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Iterative Prototyping of Aircraft Tire Wear Measurement using Laser Profilometer

Michiel J. Schuurman* and Roger M. Groves†
Delft University of Technology, Faculty of Aerospace Engineering, Delft, 2629HS, The Netherlands

Today's aircraft are equipped with multiple sensors, which monitor the integrity of aircraft systems and support predictive maintenance to increase aircraft operability and safety. Although the tires are only functional in a small time frame during flight, tire failures can have a huge operational impact on both the aircraft and airport. The Airbus Global University Partnership Program (AGUPP) has the objective and vision to foster relationships between Airbus and partner universities. One of the axes clearly identified within AGUPP is providing universities and students access to the means and facilities within Airbus. Following the AGUPP in 2017 call Delft University of Technology pitched the idea to a determine tire wear using a laser profilometer to Airbus. The idea was accepted, and for the project access to Airbus test facilities were granted with a tight time schedule and technical constraints. Having strict deadlines and short time periods where test facilities would be available meant that an iterative test development process was required to stay on schedule. The developed laser profilometer to measure main landing gear tire wear needed to be tested before being integrated into the Airbus A350 flight test aircraft and the Airbus Test Rig for Aircraft Tyres (TeraTyre) facility. The technical constraints set by Airbus was that the profilometer system should be stand-alone and not interfere or damage test facilities. These two technical constraints influenced the design and implementation of the laser profilometer system. This paper will provide a development overview of the laser profilometer system. Furthermore, preliminary results of the laser profilometer data which was gathered during ground tests will be presented.

I. Background

Current modern aircraft are monitored by various sensors for load, limit excedance and system anomaly detection. The overall goals of these sensors and systems are preventing future problems and enhancing aircraft operability. One such example of a continuously monitored aircraft system is an engine. The engines fuel flow, temperature and speeds are constantly monitored and assessed in real time to detect potential problems. Based on the analyses of this data preventive maintenance is scheduled before failure occurs. Engine Health Monitoring has increased the aircraft operability, and safety [1]. An Aircraft Health and Trend Monitoring System (AHTMS) is integrated as a whole [2] in some aircraft. This AHTMS uses data from various sources for trend analyses, and data analyses and prognostics are used to alert off "normal" conditions.

Today's aircraft tires lack a structural health monitoring system. While aircraft tires are only functional in a small time frame during flight, tire failures can have a huge operational impact on both the aircraft and airport. Furthermore, a tire issue can lead to a (catastrophic) failure scenario with possible aircraft (structural) damage requiring costly repairs and tire replacement. In the past several serious incidents and accidents have been linked to tire issues. Investigations into these events showed that the causes could be related to tires being under inflated, worn or damaged [3][4][5][6]. As pointed out in these reports the aircraft tires' condition are determined by a pilot during a walk around and maintenance inspections at a given interval. Current trends in aircraft usage optimization, time restrictions and operational wear and levels of operational tear, the inspection methods currently applied, does not always guarantee tire integrity. Unlike most aircraft systems the landing gear has no redundancy or back-up.

From a designer's perspective, the landing gear should support the aircraft during ground operations, including take-off, landing (impact) and taxiing. The landing gear load and deflection requirements together with the weight and sizing is more important than the tire, and its tread [7][8]. The landing gear designer needs to ensure that a wide variety

*Assistant Professor, Aerospace Structures & Materials Department, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands, AIAA member
†Associate Professor, Aerospace Structures & Materials Department, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands, Non-member.

of dynamic and thermal loads can be withstood by the gear configuration. The tire is chosen based on size and the final loading and available landing gear space on the aircraft.

Aircraft tire research has shown that wear is a complex phenomenon that depends upon a multitude of different interdependent variables [9]. A tire wear study showed that the tire failure distribution for a A319/20/21 had a mean of 338 cycles between failures, and a 132 cycles standard deviation [10]. Climate and seasonal changes have an impact on tires and influence on tire wear. It has been said that tire manufacturers have been reluctant to sign contracts with precise wear requirements as influential wear factors are outside of their control [9]

The principal tire testing technique is based on a predefined "energy" wear cycle which reflects operational conditions [11]. This wear test is not meant to provide an absolute wear rate nor is it meant to provide a specific number of landings before tires need to be changed. The wear test is aimed to provide a comparative index to other in-service tires. The index makes it possible to compare a tire design with another on a percentage difference scale.

