

NLR's experience with flight testing on wet and flooded runways

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Abstract

Braking performance of aircraft is affected whenever a runway is wet or flooded. Aircraft manufacturers do wet runway braking tests during the certification of a civil transport aircraft. These are normally limited to tests on smooth runways. Additional tests are sometimes conducted on wet grooved or porous friction course runways when the manufacturer seeks for additional stopping performance credit for such runways. Braking tests on flooded runways are not conducted during certification. In the past such tests have been conducted in research programmes on runway friction. The National Aerospace Centre NLR has conducted braking tests on a highly textured runway under wet and flooded conditions. The wet runway tests were conducted to demonstrate an equivalent performance of the test surface with grooved and porous friction course runways under wet conditions. The flooded tests were conducted as part of an European Research project on the prevention of runway excursions. All tests were conducted in the autumn of 2016 at a former air force base in the Netherlands (Twente Airport). This paper discusses in detail the preparation, logistics, and execution of the flight tests conducted with NLR's Cessna Citation test aircraft. The use of large water trucks to wet the runway is presented in the paper. The construction of a water pond to conduct the flooded runway tests is discussed in detail. Difficulties encountered during the preparation and execution of the flight tests are briefed. Lessons learned are shared in the paper.

1.0 Wet Runway tests

1.1 Introduction

Runways that are wet experience a reduction in the braking friction between the tyre and the runway surface. The wet runway friction capability depends on a number of variables including the texture of the surface. Surfaces with a relative high macrotexture and rough microtexture perform much better than smooth surfaces under the same wet conditions. These highly textured surfaces are often called high skid-resistance surfaces. These surfaces also show better drainage characteristics than smooth runway surfaces. By improving drainage through the surface, highly textured runways delay onset of viscous and dynamic hydroplaning that normally reduces or completely removes the contact zone in which friction between the tyre and runway is created. Hence higher braking forces are achieved than on smooth surfaces. Currently only two runway surface types are recognised as high skid-resistant: grooved and porous friction course (PFC) runways. These surfaces have been developed in the 1960s and 70s. Currently regulations allow two levels of aircraft performance to be provided in the Aircraft Flight Manual for wet runway performance: wet smooth runway performance and wet grooved or PFC runway performance. The wet smooth runway performance data must be provided, while the wet grooved/PFC performance data may be provided at the aircraft manufacturer's discretion option. A conservative level of performance credit is provided by the regulations. The credit for a grooved or PFC runway under wet conditions can provide operators lower takeoff distances or higher takeoff weights. In principle, performance credit may also be granted when landing on wet PFC/Grooved runways. The performance credit can make both the aircraft operators as well as the airport more competitive especially if the runway is relatively short.

There are other tried and tested runway surfaces available that also give adequate friction under wet conditions. However these surfaces treatments have not received performance credit under wet conditions. NLR was asked by a large international construction firm to help them to get the same performance credit given to grooved/PFC runways for their surface treatment. Their runway surface has been used for many years at a large number of airports in the world (both civil as well as military) and has shown high skid-resistance under wet conditions. As part of the work done by NLR, flight tests were conducted to demonstrate the wet runway friction characteristics of this surface treatment.

1.2 Test aircraft

The aircraft used for these flight tests is the NLR Citation jet. Originally designed for executive travel, the NLR Cessna Citation II test aircraft (registration PH-LAB) has been extensively modified by NLR to serve as a versatile research and test platform. The aircraft has two Pratt & Whitney JT15D-4 turbofan engines each rated 2,500 pounds of thrust. The aircraft is equipped with a fully modulating anti-skid braking system (MKIII). The system detects incipient skids by using a wheel speed transducer to measure the deceleration of each landing wheel, and then prevents skids by reducing the brake pressure in proportion to the deviation of each wheel from normal braking deceleration. The system modulates brake pressure to maximize braking efficiency. The left and right wheel brakes are hydraulically operated by independent master cylinders attached to the pilot's and copilot's rudder pedals. The brake system is pressurised when either pilot depresses the toe pedals. Interconnect assemblies allow either pilot to operate the brakes with equal authority. The single-wheel main gear used 22 × 8, 24 P.R., type VII aircraft tyres. The tyre inflation pressures were 115 psi for the main-gear tyres and maintained within ± 5 psi throughout the course of the test programme. The main gear tyres as well as the brake units were not new. The aircraft was configured to enable measurement of lateral and longitudinal acceleration, wheel speed rotation by using the aircraft's anti-skid system, engine parameters, aircraft speed and pressure in the low pressure pilot brake system amongst others. The aircraft was operated by NLR test pilots.

