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European Union Aviation Safety Agency

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RWYMT (RUNWAY MICRO TEXTURE) [EASA.2022.C06]

Final project report

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SUMMARY

As part of the EASA Runway Micro Texture project a method is being developed to identify when a runway surface could be defined as slippery wet. This method uses high resolution surface scans to analyse the micro texture characteristics of the runway surface. The current report summarises the activities and the main results of the project as part of work package 5.3.

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ABBREVIATIONS

ACRONYM	DESCRIPTION
ASTM	American Society for Testing and Materials
EASA	European Union Aviation Safety Agency
ESDU	Engineering Sciences Data Unit
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Center)

1. Introduction

1.1 Background of the EASA research study

The European Union Aviation Safety Agency (EASA) '2021 Annual Safety Review' categorises runway excursions as one of the top two risk areas for large aeroplanes and business aeroplanes. In a runway excursion a pilot is either not able to stop on the runway and overruns it or has directional control problems and veers off the side of the runway. The slipperiness of the runway is one the most important contributing factors in runway excursions. A runway can become slippery when it is wet or contaminated, with for example snow or ice. The ground distance needed to stop an aeroplane during landing or following an aborted takeoff will increase on wet or contaminated runways compared to a dry runway. Controlling an aeroplane on a slippery runway under crosswind conditions is also more difficult than on a dry runway.

Over the years, a number of runway overruns have occurred after an aeroplane landed on a wet runway. An analysis of aeroplane stopping performance in these events indicated that the wheel braking friction coefficient[1] achieved during the landing roll was significantly less than predicted by industry-accepted models provided in EASA CS 25.109, and assumed in the wet-runway landing distance advisory data provided in the aeroplane flight manuals. In these overruns the runway was just wet (not flooded), and was not classified as 'slippery wet' by the aerodrome operator[2]. All involved aeroplanes had fully operative brakes and anti-skid systems. Given the conditions and circumstances it is believed that deficiencies in the runway micro texture have resulted in the lower wheel braking friction levels. Micro texture refers to the fine scale roughness contributed by small individual aggregate particles on pavement surfaces. A good sharp micro texture pavement (such as gritty sand paper) can puncture and displace the thin water film trapped in the tyre footprint and thus prevent or greatly alleviate the build-up of viscous water pressures that create this type of friction loss.

Presently, there are no acceptable methods for assessing the runway micro texture directly. Many overruns could have been avoided if the braking performance had matched that specified in certification standards, or if the crew had been informed in a timely manner that the runway was slippery wet.

The recently published Global Action Plan for the Prevention of Runway Excursions (GAPPRE) has emphasised the importance of assessing the runway micro texture characteristics accurately to reduce the risk of runway excursions[3]. Also the introduction of the Runway Condition Assessment Matrix (RCAM) has further stressed the importance to identify runways that are slippery when wet (See EASA AMC1 ADR.OPS.B.037(a)).

In recent years high-resolution surface laser scanners have been used to assess the micro texture of road pavements. Runways have also been explored but to a lesser extent. Initial results on runways are promising and indicate that these laser scanners could help to identify poor micro textured runways surfaces and hence 'slippery wet' runways. However, more research is needed to define a practical application and to validate

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[1] Wheel braking coefficient = ratio of deceleration force from braked tyres relative to the sum of the normal forces acting on all braked tyres. The wheel braking coefficient is the result of the combination of all functioning braked wheels. Tyre-to-ground friction coefficient = deceleration force of a single tyre divided by the normal force on that tyre. It can be assumed that on average the wheel braking coefficient equals the tyre-to-ground friction coefficient of each braked tyre.

[2] Wet runway where the surface friction characteristics of a significant portion of the runway has been determined to be degraded.

[3] Slippery wet runways also affect the maximum crosswind an aeroplane can handle during the ground roll which is significantly reduced compared to a wet runway with good braking levels. A slippery runway combined with high crosswinds is a major causal factor in runway veer-offs.

the results obtained. For instance, correlation with flight test results is needed. Additionally, the development of threshold values for minimum micro texture characteristics of a runway is required.

