C_L = 1.3

These combination gave a realistic lift coefficient difference (0.8) and fairly realistic angles of attack (which were not the primary objective as was the ΔCL).

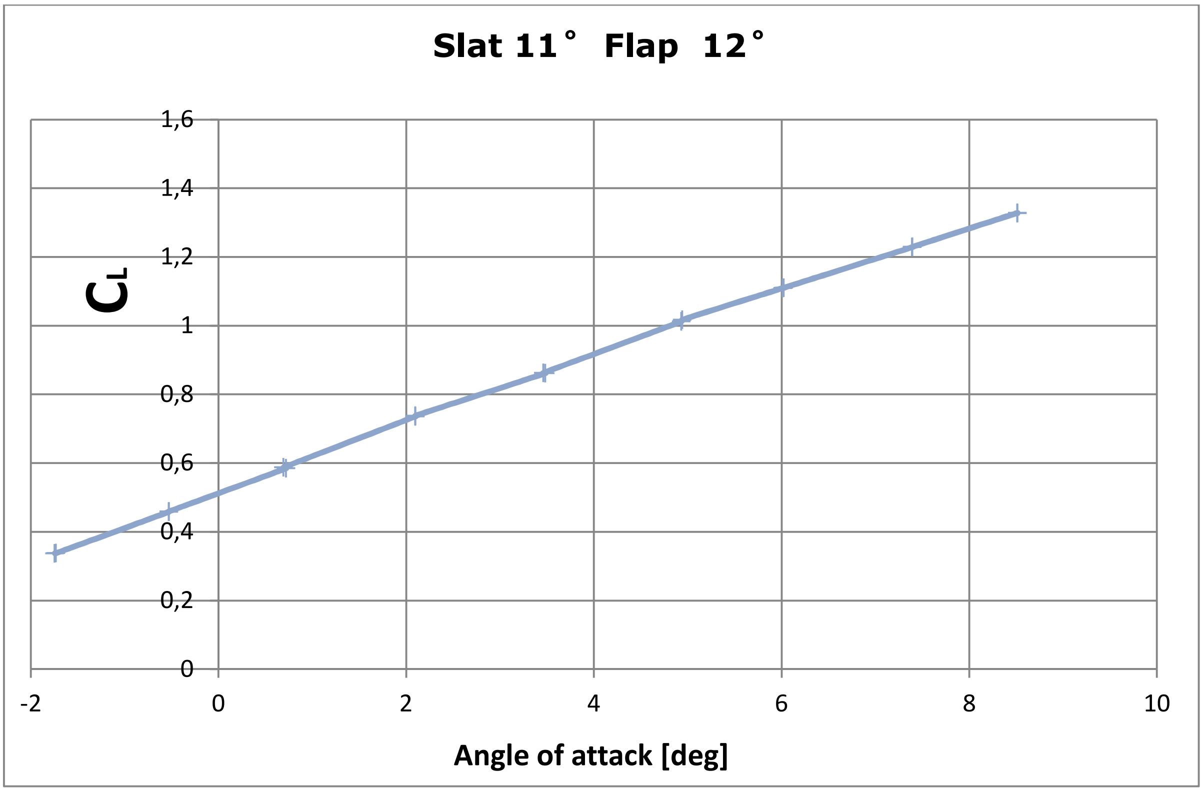

Figure 9. Measured lift coefficient curve for DLR F15 wing model at 60 m/s ($Re = 2.9\ 10^6$)

Some test runs with a clean and fluid treated wing model were done with three different sequences described in Figure 10. These tests were motivated by research reviewed in Ref. 2 and partly by the fact that performance software PEP predicts a short C_L peak to the take-off sequence. Note that in all three cases A, B and C the rotation is not started before the wind tunnel speed is accelerated up to 60 m/s.

Differences between maximum lift degradations due to fluid for all three types of angle of attack (α) sequences were negligible, however the repeatability of α in time was clearly the best in case A. As this was the type of α sequence in original AAT – research tests too it was chosen for the present study as well. The chosen speed-angle of attack (α) - time sequence was therefore as follows:

- At α = 1.0 wind tunnel speed is accelerated from idle speed to 60 m/s.
- As soon as the speed has reached 60 m/s it is kept constant and the wing section is rotated at a rate of 3.0°/s to α = 7.5°
- After α = 7.5° has been reached the wind tunnel speed is kept at 60 m/s for 40 s

The time used to accelerate the wind tunnel speed to 60 m/s is constant 30 s excluding those tests where the effect of acceleration time on lift degradation were studied (see Chapter 7.2.7).

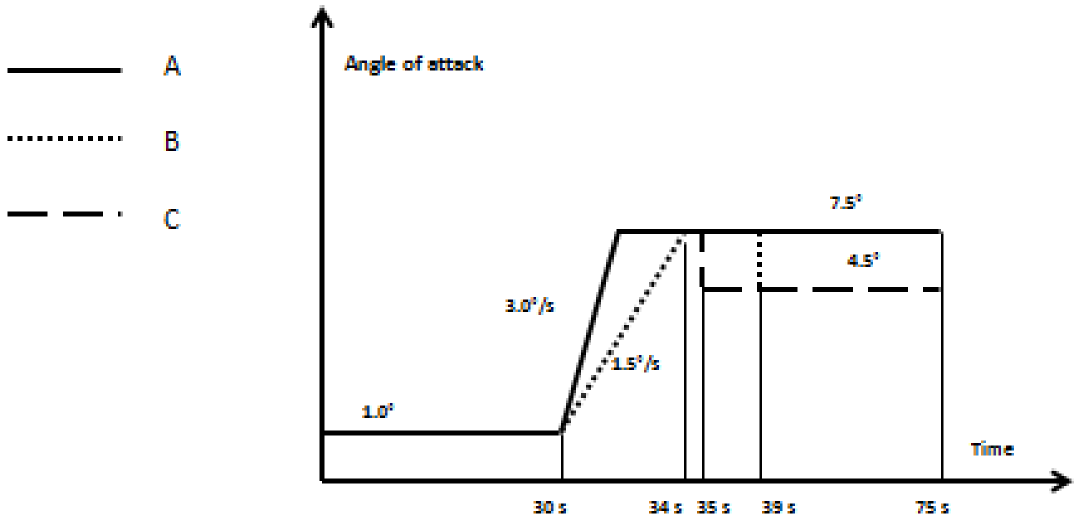

Figure 10. Angle of attack (α) sequences tested. Rotation from 7.5° to 4.5° was done with 1.5°/s in cases B and C. In all cases speed was accelerated to 60 m/s before the rotation from 1.0° to 7.5°.

6.3 Taxi Tests

Taxi tests were done with a wing section configuration of both slats and flaps retracted to simulate the real operation conditions. The wing section was kept in constant ground roll attitude (see above) while the speed was increased stepwise with 5 m/s increments. Once a significant fluid flow off from the trailing edge was detected the speed was kept constant for an extra 2 minutes – see Fig. 11.