In the past at NASA's Langley site, various test programs have been conducted to gain more knowledge on tires. Several studies were conducted to understand the boundaries of the ground interactions and responses of tires [12] [13][14]. To-date the main tire wear research which is currently performed is focused on the development of computational aircraft tire models. The numerical tire models and simulations developed range from the shimmy and vibration analyses on landing gears [15] to tire wear due to wheel spin-up [16] [17]. These studies focus on a specific part of the tire. Another more generic approach is the digital twin tire model development which could be used for predictive maintenance [18]. These recent research efforts show an increase in attention of tire wear modeling. However, the approaches chosen all rely on modeling the tire wear using numerical methods and wear data based on energy testing. As such a generic and aggregated statistical modeling cannot be representative for every aircraft tire wear.

Therefor it is proposed to conduct research on the feasibility of in service empirical tire wear measurement. By directly measuring the physical tire profile depth (profilometer) the absolute wear property can be assessed. This empirical tire data can be used for predictive purposes in the future and possibly will include the detection of non-normal wear (local) conditions affecting tire integrity. A profilometer measurement of the tire treads is more accurate and potentially could enhance understanding and better correlate the relation to the multitude of wear factors.

II. Scope of Testing

Following a call from Airbus to propose new collaborative projects, Delft University of Technology pitched the idea of determining tire wear using a laser profilometer. The proposed concept was accepted and for a limited time access to Airbus test facilities was granted, with the technical constraints defined by Airbus. The primary technological constraint laid down by Airbus at the project start was that no interference or damage would be caused by the developed profilometer. As a result, it was descided that the profilometer system was required to operate in a stand-alone mode and neither electrical power or data connections would be required from the Airbus test equipment. Also the system must be attachable without damage to the test Airbus equipment. These two design requirements provided a challenge during the technological development and integration into the various Airbus test facilities that were available during the project.

As the project time frame was 1-year, from September 2017 to August 2018, a phased and stepped development approach was chosen. Airbus had one major tire testing (TeraTyre) campaign scheduled for the period from May until August 2018 and the TU Delft project team was challenged to develop and iterate the system before being allowed to piggyback on the TeraTyre test campaign. Having this tight schedule when Airbus test facilities would be available meant that an iterative test development process would be required to be able to stay on schedule.

The test program objective was to investigate and test the feasibility of tire wear measurement using a laser profilometer on an aircraft tire for future research. In essence, the project main goals were to build a proof of concept aparatus and determine the technological feasibility.

The project work was divided into three work packages (WP). The overall Project management (WP1) would assist and coordinate profilometer unit development (WP2) and Test campaign (WP3). As WP3 dictated the planning due to time constraints and the availability to have access to facilities, WP3 drove the project time line. In order to develop and increase confidence to the profilometer system, knowledge and lessons-learned from WP3 testing would be required to be feedback into future WP2 unit development. As such each iteration was meant to enhance the system step-by-step and increase technical maturity for testing on the Airbus tire test facility (TeraTyre). In paragraph IV Ground Test and Results additional design requirements and goals will be highlighted.

III. Test instrument

Due to the project deadlines, developing and manufacturing a dedicated sensor unit including interface software would use considerable time which would mean not meeting the set deadlines. Therefore instead, a commercial off-the-shelf (OTS) laser sensor unit would be required with a preferably known interface software to in order to save development time. The Structural Integrity and Composites (SI&C) research group has experience with several types' laser and software packages. After evaluation of the technical requirements (range, power and software) one preferred manufacturer was selected. Based on tire material, color, measurement frequency and the working distance a sensor type was selected.

The unit selected for testing was the Micro-Epsilon scanCONTROL LLT2750-100. The unit has a general dimension of 170x69x73 mm and is capable of a 15μ height measurement resolution while weighing 850 grams. The scanCONTROL Class 3B laser has a optical power (adjustable) up to 20 mW and possessed a 20° laser line aperture angle and an extended measuring range between 300 and 600 mm from the laser head [REFERENCE]. The scanConrol unit projects a laser beam onto a surface which is detected with the triangulation principle. The unit data output is an x-distance and y-distance from the head space with a maximum measurement frequency of 4,000 Hz. However, for the conducted tests, a 25 Hz recording frequency was chosen as this permitted the use of the maximum 110 mm measurement width.