In 2022, EASA initiated a research project intended to address the risk of overruns caused by deficiencies in runway micro texture, and explore the use of laser-scanners to establish suitable thresholds for runway surfaces micortexture. The research project is outlined in *EASA.2021.HVP.26 Horizon Europe Project: Runway Micro Texture*. This project is funded from the European Union's Horizon Europe research and innovation programme. NLR, and its partners DLR and ESDU have conducted this research project for EASA. The current report summarises the activities and the main results of the project as part of work package 5.3.

1.2 Research objectives

The outcome of the research project proposed here should enable EASA to:

- initiate rulemaking action to revise Regulation (EU) No 139/2014 as regards aerodromes in order to establish micro texture threshold values, below which a runway would be considered as slippery wet and maintenance actions are required;
- establish clear criteria for the development of a trend monitoring programme of runway surface; and
- review the certification specifications regarding runway surface construction.

The research project should therefore deliver the following results:

- a correlation of measured micro texture characteristic derived from high-resolution surface laser scanners with aeroplane braking performance on wet runways;
- recommended runway micro texture threshold values, below which a runway becomes ‘slippery wet’;
- A practical guide, which could be used by aerodrome operators, competent authorities and accident investigation bodies, on using surface laser scanners for assessing runway micro texture.

The overall objective is to develop a practical method for assessing the micro texture characteristics of runways using commercial off-the-shelf high-resolution surface laser scanners. This method should be able to determine whether a runway (or a part thereof) is slippery when wet. The results of the project should enable EASA to initiate rulemaking action to revise Regulation (EU) No 139/2014 as regards aerodromes in order to establish micro texture threshold values, below which a runway would be considered as slippery wet and maintenance actions are required.

The results obtained with a high-resolution surface laser scanner will be converted into parameters that characterise the micro texture of a runway surface. These parameters will then be correlated with that part of the wheel braking friction of aeroplanes that is associated with the micro texture of a wet runway surface. Runway micro texture thresholds, below which a runway becomes ‘slippery wet’, can then be developed.

2. Overall project approach

The approach for the project was to firstly create a solid starting point for the work to be performed. This means making sure that the project team was up to speed with the latest research in runway friction, micro texture, surface laser scanners and identification of slippery wet runway pavements. For this purpose, relevant literature was collected and analysed.

The second part of the approach was to define and execute a flight test campaign in which braking performance has been tested on artificially wetted runway pavements using two fully instrumented aeroplanes. Different microtextural characteristics were deduced from these measurements. Wheel braking friction characteristics were derived from the flight tests. From these braking friction data a parameter that characterises the micro texture of the runway was deduced. The correlation found between microtextural characteristics obtained with laser scanner and micro texture characteristic from the flight tests data was used to define thresholds for a slippery wet runway. Based on the results, guidance material for using high-resolution laser scanners was developed.

3. Summary of project achievements

3.1 Flight tests

A key element in the research project was to collect friction data of aeroplanes that braked on a wet runway during flight tests. Such tests can be conducted on artificially wetted runways or on runways that are wet due to natural rain. The method of artificial wetting has obvious advantages over natural rain because it is available when required and giving a consistent degree of wetness. It is not feasible to wait for natural rain conditions that sufficiently wets a runway and to run braked tests with an instrumented test aeroplane. Such data can only by captured by chance. Therefore, the flight test campaign was built around a set of tests conducted on a selected number of runways that were artificially wetted.

The flight test procedures that were adopted for the research, were based on the industry common practices for wet runway testing[4]. Also, the extensive experience of NLR in conducting such tests was utilised in setting up and conducting the flight tests.

The aeroplanes used in the flight tests were the NLR Citation 550 and the DLR Dassault Falcon 2000LX (see Figure 3-1). Both aeroplanes are certified according to EASA CS25 or equivalent regulations, have modulating anti-skid systems, and can be equipped with accurate state-of-the-art flight test instrumentation. The Citation covers the lower end of the range of main gear tyre inflation pressures (115 psi) and the Falcon the higher end (185 psi)[5]. The Citation 550 is equipped with cross-ply tyres and the Falcon 2000LX with radial tyres which are both used on other CS25 certified type of aeroplanes. For both aeroplanes validated engine and aerodynamic models are available which are needed to deduce braking friction data from the recorded flight data[6].