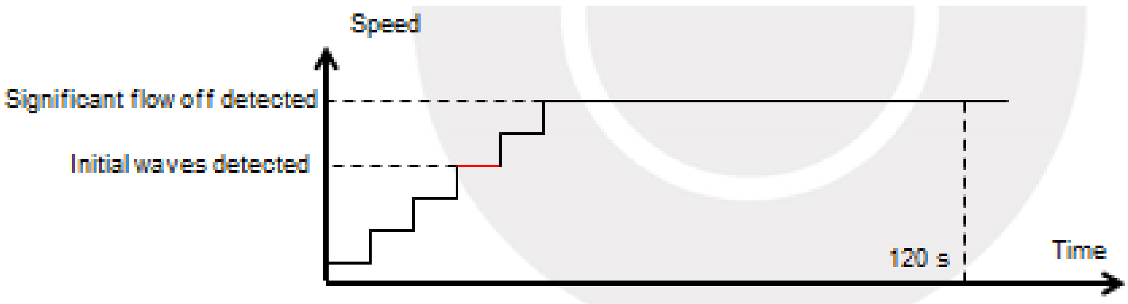

Figure 11. Speed sequence during taxi tests

7. Test Results

7.1 General Qualitative Observations

During all test runs video recordings were taken for general analysis of wave formation and fluid flow off. The general behavior of fluid flow off follows the general pattern of events described in Ref 3. However the flow off begins at the trailing edge somewhat earlier than in the one element model of Ref 3 as there is airflow also in the slot between flap and wing main element. First waves during the acceleration phase appear near mountings of the model probably due to local flow acceleration around the fittings (Fig. 12).

First waves in the mid span area (Fig.12) of wing section appear at a wind tunnel speed of 12 -15 m/s which is quite close the results of Ref 3 (10 – 13 m/s). The wave onset speed did not depend on fluid type. Most of the wing main section is clear of fluid when the speed has reached 60 m/s just prior to rotation (Fig 13). However there is still a clearly visible fluid layer at the trailing edge.