The scanCONTROL unit was connected to a Minix NEO Z83-4 fanless mini PC system operating Microsoft Windows and laser interface software. The mini PC was equipped with a solid-state drive which was used as the recording medium for the scanCONTROL data. Both the scanCONTROL laser and computer were connected to a 12 Volt nickel metal hydride (NiMh) portable battery pack. In the final stages of development, the computer and battery pack were integrated into a 240x160x90 mm fluid sealed box. External connections to the scanCONTROL laser were established for power and data transmission to the box using a special fluid sealed connection system. Furthermore, remote access was engineered to interface with the profilometer system without the need to remove the sealed box from TeraTyre testbed.

IV. Ground Tests and Results

This section will provide an overview of the three tests which were accomplished in the course of this project. Each step examined the prototype performance and helped future development to in the end perform a ground test on the Airbus test bench for tire testing.

A. Bicycle

The first step in the profilometer system development was to source and connected components together for prototyping. The objective in this first phase was to integrate the system and allow data to be recorded for later analyses. For this phase, an off-the-shelf Dutch city bicycle was procured. The bicycle was equipped with a five speed internally geared rear hub with 28 inch front and rear wheels with used tires. The front bicycle wheel tire tread would be measured. By attaching a purpose-built aluminum rack to the steering column the laser could attached and pointed downwards at the tire treads for measurement. For static testing a stand was built which would elevate the front wheel axle and allow the front wheel to rotate freely. The bicycle test setup used for static testing is shown in Fig. 1a.

This static test stand enabled data collection of the front bicycle wheel treads using the profilometer system connected to a computer and normal main power supply. Using a cordless drill the front wheel was rotated at a constant speed, and data could be collected and recorded for later analyses. The static unit data was subsequently analyzed and assessed. During these stationary tests, the power requirement of the system was measured in order to size the battery pack for the next iteration.

Following static testing the system components, including at the time a properly sized battery pack were packaged into a 'mobile system'. The purpose-built aluminum rack, to which the scanCONTROL laser unit was already connected, was re-used to carry all the required components on board the bicycle. With the system integrated, dynamic testing was conducted on TU Delft campus. The now mobile system on the bicycle was driven across the campus bicycle pathways while recording data. The dynamic scanCONTROL data was subsequently analyzed and assessed.

One data sample (cross section) from the profilometer unit is shown in Fig. 2. By stitching together multiple data samples (cross sections) as the bicycle tire rotated a three-dimensional model was created, which could be used for anomaly detection (flat spot or foreign object damage). Analyses of the static test revealed that a tire wobble was detected through data analyses. Furthermore, small stones and debris embedded into the tread area was detected during data analyses. Data visualization and deviation detection algorithm forms the basis for identifying anomalies. The dynamic

(a) Test setup bicycle.

(b) Close up laser setup on bicycle.

Fig. 1 Bicycle test stand.

test revealed that the scanCONTROL mounting to the wheel was not sturdy enough causing lateral and longitudinal movement of the scanCONTROL unit resulting in noisy data being recorded. Although in part the noise could be removed from the data, for easy analyses and accuracy, the mounting should be stationary so that the system is fixed distance to the tire tread surface.

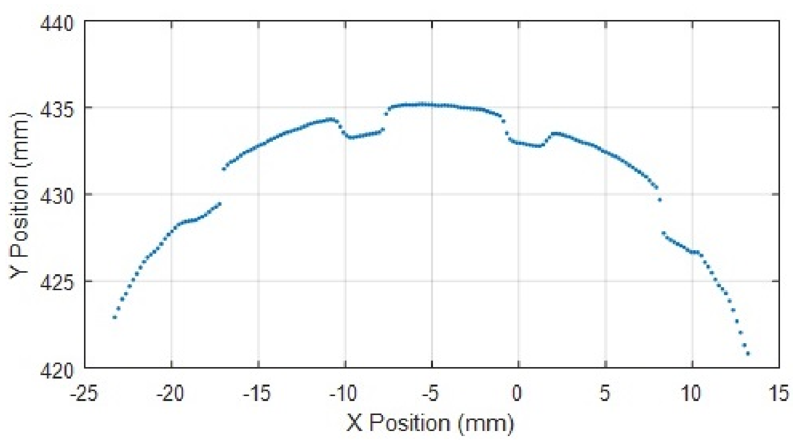


Fig. 2 Profilometer output bicycle front wheel cross section (one data sample).