[4] See for instance: *Reduced Friction Runway Surface Flight Testing – Wet Runway Taxi Test Procedures at Edwards Air Force Base*, STO AGARDograph 300, AG-300-V31, 2018; *A Review of the Problems of Aircraft Wheel Braking on wet Surfaces and a Description of a Method of Artificially Wetting Runways for Test Purposes*, AERONAUTICAL RESEARCH COUNCIL, CURRENT PAPERS 592, 1962; *Evaluation of two transport aircraft and several ground test vehicle friction measurements obtained for various runway surface types and conditions. A summary of test results from joint FAA/NASA Runway Friction Program*, NASA TP-2917, 1990.

[5] Main gear tyre inflation pressures of CS25 certified aeroplane are typically between 100 and 210 psi.

[6] Wheel braking friction coefficients are deduced from the recorded flight data (like longitudinal acceleration) using the basic equations of motion, combined with known thrust and aerodynamics characteristics.

Figure 3-1: test aeroplanes

The flight tests were conducted on a variety of runway surfaces. Four different aerodromes were selected: three located in Europe (Twente airport, Braunschweig Airport and Cochstedt Airport), and one in the United States (NASA Wallops Flight Test Facility). The choice of the test aerodromes was affected by the possibility to conduct flight tests, which requires temporarily closure of the runway for other users. Additionally, the available runway length, width and the type of pavement determined the suitability of the location. The NLR Cessna Citation was tested at all mentioned locations whereas the DLR Falcon 2000LX was only tested at the European aerodromes.

The flight tests consisted of a combination of accelerate-stops and some full landings (high speed coverage). The tests ground speeds varied in the range of 30 to 130 knots based on the anti-skid cut-off speeds, and weights used in the tests and the wind conditions. The general flight test sequence is listed below:

1. The test aeroplane is positioned for the beginning of a run, either at the end of runway or in the air,
2. Water trucks make (e.g.) two passes over the marked runway test section,
3. Surface water-depth measurements are collected and timed, measurement of wet surface temperature,
4. The aeroplane makes a test run with maximum wheel braking after entering the marked test section,
5. After exiting the test section, the aeroplane can continue to a stop and awaits the next run, or makes a 180° turn and runs on the runway/taxiway at low speed to cool the brakes. The action taken depends on the conditions of a particular run. Brake temperatures will always be checked by a ground engineer,
6. Surface water-depth measurements are collected and timed.

An example of a start of a flight test run is shown in Figure 3-2.

Figure 3-2: example of the start of a flight test run

During each test run a series of data were recorded and collected such as (but not limited to): air and ground speed, accelerations, pitch attitude, engine parameters, wheel brake parameters, flight controls, flaps setting, main gear wheel speed, aeroplane weight, centre of gravity, aeroplane position (DGPS), air temperature, atmospheric pressure, surface winds, water depth, and test surface temperature. These parameters are all measured at sufficiently high sample rates (e.g. accelerations at 50 Hz). High samples rates for instance for the measured longitudinal acceleration and (ground and air) speeds, allow for a more accurate determination of the wheel braking friction coefficients as a function of ground speed considering the length of the wetted test section on the runway. Video images and still pictures taken at relevant areas around the aircraft had also be made.

The wheel braking friction coefficient as a function of ground speed was deduced from the recorded flight data using an aeroplane performance model. An aeroplane performance model determines the forces acting on the aeroplane during the ground roll based on the current state of the aeroplane and the environment.

3.2 Surfaces tests

Measurements were made using a high-resolution surface laser scanner on the sections of the runway tested using the test aeroplanes. For the research study an AMES 9400HD portable surface scanner was used. This scanner has been successfully applied by NLR in some preliminary studies into micro texture assessment of runway pavements. The device is designed to be used at outdoor locations like roads unlike some other available devices which can only be used indoors or in a laboratory setup. Laser surface scans were conducted at the expected tyre-runway interface during the testing at both sides of the runway centreline. Along with measurements using the laser scanner also tests were conducted using a British Pendulum Tester. Both devices are shown in Figure 3-3.