1.2 Flight test preparations – wet runway

Tests were conducted at Twente Airport. This airport has a single runway with a length of 2,406 m and a width of 45 m and a top layer with a high-skid resistant surface treatment. The runway has a small longitudinal slope with an average of 0.2%. The cross slope varies between 1.3 and 1.6%. Closer to the runway centreline (within 4 m) the cross slope was less varying between 0.7 and 0.9%. The average macro texture depth of the runway was 1.4 mm as determined by the sand patch method.

In absence of natural rain conditions, the runway was artificially wetted. This is a common way to wet runways for flight testing. At the start of the project it was unclear how much water was needed to get the runway wet. As the runway had a high macrotexture it was expected that a lot of water would be needed. A review of previous wet runway tests done by e.g. FAA, NASA, and others gave some useful information on the best practices. However most of these tests were conducted on rather smooth runways, requiring less water to get it wet. Therefore before the flight tests were conducted, experiments were organised to determine the amount of water needed to wet the runway. For this purpose water trucks were run along a section of the runway, dropping water at different rates (see Figure 1). Each time the water depth was measured at fixed locations from the centreline that corresponded to the location of the main gear wheels of the test aircraft. The water depth was measured using the NASA

water film depth gauge (see Figure 2) at different time intervals. This device has been used for many years in wet runway testing. The NASA gauge works on the principle of reflectivity. Plexiglas rods of different lengths that protrude through its body are calibrated and marked with numbers from 0.0 to 0.10 inch to indicate water depth. Since water is highly reflective and will reflect more light than the runway surface, rods that are not touching the water will appear lighter than those that are touching or submerged in water. The dark rod with the highest number, therefore, indicates the water depth. Wind during these test varied between 6-10 kts and the temperature varied between 20-24 °C. There were no clouds during the tests. Figure 3 gives some results of the water depths measured as function of drainage time during the initial tests at Twente airport (speed of water trucks was 10 km/h, flow rate around 3-4 m³/min). Water depths of 1-2 mm were measured around 150 sec. after water application in this example. A water depth range of 0.5-0.8 mm was measured 150-230 sec. after water application and a range of 0.25-0.50 mm was after 230-300 sec. All water depth measurements were taken at the wheel track of the Cessna Citation test aircraft. Based on these initial tests the amount of water needed to wet the runway for the full-scale aircraft braking tests was estimated. Tests conducted by FAA and NASA showed that runway water depths of more than 1.5 mm are not feasible as the water is drained immediately when water trucks spray the runway surface and the aircraft cannot land directly after the trucks are done spraying. Water depths between 0.25 and 0.8 mm are more realistic to achieve. For the present flight tests this range of water depths was set as the target range. Higher values (if achieved) are of course also acceptable as long as runway does not become flooded (more than 3 mm water depth). Runways with a water depth lower than 0.25 mm are not considered wet.

During the initial experiments local farmers were contracted to provide water to wet the runway surface. This proved to be challenging in several ways. The drivers of the water trucks had no previous experiences in operating at an airport. It was somewhat difficult to brief them on the normal procedures at the airport. The farmers were also asked to clean the water tanks before filling them with water. Immediately after the first run a large amount of dirt was noticed coming out of the water tanks. This had to be removed after the tests. Clearly the farmers understanding of a clean tank was different from what was expected by NLR. After these first experiments it was decided to find a different contractor to supply the water trucks to make the runway wet.



Figure 1: Tests to determine amount of water required to wet the runway.



Figure 2: NASA water film depth gauge.