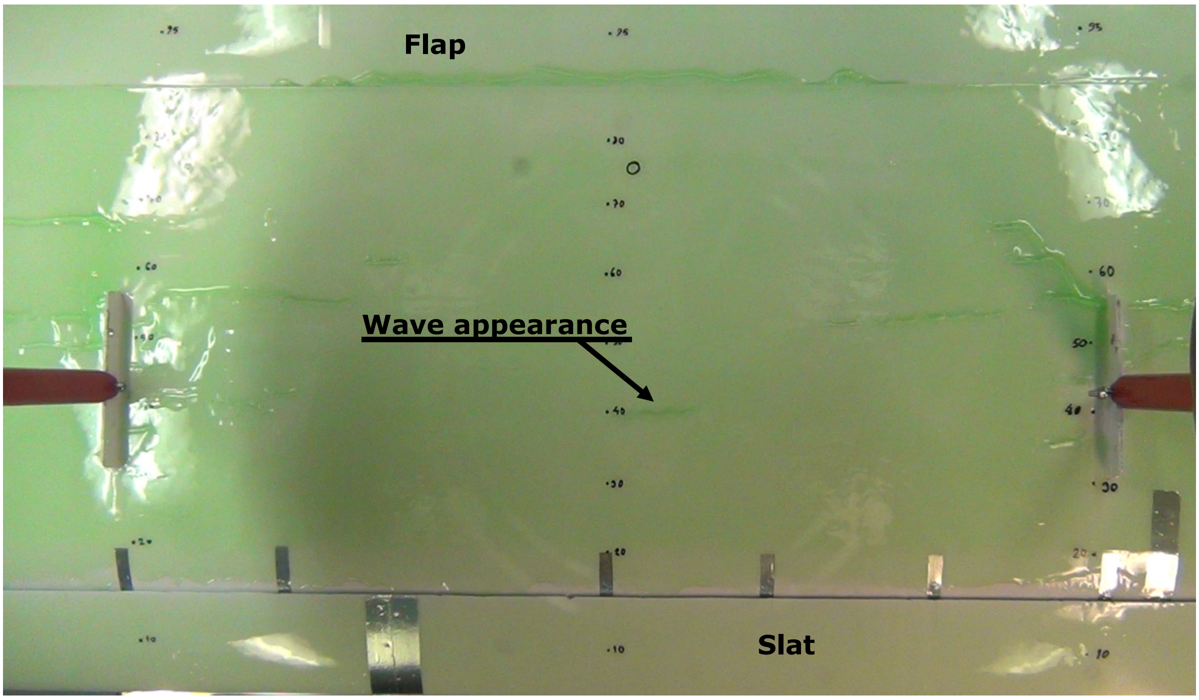

Figure 12. Wave appearance in the mid span area at position x/c = 40 %

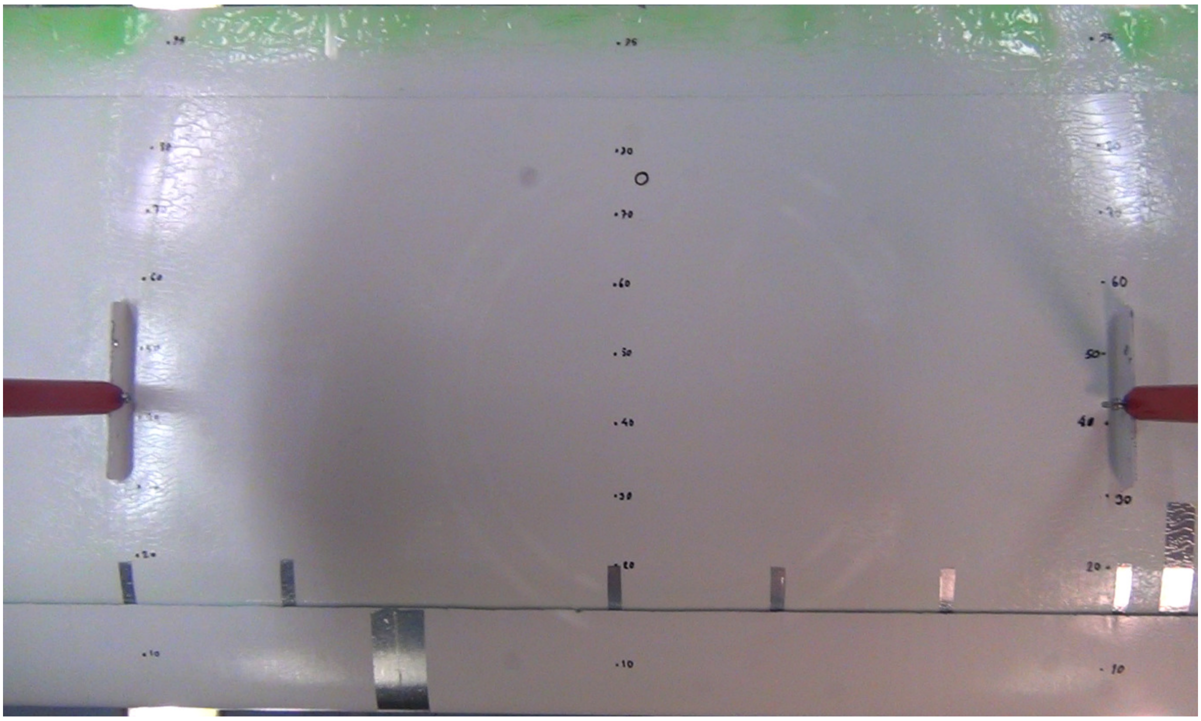

Figure 13. Fluid distribution just prior to rotation

Within one second after rotation a secondary flow appears from the lower side of the wing section. The secondary wave is visible in Fig. 14 at a 47-50 % chord position. In Fig. 15 there is a graphical presentation of the secondary wave movement in case of Type II fluid. The average speed (linear fit in Fig. 15) of the secondary wave is 7.2 %/s = 0.047 m/s. This means that the secondary wave reaches the trailing edge within about 10 s after rotation. According to the results of chapter 7.2 the lift degradation has reduced to half within 10 s in most cases. According to Ref. 11 the secondary wave is responsible for most of the lift loss.

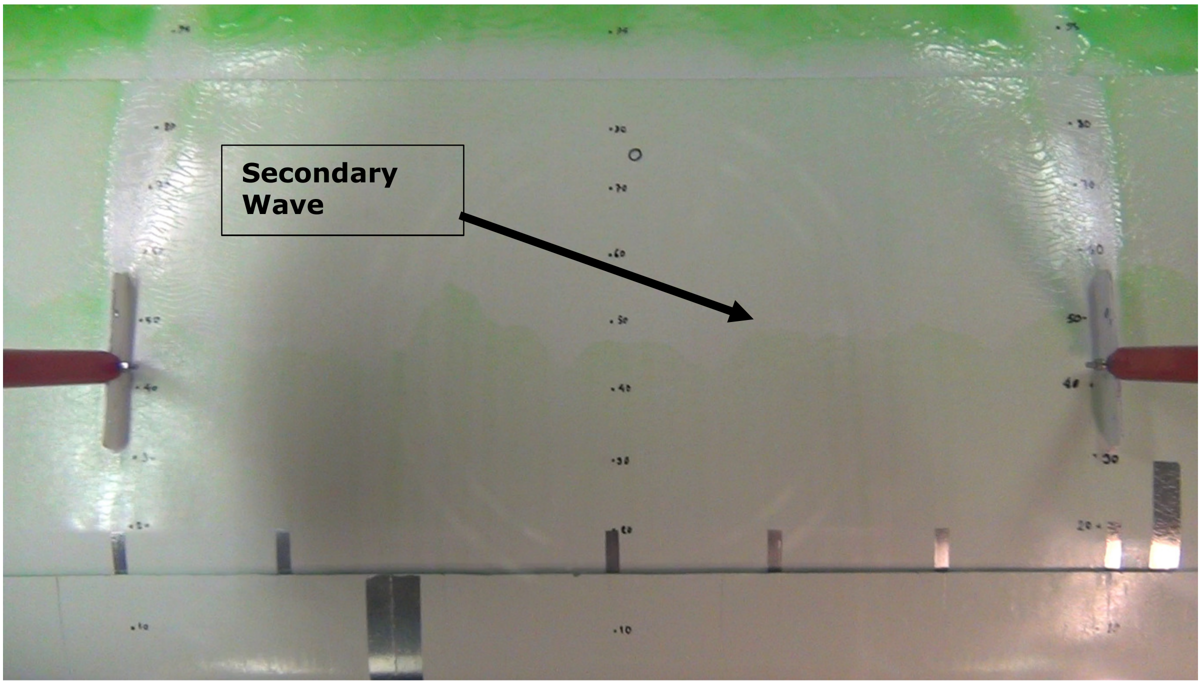

Figure 14. Secondary wave at a position at 47 -50 % chord position.

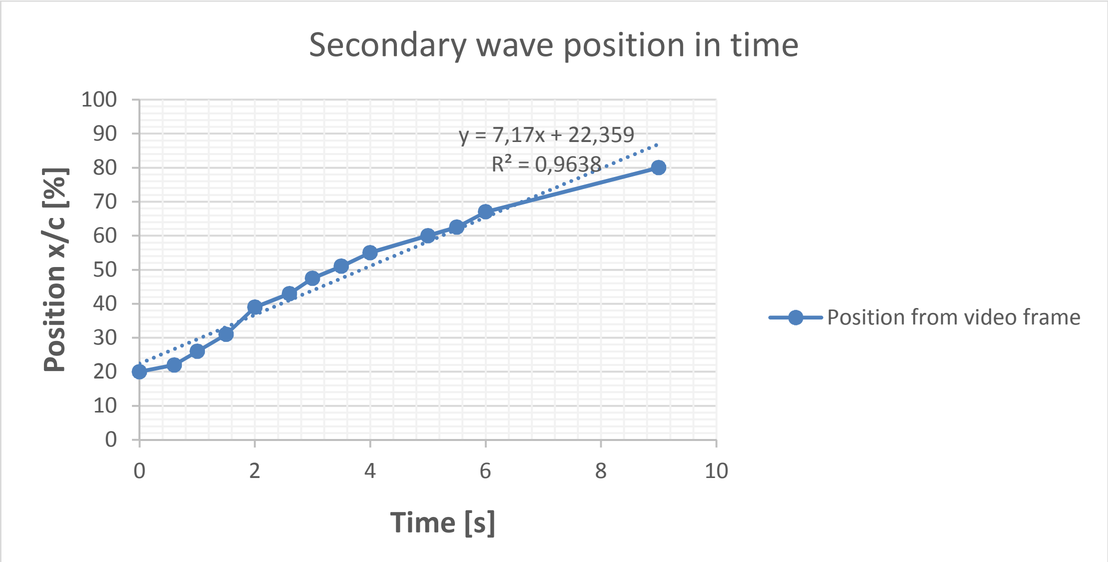

Figure 15. Secondary wave movement along the wing section chord. The dotted line is a linear fitting of the measured curve.

7.2 Lift Degradation Test Results

To determine lift degradation for different parameters the clean wing case was measured just prior to the fluid test to eliminate different daily changing factors on the results. In the following the lift degradation variation in time is presented in figures where time point 0 represents the situation where rotation has just ended and angle of attack $\alpha = 7.5^\circ$ has been reached. Results are presented in per cents (%) of clean wing lift coefficient. As reasoned above in chapter 6.1 an acceptable lift coefficient loss may be considered as 5.24 %.