Besides the surfaces tested with the aeroplanes additional tests were conducted on other surfaces like concrete and asphalt pavements with different levels of micro textural smoothness using both the surface scanner and the pendulum tester. These surfaces included runways and taxiways. The laser scanner results were used to derive different micro texture characteristics.

Figure 3-3: illustrations of the surface laser scanner and British Pendulum tester

3.3 Data analysis

The braking friction generated by an aeroplane tyre depends on a number of variables including: tyre inflation pressure, runway macro and micro texture, ground speed, wheel slip (as controlled by the anti-skid and brake application by the pilot), water surface depth, tyre dimensions, and surface temperature. For the research project it is important to identify a single parameter from the flight test data that characterises the influence of the micro texture on wheel braking friction. For this purpose a tyre braking friction model from ESDU was used. ESDU has developed a comprehensive semi-empirical mathematical model that can predict the wet runway braking friction of aeroplane tyres as function of runway texture characteristics (both macro and micro), water depth, tyre slip, ground speed, surface temperature and tyre characteristics[7]. The micro texture characteristics of the runway are modelled through a parameter called *micro texture sharpness*. This is an empirical parameter that emulates the effect of micro texture on braking action. For each flight test run the water depth, macro texture depth, and tyre characteristics was measured as well as other variables that are input to the ESDU model. This means that under the assumption that the ESDU model accurately predicts wheel braking friction[8], the micro texture sharpness parameter can be estimated by matching the ESDU model results with the measured tyre braking friction versus ground speed data by varying the sharpness parameter.

Besides measurements with the surface laser scanner, tests had also be conducted using a British Pendulum Tester. This is a dynamic tester used to measure the energy loss when a rubber slider edge is propelled over a test surface at low speeds. The surface friction is determined by the energy loss in the pendulum which is indicated by the height of the swing of the pendulum after it passes over the surface[9]. Tests were conducted on the same surface and spot that was scanned with the laser scanner. The British Pendulum Tester provides an *indirect* measure of the micro texture of paved surfaces. The recordings from the British Pendulum Tester were also converted into the *micro texture sharpness parameter* F1 using a model developed by ESDU.

There are several ways to analyse the data obtained from the high-resolution surface laser scanner in terms of the applied processing technique and the different characteristics that describe the micro texture of a runway surface (e.g. micro texture depth). Different techniques to process the raw laser scanner data were analysed. This encompassed things such as filtering, spike removal, and consideration of tyre contact areas. An example of separating a raw laser trace in a micro and macro texture part is shown in Figure 3-4. Several micro texture characteristics have proposed in the past by researchers. These were explored in the research project along with new developed parameters. The micro texture characteristic and processing technique that give the best correlation with the micro texture sharpness parameter derived from the flight tests, were used to establish micro texture thresholds.

By testing on a range of runways with different micro texture characteristics, a correlation can be established between the *micro texture sharpness parameter F1* derived from the flight test data and the British Pendulum test (BPT) with a *micro texture characteristic* obtained from the high-resolution laser scanner measurements. Figure 3-5 provides a schematic overview of this approach. An example of a correlation between the micro texture sharpness and a micro texture parameter derived from the surface scans is shown in Figure 3-6.

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[7] *Aircraft tyre rolling or braking on dry or precipitate contaminated runways: Summary of the model*, ESDU-Engineering Sciences Data Unit – ISH Global, Data Item 05011, London, 2015 (With Amendments A to D); and *Model for performance of a single aircraft tyre rolling or braking on dry and precipitate contaminated runways,* ESDU-Engineering Sciences Data Unit – IHS Global, Data Item 10015, London, 2015 (With Amendments A and B).

[8] Comparisons with test results obtained with individual aeroplane tyres braked on wet surfaces show that there is generally good agreement between measurements and calculations over the range of independent variables. Overall, the ESDU modelling reflects the trends in the measurements as ground speed, slip ratio, water depth, tyre pressure and texture depth change.