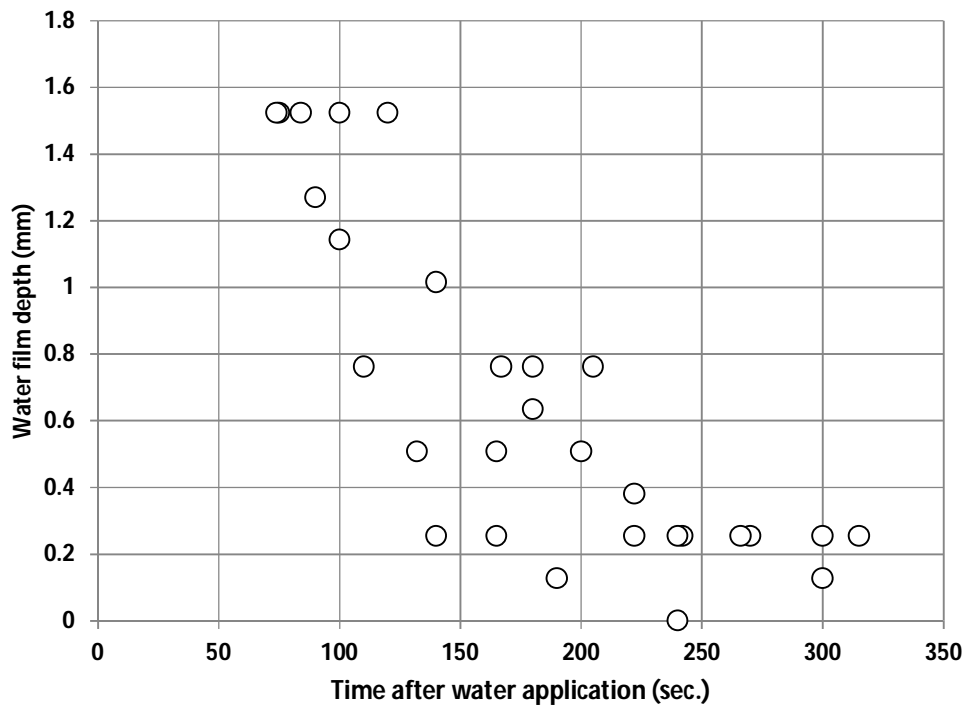


Figure 3: Example of measured water depths as function drainage time during initial tests.

1.3 Flight tests – wet runway

The test aircraft was dispatched prior to wetting the runway for a test condition. A section of 300 m long and 45 m wide of the runway was wetted using 6 water tank trucks. The tanks had a capacity of 35 m³. During each run about 8 m³ of water was released by each water tank truck. The trucks were arranged as shown in Figure 4. This layout ensured a timely exit of the trucks when they had finished spraying the runway. Figure 5 shows a picture of the water trucks on the runway. Shortly after the wetting of the test section the aircraft landed and maximum brakes were applied in the wetted area. The pilots used full brake-pedal deflection, which permitted the anti-skid brake system to modulate pressure to a value commensurate with the friction level available. The area in which the aircraft should brake was indicated by markers set at the runway edge. Braking started after passing these markers. Figure 6 and Figure 7 show pictures of the aircraft braking at the beginning of the wet section and at the end. The time between ending of the water spraying and the aircraft braking in the wet section was between 20-30 seconds during the tests. The aircraft was kept on the centreline during the ground roll. After the aircraft landed the water depth was measured in the middle of the wetted area, 2.70 m from both sides of the runway centreline (corresponds to main wheel location). Several water depth measurements were recorded at different intervals from the time the aircraft entered the wet section of the runway. These data are used to estimate the water depth when the aircraft was in the wet section.

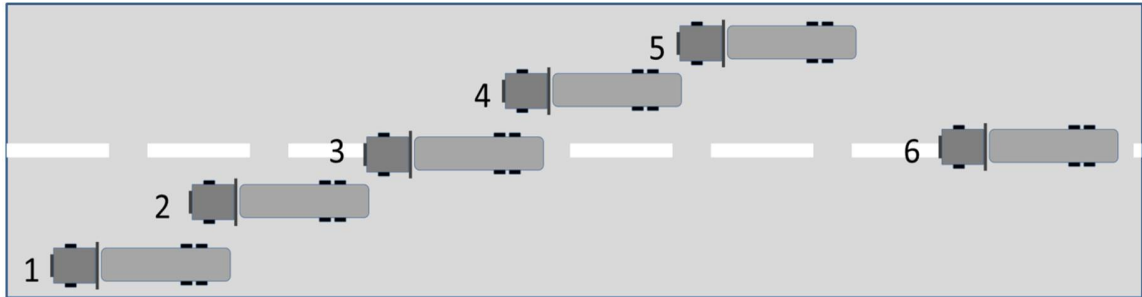


Figure 4: Arrangement of water trucks.

Five braked tests were conducted: two under dry runway conditions, and three under wet runway conditions. In two wet runway runs all water tanks 1 to 6 were used. The average water depth during aircraft braking was around 1.3 mm in these two runs. The third wet runway run, water tank 6 was not used. The water depth during aircraft braking during this run was around 0.7 mm. Video recordings of all wet runs confirmed that the aircraft was running through a wet area.