All results in Chapters 7.2.1 – 7.2.8 are based on indicated angle of attack during tests. Chapter 7.2.9 summarizes the maximum lift losses in different cases with and without the angle of attack correction due to the elasticity of model suspension setup.

7.2.1 Comparison of 1-step vs. 2-step Treatment

Deicing treatment in one (neat Type IV) and two steps (diluted Type I + neat Type IV) is compared in Fig. 16. In two step treatment the Type I fluid is a mixture of 70 % water and 30% Type I fluid.
There seems not be significant difference between lift degradation time history for the 1-step and the 2-step deicing treatment.

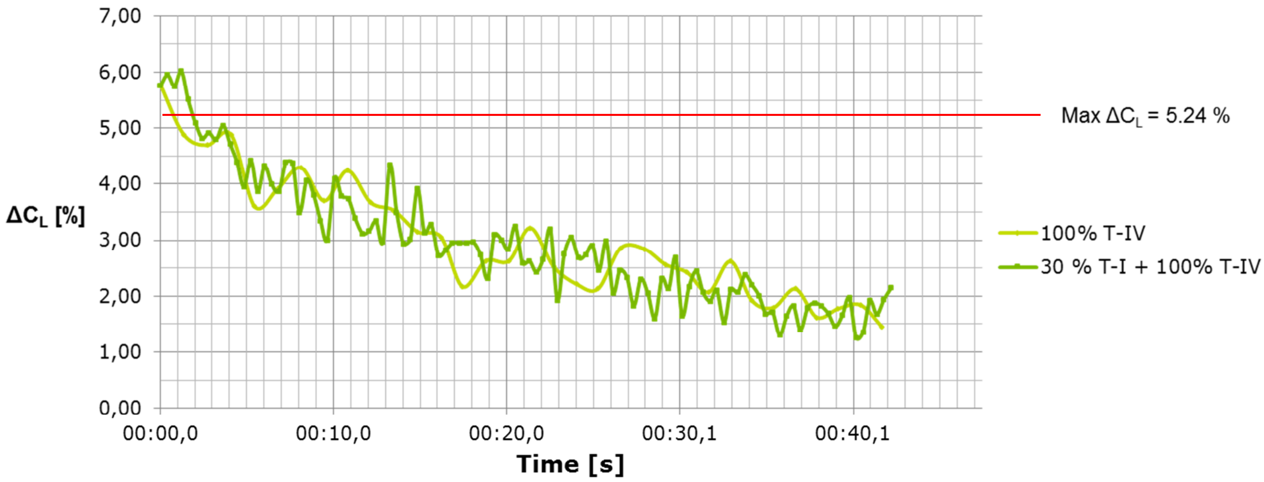

Figure 16. Comparison of lift degradation on 1-step and 2-step deicing treatments

7.2.2 Diluted vs. Neat Type IV Fluid

Comparison between lift degradation with neat Type IV and diluted Type IV (25 % water) treatment is shown in Fig. 17. During the first 10 seconds after rotation the lift degradations are quite equal. However after that the diluted fluid case the ΔC_L stays above 3 % for about 30 seconds whereas the neat fluid case continues to decrease steadily.

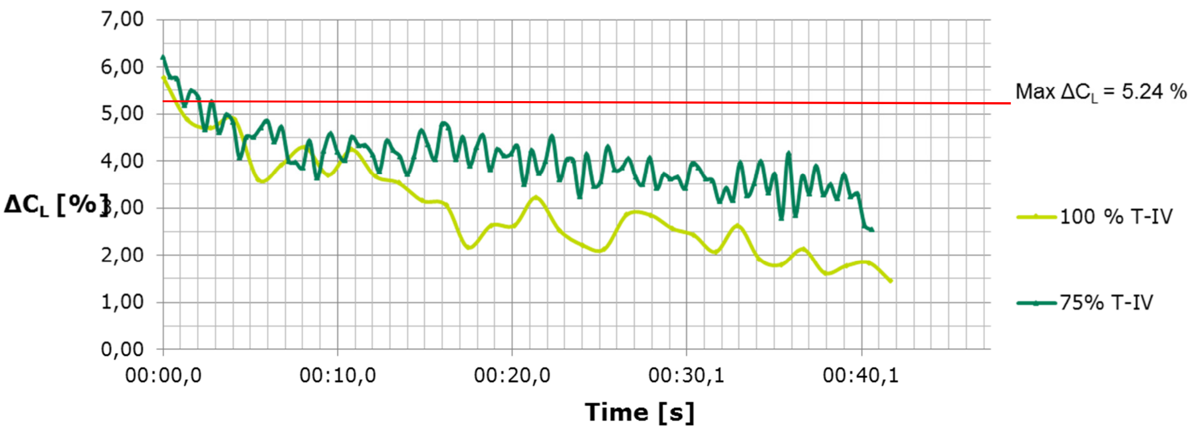

Figure 17. Comparison of neat and diluted Type IV fluid

7.2.3 Effect of Wind Tunnel Air and Coolant Tank Temperature

As there was no possibility to control the wind tunnel temperature the test temperature depended on the outside air temperature. Outside air temperature varied during the tests between -9°C and +3°C. The temperature variation was limited, however large enough to detect an effect as can be seen in Fig. 18.

With a temperature difference of 6°C the lift degradations differ clearly until 30 s after rotation. Thereafter the curves merge.
Effect of the coolant tank temperature on lift degradation is obviously much less than the effect of air flow temperature as can be seen in Fig.19. One explanation could be that the fluid boundary layer near the tank surface is most probably laminar whereas boundary layer of air near the fluid surface is mostly turbulent which implies a better heat transfer than in the case of laminar flow.