Both the stationary and dynamic bicycle testing made use of an inexpensive test article and was beneficial to the iterative testing approach. The step from stationary to dynamic testing increased system maturity, measurement capability and system confidence. The data recorded during these tests revealed observable tire tread and wheel anomalies and features. The dynamic bicycle testing showed the necessity of a fixed mounting unit in order to have noise free data. However, a bicycle tire has a 40 mm width which is not representative for a large commercial A350 aircraft tire which has a width 560 mm. Furthermore, the bicycle treads has blocks, grooves and dimples, which are not a representative tread pattern compared to a circumferential grooved aircraft tire.

B. F16 tire testing

In order to get a more representative tire measurement it was decided to make use of the available aircraft on static display at the Faculty of Aerospace Engineering. In the faculty hanger, a F-16 (Fig. 3 was available which is fitted with Goodyear 25.5x8.0-14, 20-ply aircraft tires (NSN 2620011426461) having a width of 200 mm. The main left and right hand tire were chosen as they were at both ends of their service life.

Fig. 3 F-16 profilometer Ground Test, main landing gear tires (right hand main wheel shown with green arrow).

The left hand tire (Fig. 4a) was bald and in one area the ply was visible, which meant this tire was well beyond its operational service life. The right hand tire (Fig. 4b) on the other hand, was new and showed no signs of wear, which meant it was at the beginning of its operational service life. Despite efforts, equipment was not available which would allow the F-16 up to be hoisted in the air or jacked-up to allow for free rotation of the tires. Therefor a purpose-built armature attached to the wheel axis was build that could be rotated around the tire circumference for an almost full tire tread sweep (290°angle). Because the armature with the laser unit was rotated around the tire axis, a comparison could be made between the two tire tread measurements.

Analysis between the left and right hand F-16 tire data shows a distinct difference. Fig. 5 depicts the right main landing gear tire (top trace) and the left main landing gear tire (bottom trace) cross-section. Clearly, the three treads are detected in the right hand tire, but are not present for the left hand tire. The delta between the two traces shows the tire wear. Further analysis also shows that in one area (right side) the left hand tire wear is past the two bottom grooves of the right hand tire. This suggests the tire ply should be visible at that location, which was already noted before. The 110 mm scan width of the measurement system was not sufficient to detect the full 200 mm width of the tire, as no information is captured on the state of the tire shoulders.

C. A350 Flight test Aircraft Campus ground test

As part of the AGUPP project arrangement, access was granted to the Airbus A350-900 Flight Test/Campus Aircraft see Fig. 6a. This former A350 Flight Test aircraft was deployed in the A350 XWB test program which included performance testing at high and medium altitudes, cold weather and hot temperatures and long-range flights. Currently, the aircraft is preserved without engines at Toulouse-Blagnac Airport where it is designated as Flight Test/Campus Aircraft. The aircraft is still being used for a variety of tests and serves as an easy accessible A350 exemplar. The A350-900 has two main landing gear bogies with a 4-wheel configuration. For this test iteration, it was decided to test the system on the A350 Flight Test/Campus Aircraft while towing it around Toulouse-Blagnac Airport. The main goal of the towing test was to evaluate the profilometer proof of concept on an actual aircraft and to assess system maturity.

In the towing test design phase two possible profilometer locations were identified on the A350 main landing gear. Both locations were based on mounting capability and the profilometer maximum detection range (600 mm). The first

(a) Left hand tire - bald tread.

(b) Right hand tire - new tread.

Fig. 4 F-16 main landing gear tires.