After the landing tests were finished it was decided that an additional low speed test should be conducted under wet conditions because the three wet runway tests were all conducted at relatively high ground speeds. For this low speed test the aircraft was positioned on the runway at a predetermined point from the area that was wetted. Wetting was done by two water tanks that run along the test section of 250 m long at a speed of 5 km/h. The tank configuration was with truck 3 and 6 both running along the centreline (see Figure 4). Immediately after the trucks had finished spraying they left the runway at which the aircraft commenced a takeoff. The position of the aircraft relative to the wet test section on the runway was chosen as such the aircraft would enter the area at a low speed. Full braking was commenced when the aircraft was in the wet area. Water depth was around 0.4 mm during the test. Video recordings of the test run also confirmed that the aircraft was running through a wet area.



Figure 5: Wetting of the runway using water tank trucks.



Figure 6: Aircraft braking at the beginning of the wet test section.



Figure 7: Aircraft braking at the end of the wet section.

The tests in which the aircraft landed just after the water trucks left the runway, required an accurate timing. A briefing was given to the water truck drivers about the procedures. Before the actual wet runway tests were conducted a “dry” run was conducted to make the truck drivers and test pilots acquainted with the test procedures. This run also validated the procedure timings. In this dry run the aircraft took off after which the water trucks took their designated position on the runway. At a pre-defined distance from the runway threshold the tests pilots gave the call to start the trucks. The aircraft landed shortly (within one minute) after the last truck had left the runway. After this first dry run a short de-briefing was organised and some small adjustments were made to the test procedure. All wet runways tests in which the aircraft landed were conducted in this manner. After the testing was finished and the data were analysed, it was realised that more tests could have done without the need for the aircraft to actually takeoff and land. As the runway was quite long, aborted takeoff tests could also be done at high speeds instead of actually landing the aircraft. It should be noted that braking should be done with the engine at idle thrust for post processing purposes. It typically takes about 5-7 seconds for engine the spin down from takeoff thrust to idle thrust.

The aircraft test speeds in combination with the landing weight were chosen as such that the kinetic energy level did not exceed a critical value. If the critical value is exceeded, too much heat builds up internally in the brake. The rotors and stators produce less friction in this condition, resulting in a lower braking force. This is seen as a reduction of the effective braking friction coefficient. The lower landing weights used in the flight tests

in combination with a fairly high lift force also helped avoiding that the brake torque limited region would be reached instead of the anti-skid limited region (e.g. due to lower normal force on the main gear). The highest effective friction coefficient is found in the anti-skid limited region. The anti-skid brake system on the Citation test aircraft automatically disengages when the ground speed falls below approximately 12 kts.

2.0 Flooded runway tests

2.1 Introduction

Statistics show that the likelihood of a runway excursion during takeoff or landing is much higher on flooded runways than on dry runways. Extreme loss of tyre braking can occur during rejected takeoffs and landings on flooded runways. As a result the stopping distance increases significantly and could exceed the available runway length. Most research in the past has focused on the braking capabilities of aircraft on wet runways instead of flooded runways (the threshold between a wet and flooded runway is 3 mm of water). Most of the knowledge of aircraft braking performance on flooded runways was gained with older aircraft designs. This knowledge is still used to determine the takeoff and landing performance of today's modern aircraft. During the development of the European Action Plan for the Prevention of Runway Excursions it was recognised that current aircraft designs may act differently when braking on water flooded runways from aircraft tested earlier, due to new tyres and anti-skid system designs. Also the water depths during these earlier tests were often just above the wet-flooded runway threshold. Flight tests with more modern aircraft designs were therefore scheduled as part of a research project under EU's Horizon 2020 Research and Innovation Programme. NLR therefore conducted tests with the Cessna Citation II research aircraft on a flooded runway to determine the braking capabilities under such conditions. Also Airbus did the same tests using an A400M as part of this research programme after the tests with the Citation were completed.

2.2 Flight test preparations – flooded runway

The objective of the test programme required a runway covered with a target depth of around 15 mm of standing water. This is a lot more than for a wet runway. The build-in cross slope of a runway prevents that such a quantity of water stays on the runway, unless there is heavy rainfall. A water pond is therefore needed to create an area of sufficient water depth that stays at this level for long enough time for an aircraft to pass. Such water ponds are normally constructed using flexible re-enforced rubber strips as dikes to contain the water. These rubber strips are then put into grooves that are cut into the runway surface (see Figure 8). This is a classical way of building a water pond on a runway. It has been used for water certification ingestion tests as well as for braked tests with a wide range of civil transport aircraft since the 1960s. Earlier water ingestion tests conducted by NLR at Cranfield airport also used this approach.