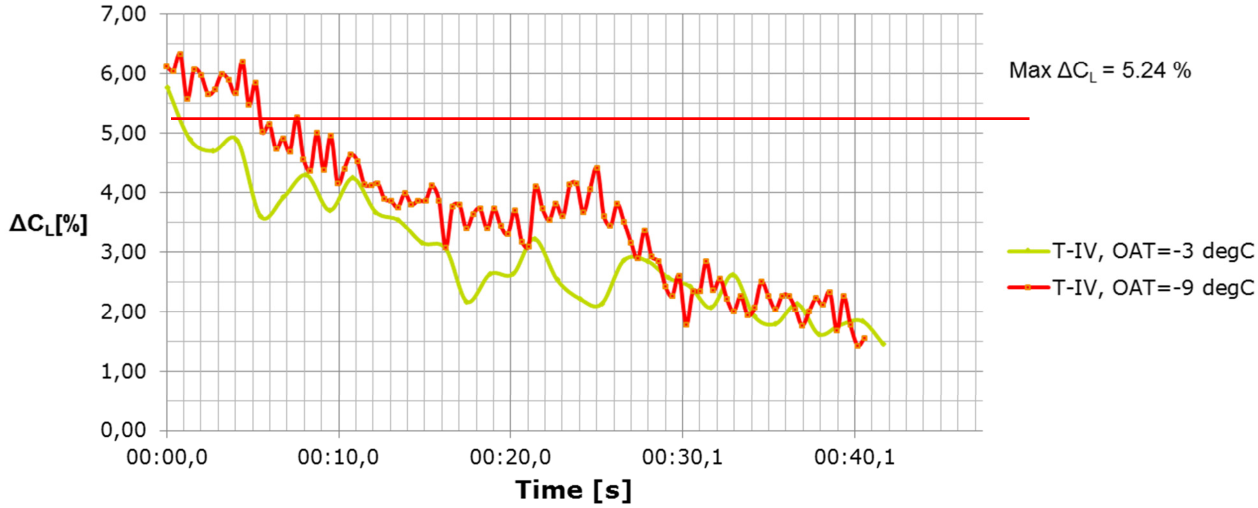

Figure 18. Effect of wind tunnel temperature (=OAT) on lift degradation

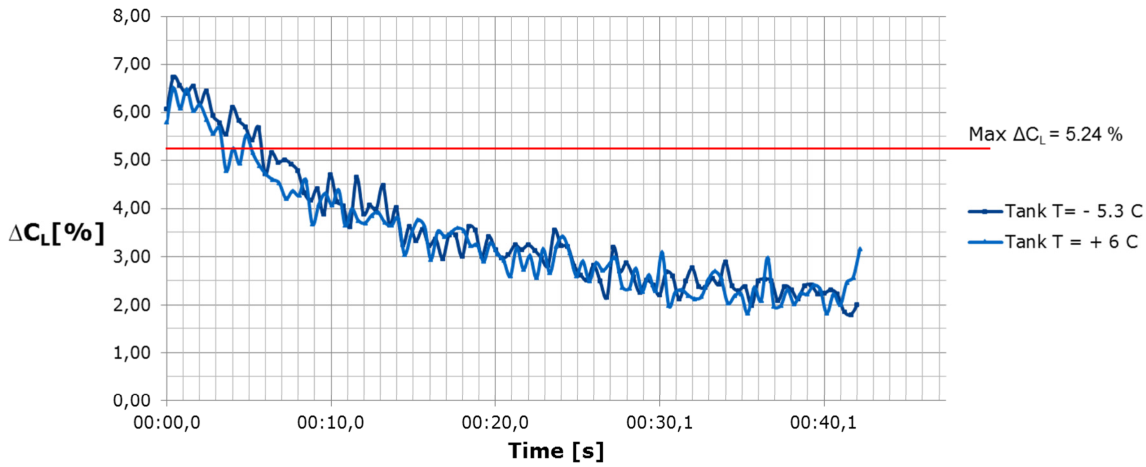

Figure 19. Effect of coolant tank temperature on lift degradation

7.2.4 Type II vs. Type IV Fluid

There is an unexpected difference between Type II and Type IV treatments in lift degradation. Though Type II fluid is thinner than Type IV (see chapter 5) it leads to a larger lift degradation as seen in Fig 20. It is an already previously documented fact that fluid viscosity is not the only factor determining flow off properties and lift degradation. However the two fluids considered in the present study are made by same producer. As the Type IV fluid has a longer hold over time there remains a question about the benefit of using this particular Type II fluid.

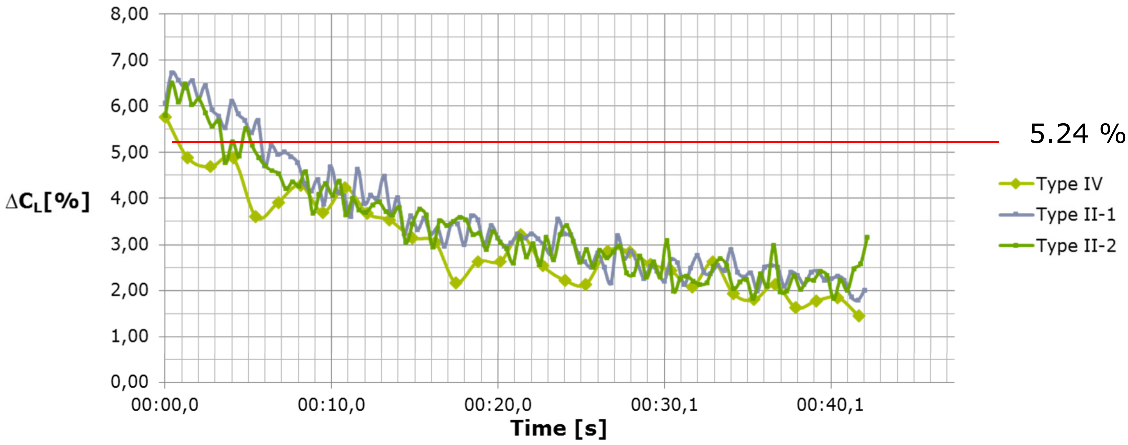

Figure 20. Comparison of Type II and Type IV fluids

7.2.5 Effect of Initial Fluid Thickness

The initial fluid thickness was very difficult to be varied as after the fluid had been applied as evenly on the surface as possible all the extra fluid tended to drip off the wing upper surface. Fluid thickness effect is presented in Fig 21. Though the thickness difference is only 0.5 mm it represents a difference of 42 % difference in initial thickness. There is no significant difference in lift degradation when the initial thickness is varied. This is in line with previous studies[3] on the subject.

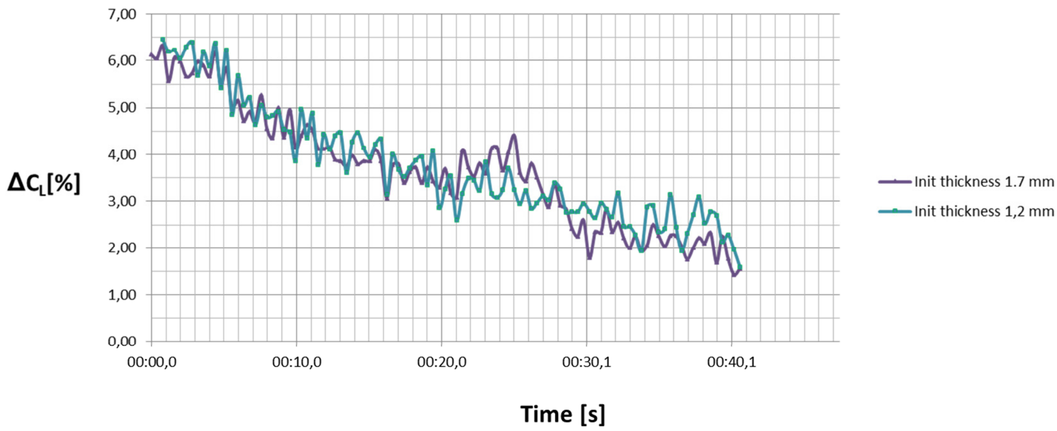

Figure 21. Effect of initial fluid thickness on lift degradation for neat Type II fluid.