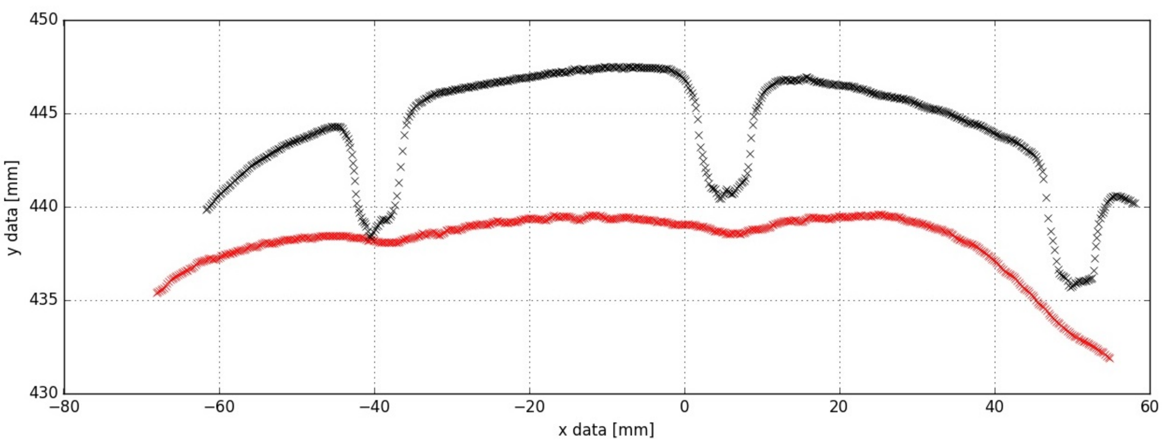
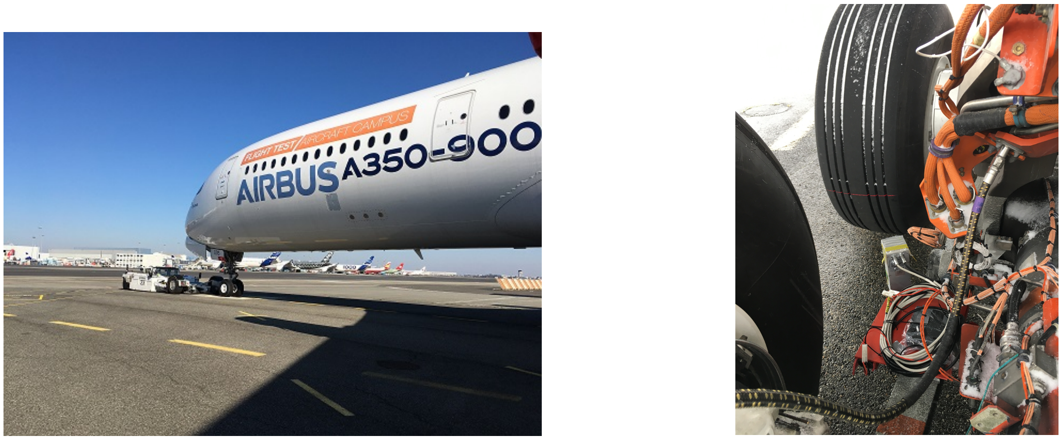


Fig. 5 F-16 Tire cross section comparisons between a new right hand (black) and left hand bald (red).

option was to fix the unit onto the main gear leg fairing door which in turn is attached to the main gear strut. In this proposed setup, the laser would be aimed at the aft wheel. The second option was to attach the profilometer unit to the landing gear bogie brake strut assembly. This would allow the profilometer to measure the forward wheel of the bogie. The main technical constraint set by Airbus at the start of the project was that the profilometer system would not interfere with or damage facilities and equipment. As the connection to the leg fairing door was technically hard and did not fall within the certified force requirements, this option was rejected. Therefor the second mounting option was chosen, which resulted in fabricating a purpose-built cradle see Fig. 6b which could be mounted on the outboard brake strut. The cradle unit was padded with foam material as not to damage the brake strut assembly. For securing the cradle onto the brake strut assembly, metal toggle clamps with rubber ends were selected. The removable clamped cradle created an excellent base plate where the required profilometer system components could be housed.

On February 28th 2018 a towing test was performed on Toulouse-Blagnac Airport with the profilometer unit attached to the A350 Flight Test Aircraft brake strut. Due to the weather conditions, the scheduled route and test were shorted due to airport snow operations. An example tire cross-section recorded is provided in Fig. 7. The data recorded during this towing test showed that no wear (delta), this was also expected due to the limited recording time and towing operation.