Figure 8: Flexible rubber strip in a runway groove.

Initially the tests were planned to take place at Cranfield airport. However, due to several reasons it became impossible to use this location. After considering a number of alternatives the same test location as for the wet runway tests was chosen, namely Twente Airport. This runway is ideally for such tests as it has a long and wide runway. Furthermore the traffic volumes are very low at this airport. However, the runway at Twente did not have a water pond facility at the start of the project. This facility had to be constructed. A classical water pond consists of series of grooves into which flexible rubber strips are put to form dikes. To gain some experience with such a setup, a small test pond was constructed at the NLR premises before making one at Twente airport. This water pond measured 4 by 10 m and is shown in Figure 9 (empty). The test pond was filled to several water levels. A large water truck was also run through the pond to see how the construction would behave (see Figure 10). Experiences were gained in grooving, fixing the rubber strips into the grooves, measuring of water depths and managing leakage of the pond with these experiments.



Figure 9: Test water pond.

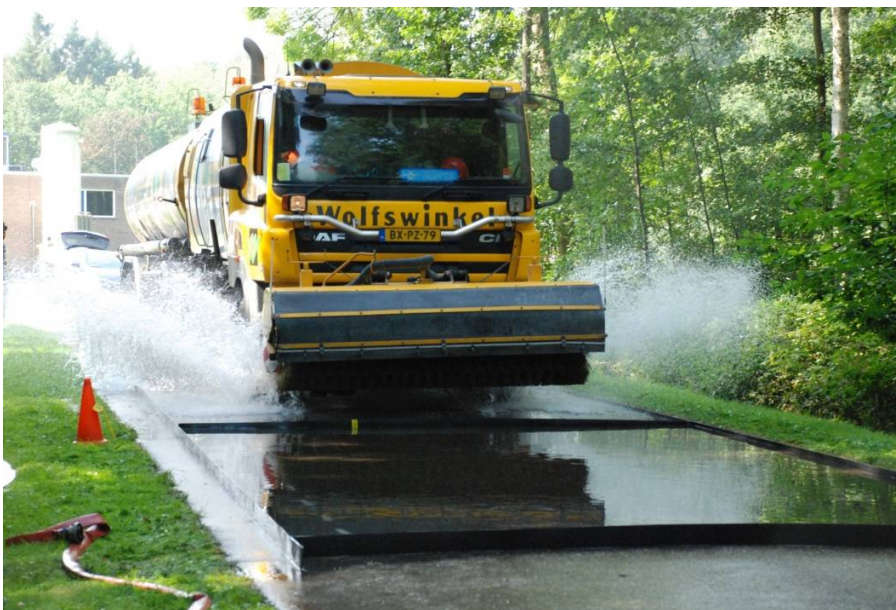


Figure 10: Large truck running through the test water pond.

After positive experiences gained with the test water pond it was decided to construct a water pond at the flight test location. The runway at Twente airport has a very consistent longitudinal slope of 0.2% along the runway. Likewise the cross slope is also very consistent along the runway being 0.6-0.8% at the runway centreline and 1.5-1.6% further away from the centreline. The longitudinal slope required that several rubber cross dams had to be constructed to get reasonable consistent water levels in the water pond. These cross dams were placed every 7.7 m to form 13 separate sections. The construction of the grooves into the runway is shown in Figure 11. The final water pond on the test runway is shown in Figure 12. As the aim of the flight tests is to analyse

braking performance it was not necessary to have the nosewheel running through the water. Therefore no pond was construction for the nosewheel to run through. Keeping the centre part dry also provides additional controllability in case the aircraft deviates from its track during the test run.



Figure 11: Construction of grooves into the runway for the water pond.



Figure 12: Water pond at Twente airport.

The overall length of the water pond was 100 m. This is sufficient long to obtain useful test data. Braked tests done by NASA used a water pond of similar length. The water pond starts 1.15 m from the centreline and stretches to 5 m from the centreline. The target average water depth in the water pond at the main wheels was set to 15 mm. Along each section the actual water depth will normally vary both in longitudinal as well as in lateral direction as the test section is not completely flat. However the main gear tyres should be exposed to target water depth when the aircraft does not deviate significantly from the runway centreline. Deviations from the centreline were observed on a few test runs, however, these were not significant enough to influence the test results.