7.2.6 Effect of Acceleration Time

Acceleration time is the time in which the wind tunnel speed is accelerated from idle speed to 60 m/s. In Ref. 3 it was discovered that acceleration time has a distinct almost linear effect on the fluid flow off from the wing upper surface. This obviously seems to apply also to lift degradation. As seen in Fig.22 the lift degradation curve is shifted to the right the same amount of seconds as the acceleration is shorter to the original one. This result is intuitively understandable as rotation is 5 seconds earlier it takes the same 5 seconds for the fluid to flow off after the rotation.

Note that in reality the acceleration times e.g. for an A321 vary from 19 to 33 seconds according to Ref.12.

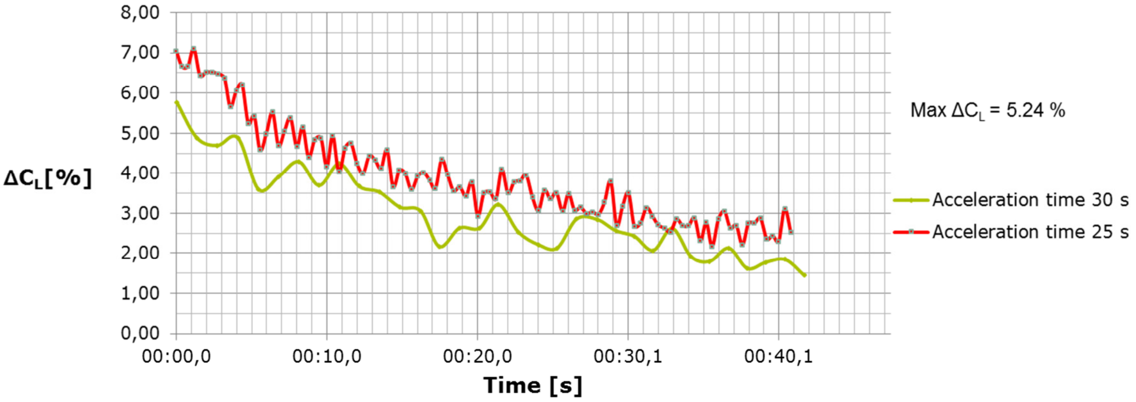

Figure 22. Effect of acceleration time on lift degradation for neat Type IV fluid.

7.2.7 Type I Fluid

To compare deicing and anti-icing fluids there is a comparison of lift degradation created by Type I fluid (30% TI + 70 % water) treatment compared to neat Type IV treatment (Fig 23). Type I has a marginal effect on lift compared to anti-icing fluids. As Type I fluid is Newtonian and essentially a thinner fluid it produces much less aerodynamic effects than thickened fluids.

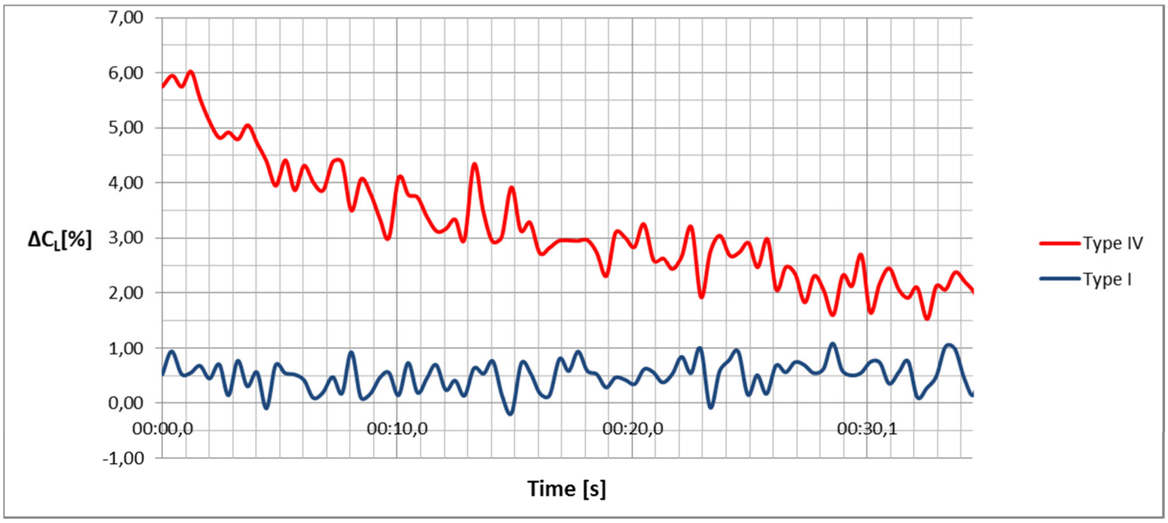

Figure 23. Lift degradation produced by Type I fluid

7.2.8 Real Frost

Effect of real frost on lift degradation was tested by cooling the coolant tank temperature well below the surrounding air temperature. Majority of operative problems considering frost is related to cold soaking over wing fuel tank area due to cold fuel. Therefore the present study concentrated only on frost limited to this area. This kind of a frost on wing tank area surfaces is also called as Cold Soaked Fuel Frost (CSFF). The structure of CSFF is different from the so called hoar frost that is generated by heat radiation from the wing skin. For this reason it was considered important to study a real frost instead of sandpaper simulations which have been an "industry practice" for years. The author of the present study has not found any previous studies published on aerodynamic effects due to a real cold soaked frost.

Frost was generated by first cooling the wing section model in a freezer and continuing to cool the tank area with liquid nitrogen which was led through copper pipelines through the tank. A temperature difference between coolant tank and surrounding air of 23.5°C was reached but probably due to the relatively dry air (RH = 48%) only a very thin layer of frost was created. Frost thicknesses of 0.05 – 0.1 mm were achieved. The average frost layer gives a relative thickness of k/c = 0.00012 (c=0.65 m).

The results of lift degradation tests for the CSFF frost are shown in Fig. 24.