The towing test revealed additional requirements were needed for proper data collection under all conditions. Future unit capability should include an easy way to tune the detection level when testing in different weather (light) conditions.



(a) Airbus A350-900 Flight Test / Aircraft Campus.

(b) Profilometer system cradle on left main landing gear outboard brake strut.

Fig. 6 A350 ground test.

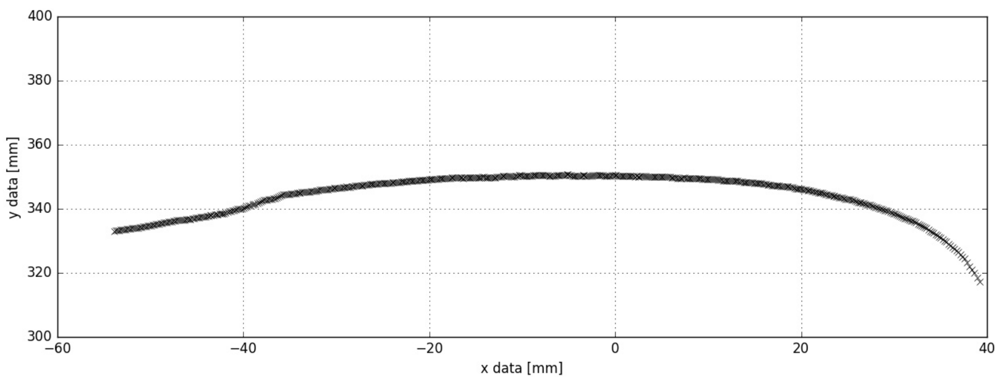


Fig. 7 Profilometer plot showing cross section A350 Main Landing gear tire.

The knowledge and experience gained were feedback into the further development of the unit's next test phase.

D. TeraTyre testing

During the Airbus A380 development it was noted that additional knowledge was required to determine the lateral load factor during aircraft maneuvering. The lateral load factor is the lateral load response versus the tire side slip angle and influences the landing gear strength (weight) design. Previous designs used theoretical values for this parameter [19]. To gain the required knowledge and understanding NFM Technologies constructed a tire test rig for Airbus which is called the Test Rig for Aircraft Tires (TeraTyre) [20].

The developed tire test rig can rotate the tire at a high slip angles which normal dynamo-meters cannot do. The TeraTyre test rig has overall dimensions of 14.5 x 4.5 meters and is 5 meters tall. The rig weighs 115 metric tons and is powered by a 1500 horsepower engine which allows the rig to reach a maximum speed of 90 km/h. The TeraTyre test rig can move and test one aircraft tire at a time along a linear or curved trajectory. With its pneumatic turret system the tire can be loaded to different weights. Due to the high slip angle capabilities, the aircraft tire is tested to its limits and well beyond ordinary wear seen in normal service life operation. With the extreme conditions to which TeraTyre is testing tires, the profilometer capability can be investigated and aircraft tire wear can be evaluated.

After an initial TeraTyre rig site visit at Châteauroux Airport (France) the profilometer test setup was discussed. The main goal of the unit was to have it work stand-alone and not to interfere with the testing rig. The optimal profilometer setup position would be to mount it on the rotational turret of the tire which already included some mounting points. This allowed for a head-on measurement of the tire throughout the test profile and be representative for future possible

Fig. 8 Test Rig for Aircraft Tires (TeraTyre) at Châteauroux Airport with in the centre the aircraft tire being tested.

mounting on an aircraft. To facilitate integration it was decided to work on the setup from two directions. Delft would provide a mounting with the scanControl unit and the TeraTyre technicians would provide a mounting bracket from the TeraTyre turret which would be bolted to the Delft setup housing the laser unit. It was suggested to encase the laser and protect it from separating tire parts and potential debris. In the past, when tires were tested rubber debris and parts separated which potentially could damage the profilometer equipment.

The Airbus test campaign for its A350 main wheel tires was running from June to October 2018. As the profilometer development project was able to meet deadlines the final iterated laser profilometer system could be tested in the final stages of the test campaign. In September and October 2018 two series of tests were conducted where the profilometer system was attached to the TeraTyre test rig. In order not to interfere with Airbus TeraTyre testing the test profile (speed, angle and weight) was left to the TeraTyre test manager. The main goal for this profilometer testing was to determine if tire wear would be detected by the developed unit.