[9] The pendulum and the footpad swing freely, allowing the rubber slider to scrape the surface when the pendulum traverses the vertical orientation. A certain amount of energy is then dissipated by friction of the rubber slider. The pendulum then swings upward to a height lower than the equivalent release point on the other side. This difference in height gives a measure of the dissipated energy and is often considered a measure for the effect of surface micro texture.

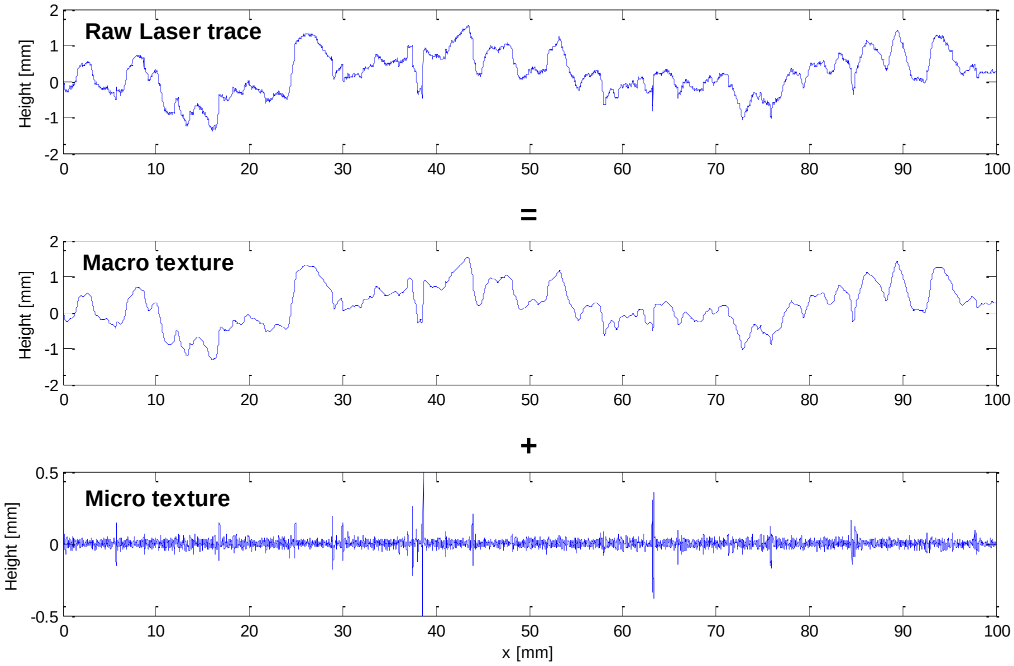

Figure 3-4: Example of separating the raw laser trace in a micro and macro texture parts