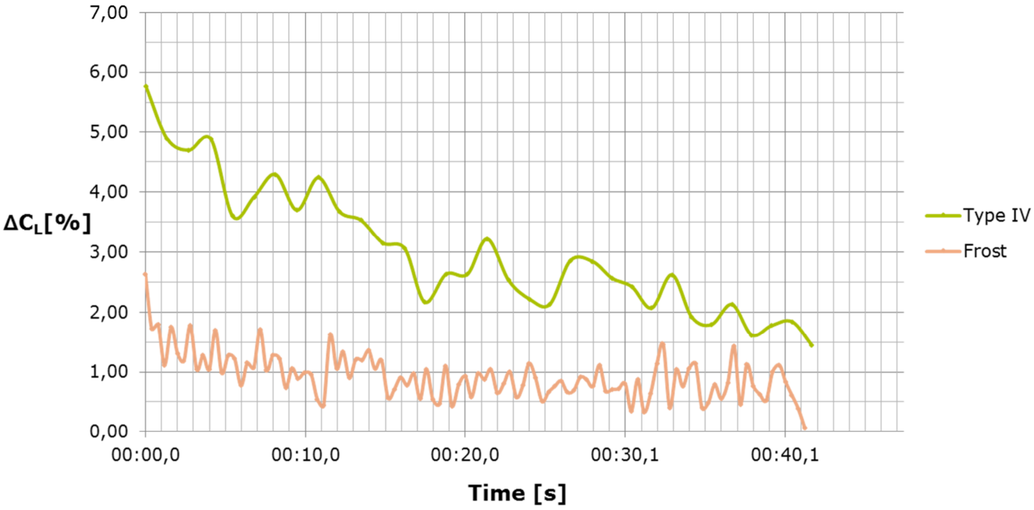

Figure 24. Effect of real frost on lift degradation. Frost k/c = 0.00012

7.2.9 Pitching Moment Corrections to the Lift Losses

The lift coefficient measurements for a clean wing gave well repeatable results at the fixed angle of attack of interest of 7.5°. For 10 separate clean wing tests the lift coefficient mean value was 1.281 with standard deviation of 0.0028, which gives a coefficient of variation of 0.216%. This means that the angle of attack deviations between indicated and visually measured ones did not cause large variations in the clean wing lift coefficients. However for fluid treated cases some error were generated to the results due to the fact that fluid treatment altered the pitching moment which in turn altered the actual angle of attack. For this reason the angle of attack and lift coefficient degradation values were corrected for pitching moment effects as described in Appendix.

The effect of fluid treatment on pitching moment was clearly transient. Therefore the corrections to the lift coefficient degradations due to the deviated angle of attack effects were also transient (Figure 25).

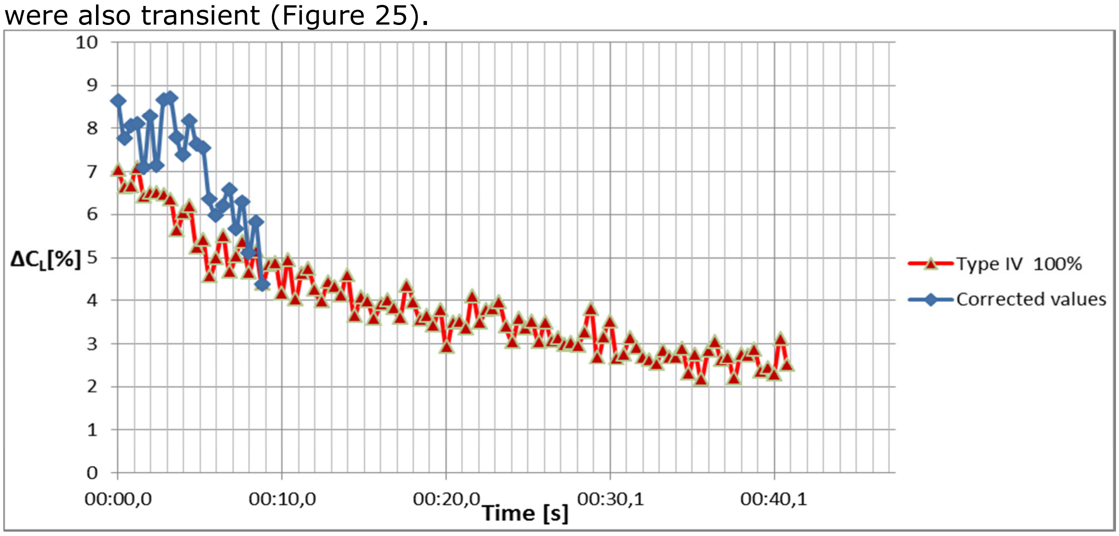

Figure 25. Corrected lift coefficient degradations due to the angle of attack deviation caused by pitching moment differences between clean and treated wing.

As shown in Fig. 25 there is a period of approximately 5 s when the pitching moment affects the results which after the effect of angle of attack deviation to the lift coefficient degradation due to the fluid application will diminish within the first 10 s after rotation. This applies to all fluid treatment tests. The difference in time when the lift degradation falls under the “critical” value of 5.24 % between corrected and non-corrected data varied from 0.4 s to 3.4 s.

For all 14 fluid tests the calculated mean correction to the lift coefficient degradation during the 5 first seconds after rotation was 1.46 % with a standard deviation of 1.21%. This means that the correction data was very noisy. This is observable also in Fig 25. Considering the results shown in Chapters 7.2.1 -7.2.8 the short term peak values in lift coefficient degradation values will actually be some percent units higher than in the figures 16 - 23. However due to the transient nature of the pitching moment correction the general behavior of, or the relative difference between the results in Chapters 7.2.1 - 7.2.8 does not change.

Also the frost measurements were studied for possible corrections due to pitching moment differences. However the corrections appeared to be negligible.

7.3 Taxi Test Results

Test arrangements for taxi tests are described in chapter 6.3. Taxi tests were conducted using neat Type IV fluid. The following appeared during taxi tests:

- Wave onset speed was between 11 – 12 m/s
- Significant flow off was not detected below a speed of 15 m/s
- After a 120 s taxi at a speed of 15 m/s (30 kt) the fluid flow off was 53.2 %

These results are consistent with earlier results in Ref. 3

8. Conclusions

Wind tunnel experiments were conducted at Aalto University Low Speed Wind Tunnel facility during the winter period 2012-2013. Objectives were to study primarily the lift degradation during take-off after anti-icing treatment with different parameters. Anti-icing fluid behavior was studied also qualitatively by video recordings.

Considering lift degradation due to anti-icing fluids the main findings were:

- No significant difference between 1-step and 2-step deicing treatment
- Diluted Type IV fluid (75% TIV) gave practically equal lift degradation with the neat Type IV during the first 10 s after rotation. After this diluted fluid created somewhat worse lift degradation than neat fluid however the effect was well below 5.24 % which is considered as maximum acceptable.
- Comparison between Type II and Type IV fluids revealed unexpectedly larger lift degradation for Type II than Type IV fluid.
- Acceleration time has a straightforward time shifting effect on lift degradation. Lift degradation delays as many seconds as the time is shortened to reach wind tunnel speed of 60 m/s. This finding is consistent with results of Ref. 3.

It should be noted that though the 5.24 % lift loss limit is a widely used reference, it is not in the present study considered to be an acceptable limit due to violation with certification standards.

In present study also some tests with a real cold soaked frost were done. Lift degradation created by frost was significantly less than by anti-icing fluids. This fact motivates for further tests with CSFF frost due to considerable de/anti-ice fluid consumption on northern hemisphere every year.