The water pond was filled to the target depth using water trucks as shown in Figure 13. Water depths were measured using a specially constructed wedge which is shown in Figure 14. Prior to each run water depth measurements were taken and recorded at pre-defined positions in each section of the water pond (see Figure 15). These positions matched the location of the main gear tyres. Water proof road marking chalk was used to locate these positions. However, it was noted after a few runs that the aircraft main gear tyres removed the chalk. In later tests a water proof spray paint was used instead. This proved to be much more resistant against the tyres running over it. If the water depth was well off the target value, water was either removed from the section or added. After each pass of the aircraft, about 30% of the water went out off the water pond, requiring a refill. Leakage at the side of the pond was also noted (see Figure 15). It was decided that no further sealing of the rubber strips was needed as this loss was not significant. Typically the water pond kept to its target water levels for more than 20-25 minutes under calm wind conditions. At high wind conditions this time reduces.

High winds can also make it difficult to maintain consistent water levels. Based on previous experiences with water pond testing a maximum wind speed of 12 kt. was defined for the test programme. Figure 16 and Figure 17 show the surface of the water pond under calm and light windy conditions. In order to minimise the influence of wind on the water depth measurements, a metal ring was placed around the water depth gauge as illustrated in Figure 18. This practice was taken from other water ingestion tests.



Figure 13: Filling of the water pond.



Figure 14: water depth gauge.



Figure 15: Example of measuring water depth level in each section.



Figure 16: Water pond in calm wind conditions.



Figure 17: Water pond at 8 kt. wind.



Figure 18: Measuring of water depth using a metal ring around the water depth gauge.

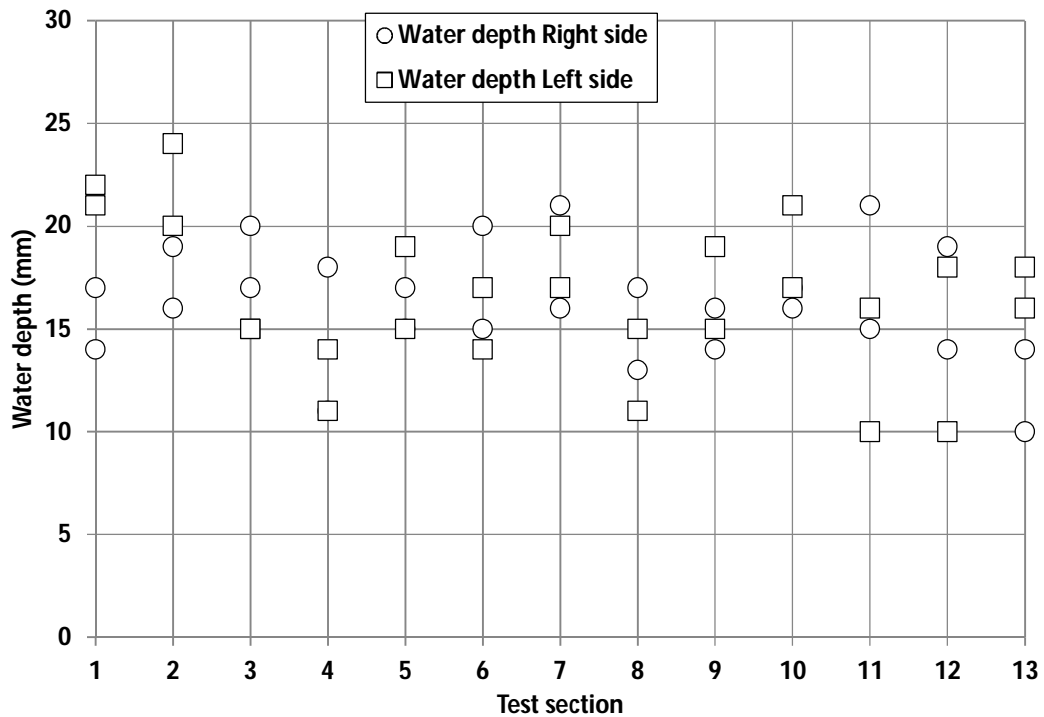


Figure 19: Example of the water depth levels measured along the water pond (numbers refer to section).