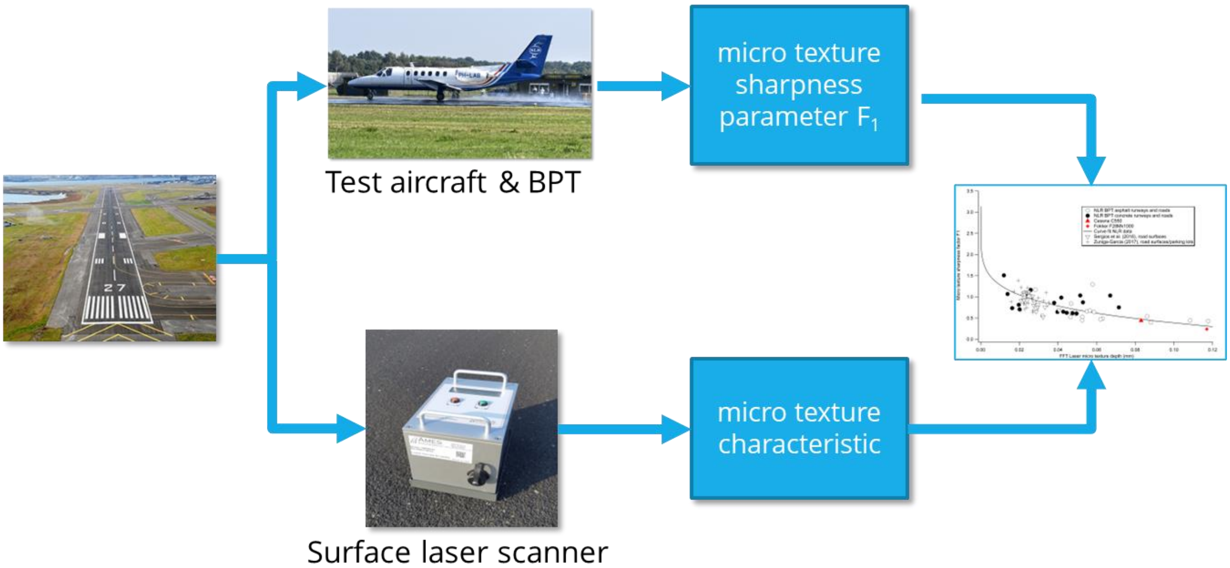

Figure 3-5: Correlation of test data with surface laser scanner results

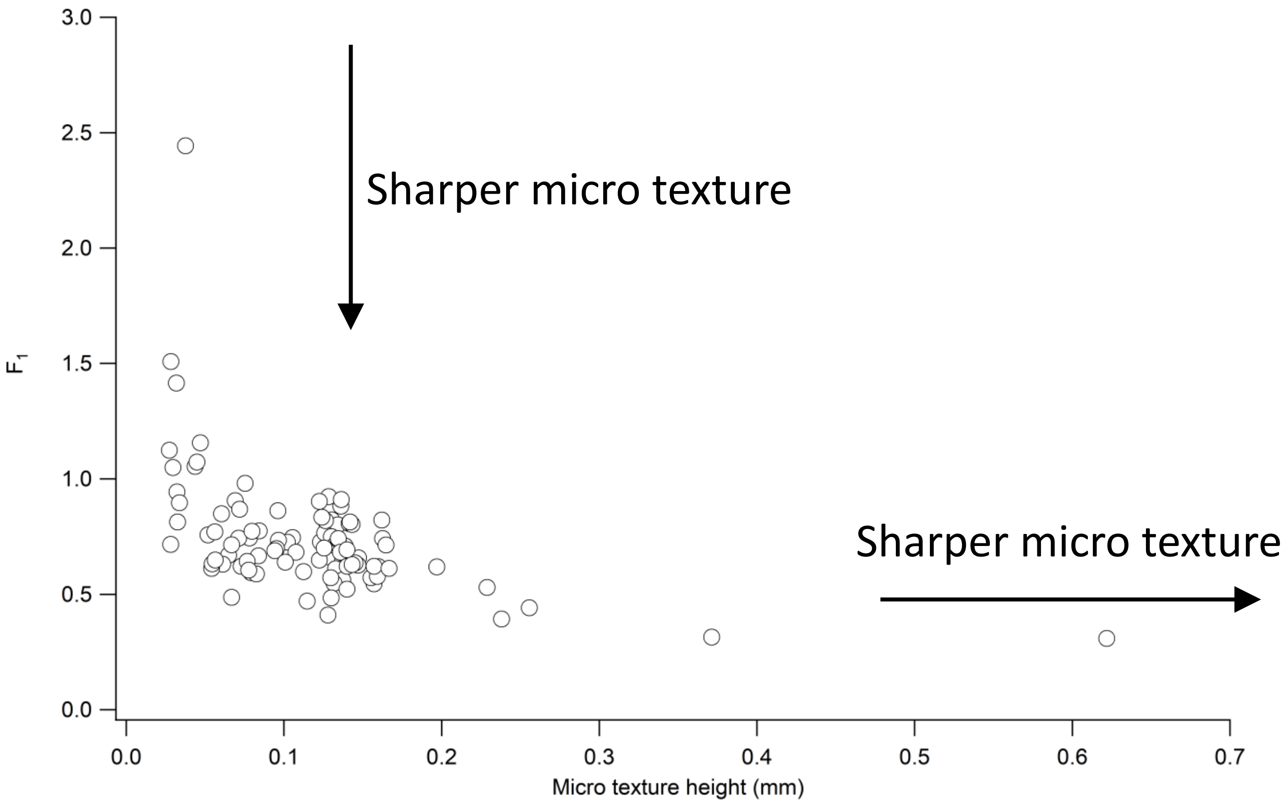

Figure 3-6: example of correlation between the micro texture sharpness and a micro texture parameter derived from the surface scans