9. References

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Appendix
Lift Coefficient Degradation Correction for Angle of Attack Deviation due to Pitching Moment

The aerodynamic pitching moment is transmitted to the balance mechanism via a horizontal bar (see Figure A1) with a thin profile to avoid aerodynamic interference.

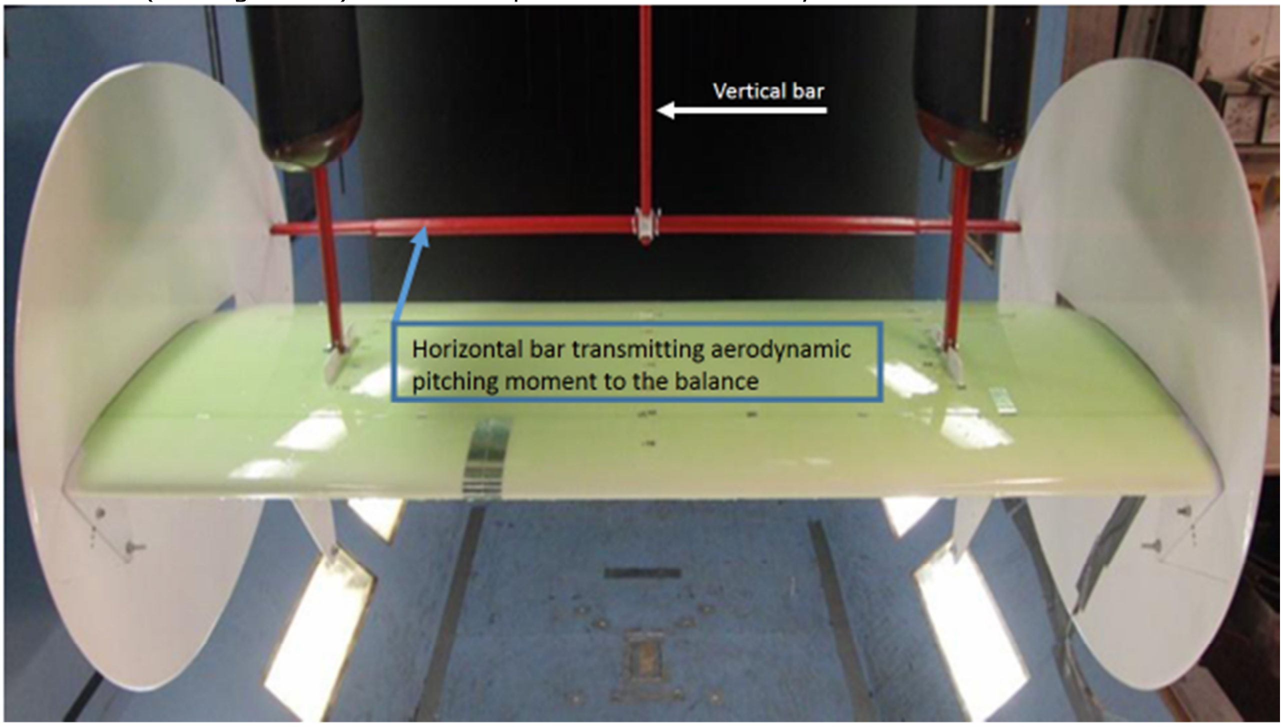

Figure A1. Wing model suspension setup and pitching moment bar

Due to the low bending resistance of the horizontal bar there will be measurable bending displacements in the direction of the vertical bar (Fig. A1) once aerodynamic pitching moment is affecting the wing model. This kind of a displacement alters the actual angle of attack compared to the indicated one that is measured directly by the movement of the vertical bar.

To correct this deviation it is assumed that the difference between the indicated and the actual (measured) angle of attack is directly proportional to the aerodynamic pitching moment:

$$\Delta\alpha = (\alpha_m - \alpha_i) = k\, M_y$$

Where α_m is the visually measured (actual) angle of attack and α_i is the electronically indicated angle of attack (via the vertical bar in Fig. A1). When the aerodynamic pitching moment M_y is zero the difference $\Delta\alpha$ should be zero as is the case in the equation above.

To find the proportionality factor **k** visual measurements of the angle of attack were made through the wind tunnel door. Wind tunnel was run by constant speed of 60 m/s and rotated stepwise through indicated angles of attack from -0.4° to 8°. Measurements were done using a horizontal laser beam and an angle of attack scale painted on the outside of the model endplate. The resolution of the angle of attack measurements (visually) were estimated to be 0.1°.

The results of these measurements are presented in Fig. A2. The calculated proportionality factor (least squares fit) is **k = 1/128.15 = 0.007743°m/N.**

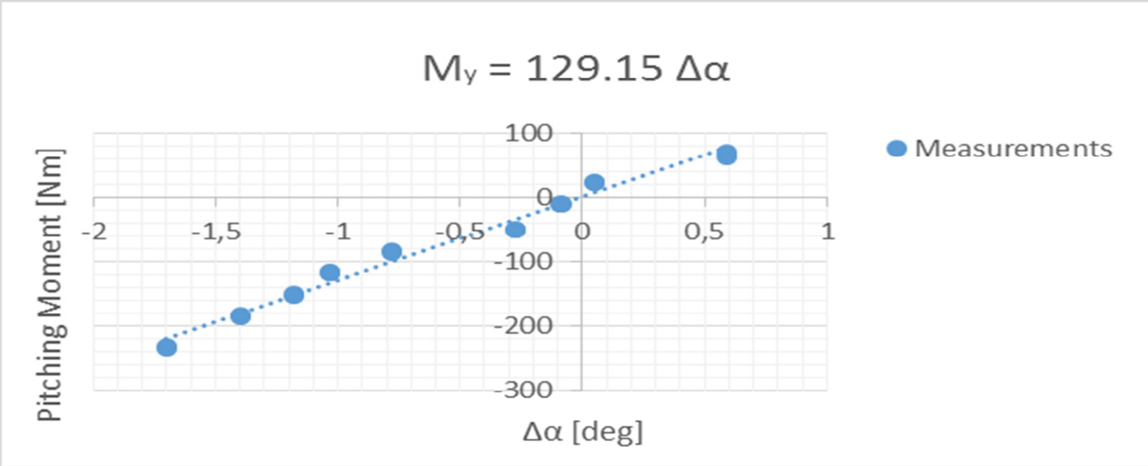

Figure A2. Measured correlation between Δα and pitching moment M_y

As the lift coefficient is proportional to the angle of attack the relative difference of the lift coefficient (in percent's) is proportional to relative difference of the angle of attack. With this reasoning the relative difference in angles of attack between clean and fluid treated wing may be regarded as approximately equal to the relative difference of lift coefficient difference. There will be a second order error due to the altered lift coefficient slope, however this may be neglected as the relative difference of the slope is of the same order of magnitude as the relative angle of attack difference.