The target water depth was set to 15 mm at the main gear tyre track. This is slightly above the normal certification limit of 13 mm for transport aircraft. In many of the earlier flight tests on flooded runways the water depth was much less and close to the wet-flooded runway threshold of 3 mm as defined in the regulations. For the present tests a high water depth was chosen as this is more representative to a runway under extreme rain conditions. During the test programme the overall average water depth level was somewhat higher than this target (16.7 mm). This was not considered a major issue for the objectives of the project. An example of the measured water depths in the different test sections is shown in Figure 19. Two measurements were taken in each left and right section. The direction of flight is from section 1 to 13.

2.3 Hazard assessment – flooded runway

A considerable amount of time was spent in identifying the flight test hazards. A brainstorm session was organised with several internal and external experts to identify flight test hazards. Mitigations were proposed if the hazards were classified as medium or higher. The experts consisted of three engineering test pilots of which two external, and one flight test specialist. An asymmetrical entry of the water pond by the aircraft was one of the hazards that was classified as medium risk for which mitigating measures had to be defined. One of the mitigations against this risk was the use of a visual lead in

marker and the symmetrical construction of the water pond around the runway centreline. This would help the aircraft entering the water pond in a correct manner (symmetric).

2.4 Flight tests – flooded runway

The test matrix was developed keeping in mind how the data reduction process would be done. As an aircraft passes through the water pond, the tyres displace the water. This causes a drag force acting on the tyres called displacement drag. Water thrown up by the tyres could hit the airframe causing an impingement drag force. To account for these drag forces tests runs in an unbraked condition were required. Therefore the test matrix had to incorporate both an unbraked and a braked run for a given target entry speed. It is important that true airspeed and ground speed during the water pond passage are more or less equal for both test pairs. The aircraft weight should be similar or equal in both test-pairs, as well as the average water depth and control surfaces deflections. The aircraft was tested with flaps in the up position during all runs to minimise potential damage to the flaps and to obtain the highest test speeds in the water pond. The maximum test speeds are determined by the rotation speed of the aircraft which depends on flap setting and aircraft weight. A flaps up setting ensures the highest achievable speeds for the chosen flight test approach. The runs were arranged in such a way that there was a build-up approach as to the water pond entry speeds which increased 10 Kt. between each two runs. This was done from a flight safety point of view. Some high tests runs were repeated to validate the results.

For each test run the water pond was filled to the target water depth level. The aircraft was positioned at a pre-determined distance from the water pond. As soon as the water pond was ready, a static takeoff was commenced. The engines were set to idle at a marked position before the water pond. The position of the idle thrust marker and the position for the static takeoff were determined as such as the aircraft would enter the water pond near the target speed and with the engines in idle thrust. The calculations for this were done using an in-house developed performance program. The results of these calculations were validated before conducting the actual tests with the water pond. An example of a typical run is shown in Figure 20. This shows the time-history plot of the (uncorrected) longitudinal acceleration and the ground speed. As can be seen from the plot the aircraft is accelerated to a certain speed from the static takeoff point. After reaching the idle marker the engines were set to idle at which the normal acceleration starts to drop. As the aircraft reaches the water pond the aircraft is slightly decelerating due to aerodynamic and rolling friction forces being larger than the idle forward thrust. This was the case for all test runs conducted. When entering the water pond the aircraft starts to decelerate more as illustrated in Figure 20. Depending on the test point the test pilot would apply maximum brakes or leave the aircraft rolling without brakes being applied. During a braked test run, maximum brakes were applied by the pilots just when the aircraft had entered the water pond (see Figure 21). Just before leaving the water

pond the brakes would be released again (see Figure 21). Between each run sufficient time was taken for the brakes to cool down. Also the airframe and tyres were inspected for damages after each run. Video recordings and still images were made from the outside and inside the aircraft. These images were used in case water ingestion into the engines was suspected (see e.g. **Figure 22**). The videos and still images were also used in the post processing to analyse spray patterns for hydroplaning indications.