3.4 Determination of micro texture threshold

Another important research objective was to develop recommended runway micro-texture threshold values, below which a runway becomes 'slippery wet'. A 'slippery wet' runway is a runway whose surface friction characteristics for a significant portion of it have been determined to be degraded below the minimum standards. A 'slippery wet' runway was originally defined by ICAO as a wet runway on which *twice* the dry braked stopping distance (with maximum braking, no reverse thrust, and normal landing configuration) is needed to stop an aeroplane[10].

For the proposed research project threshold values for the runway micro texture will be determined in two ways. First landing stopping performance calculations will be made using the already mentioned ESDU friction model (see footnote 7) for a wide variety of CS25 type of aeroplanes for which idle thrust and aerodynamic data are available. These aeroplanes included business jets, regional jets, narrow and wide body civil aeroplanes. Point mass models to simulate landing stopping distances were developed for these aeroplanes using standard industry practices[11]. The simulated landing stopping performance on a dry runway was compared to that for a wet runway considering different values of the *micro texture sharpness parameter* and landing weights. The value of the micro texture sharpness parameter that produces a wet runway stopping

[10] In 1981, arising from a comment on the recommendations of the AGA Divisional Meeting (AGA/81), the Air Navigation Commission agreed that the ICAO Secretariat should re-examine the criteria for the development of equipment for determining the friction characteristics of wet runways. Initially a maintenance level and, later, a minimum friction level was introduced. A link to the operational aspect was sought through an aeroplane *stopping distance ratio between wet and dry of* ***two*** and the introduction of the term "slippery when wet". (source: ICAO Circular 355)

[11] E.g. *Jet transport performance methods*, Boeing Report D6-1420, 1989.

distance of twice that for an operation on a dry runway could then be considered as a threshold value in accordance to the original definition by ICAO for a slippery wet runway. For each aeroplane model assessed the exact value of this critical micro texture sharpness parameter will not be necessarily the same. An average value or the most critical value from all aeroplane models considered can be chosen as the threshold. With the help of the best correlation established between the micro texture sharpness parameter (from the tests) and a micro texture characteristic obtained from the high-resolution laser scanner, a threshold for the micro texture characteristic can be derived. This approach is illustrated in Figure 3-7. Note that within the ESDU modelling the micro texture becomes *smoother* as the value of the micro texture sharpness parameter *increases*. The micro texture characteristic could be the micro texture asperity height or another parameter such as a shape factor (ratio of the micro texture asperity height and width). Part of the research was to determine the micro texture characteristic that gives the best correlation with the micro texture sharpness parameter derived from the flight tests. This correlation can be used in the establishment of the threshold.