Typical run

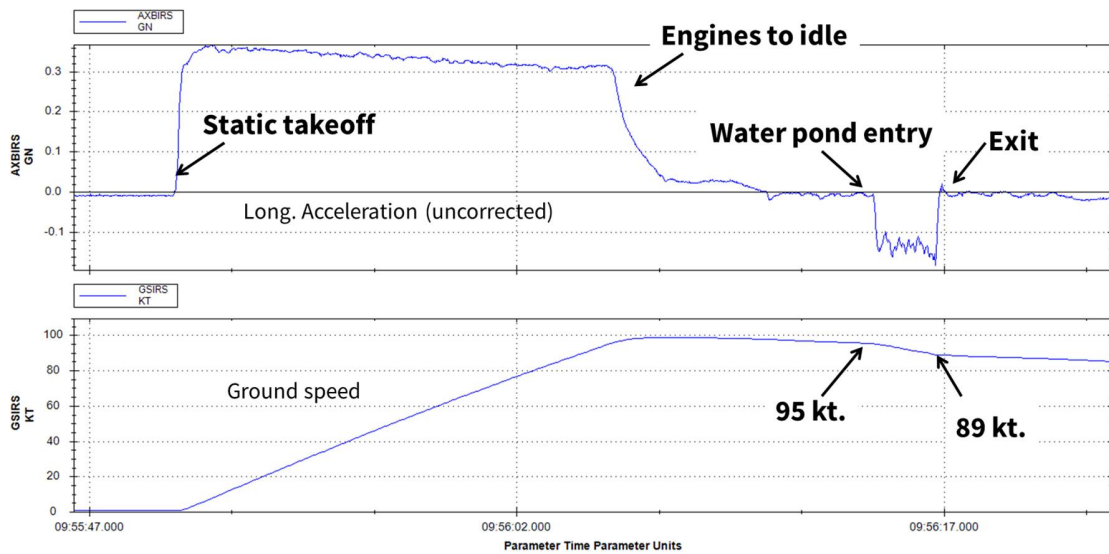


Figure 20: Longitudinal acceleration and ground speed time-history plot for a typical test run.

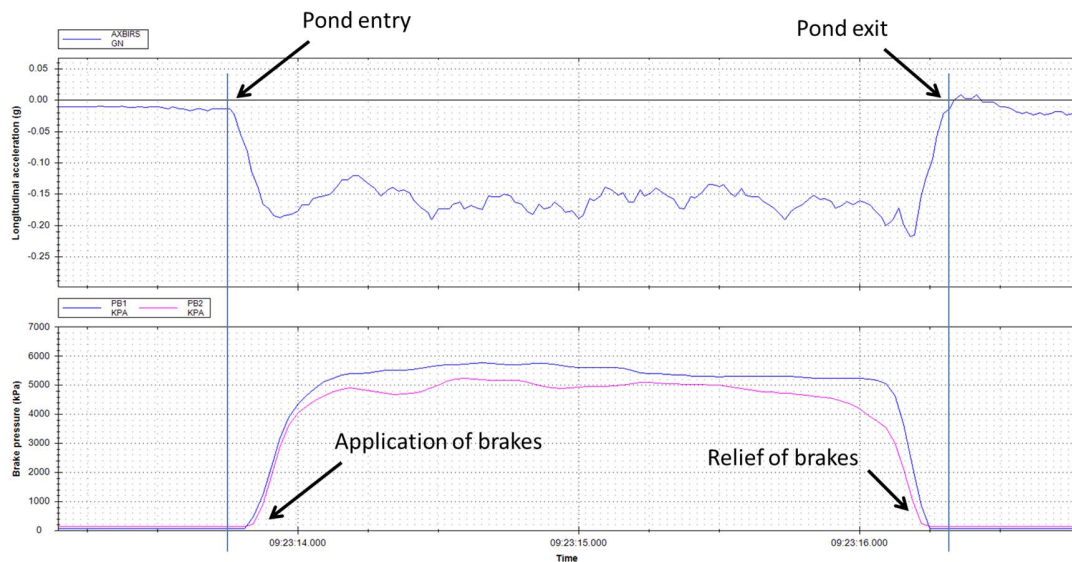


Figure 21: Example time-history plot of longitudinal acceleration and brake pressure when running through the water pond (ground speed between 85-78 Kt.).



Figure 22: Cessna Citation test aircraft running through the water pond.

Having sufficient water throughout the test programme is critical for a successful campaign. After each run through the water pond, water had to be added. About 30% of the water in the pond was sprayed outside the pond area after each run. During the tests two water trucks were available. Only one was used to refill the water pond which was placed on the runway centreline. In this way both sides of the water pond could easily be filled (see Figure 13). As soon as a truck got a low water quantity, the second truck was used and the empty one was re-filled at a nearby canal. In this way there was always sufficient water to fill the water pond.

3.0 Conclusions

NLR was involved in testing its Cessna Citation II research aircraft on a wet and on a flooded runway. This paper describes these two test programmes. Both programmes had their own challenges and logistics issues. Based on lessons learned from previous tests and by conducting pre-tests, the flight tests were very successful.