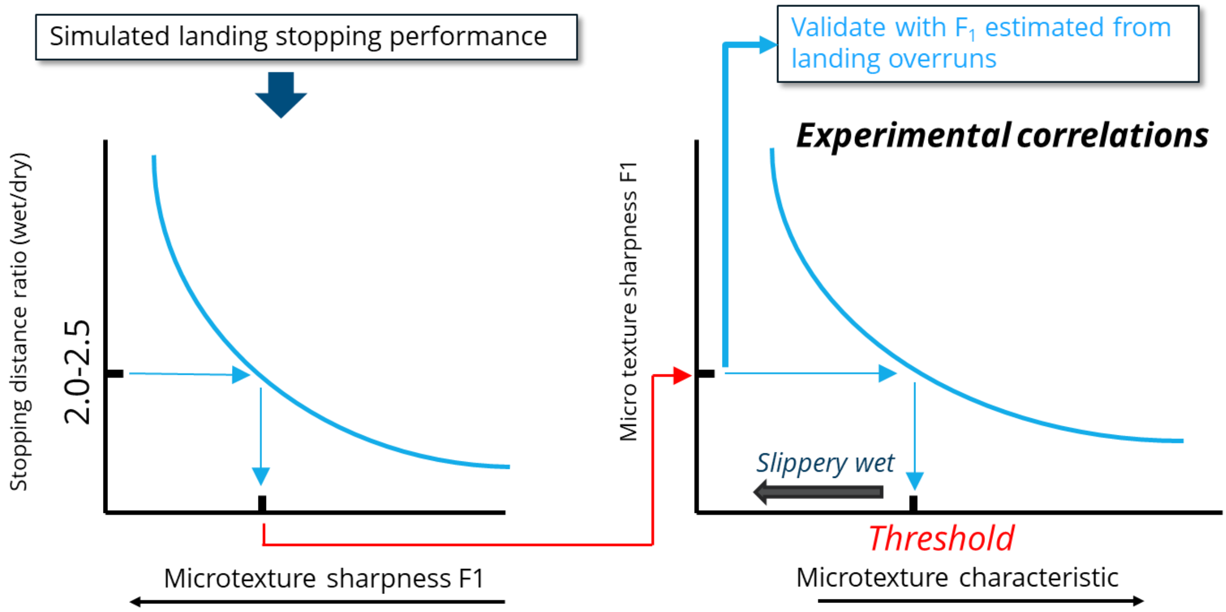

Figure 3-7: Illustration of the approach to derive a threshold for the runway micro texture characteristic

4. Dissemination of the results

It is important that the results of the research project are widely disseminated to the relevant stakeholders so that the outcome of the project will be effective. That is the aviation community should benefit from it through an increase in flight safety levels (e.g. reduction in runway excursions). The dissemination activities ranged from raising the awareness of the project to the final goal of establishing a long-term impact of the project results on its target users (e.g. aerodrome operators and accident investigators). Different means of dissemination methods were used, varying from media enouncements, webinars, scientific papers being published in, articles, LinkedIn, seminar presentations (at e.g. ISASI, SAPOE, AIAA, ICAO) and events with stakeholders. The project was also presented during a final webinar[12]. Public project deliverables are posted on the EASA project website[13].

[12] https://www.easa.europa.eu/en/newsroom-and-events/events/research-project-runway-micro-texture-rwymt-final-dissemination-event

[13] https://www.easa.europa.eu/en/research-projects/runway-micro-texture-rwymt

5. Final remarks

5.1 Next steps

Several steps should be taken after the project. First choices need to be made which micro texture parameter derived from surface scans should be used. This is still open for discussion. The proposed threshold should be evaluated in order to establish a common accepted criterium for slippery wet surface related to micro texture or macro texture (in case the macro texture is very smooth). This should be done at a working group level such as the ICAO friction task force. The present research study focussed on the use of high-resolution surface laser scanners. However, other devices could also fulfil the requirement in scanning the runway surface with sufficient detail. For instance, optical devices should be explored. Also, further developments in laser scanners should be considered. The approach and method developed needs some validation before full operational use by aerodrome operators and AIBs. Further validation is recommended by analysis of 'slippery wet' runways as identified by for instance onboard measurements (like RunwaySense on Airbus aircraft).

5.2 Open issues

There are a number of open issues that can play a role in the assessment of wet runway surfaces.

For instance, the operational water depth measurements remain challenging. Although developments have been made some aerodromes are assessing water depths on their runways during rainfall using automated systems, their accuracy and validity remains uncertain.

A factor that is known to affect wheel braking friction is surface temperature. This factor is currently not taken into account in wet runway assessments.

Macro texture depth effects are known to affect wheel braking friction on wet surfaces. Currently there are no clear guidelines on minimum values of the macro texture depth related to slippery wet runways.

For a slippery wet runway a default wheel braking friction coefficient is currently assumed for performance calculations. This default value was not based on data related to slippery wet runway braking.

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