Fig. 9 shows an unfiltered data set for Test wheel 9.The data is for a single measurement point which was in the field of view, the tread depth is calculated by subtracting the profile measurement of the valley and the groove. At the start of the test, the detected tread depth was ten mm, which is reduced by the end of testing to four mm. Depending on the test profile speed, slip angle and weight differences a distinct difference in the data traces and amount of wear. The preliminary data analyses showed a decrease in tire tread depth, which demonstrates wear was detected by the profilometer system. In a follow-up paper, the test results will be discussed in more detail.

V. Conclusion

The iterative prototyping of the profilemeter system was advantageous in the development. The stepped approach from simple to more complex allowed for an incremental increase in profilometer system maturity. The knowledge and experience gained during each ground test were directly fedback into the next development cycle. The technical conditions to have a standalone non-interfering system being attached to Airbus test facilities was an engineering challenge. However, by talking with test engineers and visiting the test equipment beforehand an optimal attachment was found for the profilometer system during each iteration. A small and dedicated team with sufficient resources were capable of performing a proof of concept test campaign within 1-year.

The data acquired during the different profilemeter ground test show potential in the system. From the initial bicycle test to the full aircraft tire on the TeraTyre test rig a sizable amount of data was collected. Preliminary TeraTyre test plots show that tire wear can be detected. The laser setup has enough accuracy to pick up induced tire wear during TeraTyre tests. The profilometer system that was developed reached its objective. More analyses and research is required to

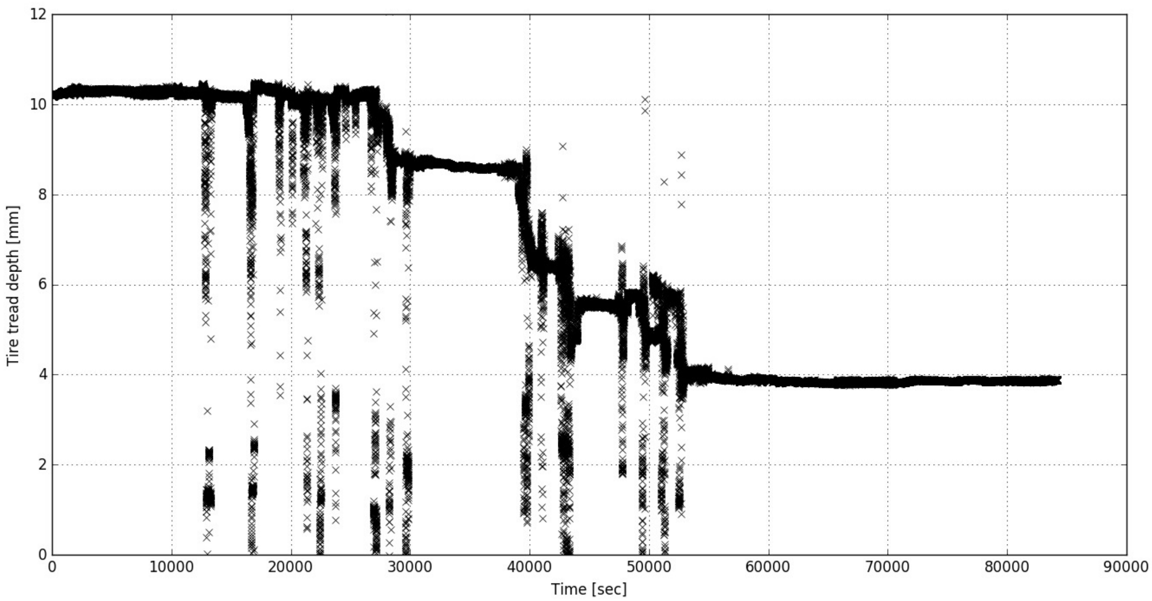


Fig. 9 TeraTyre Profilometer tire wear plot result Test wheel 9.

assess the system capabilities and limits. The data acquired paves the way for future work and research in direct tire wear measurement.

VI. Acknowledgements

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References

[1] Tumer, I., and Bajwa, A., "A survey of aircraft engine health monitoring systems," *35th Joint Propulsion Conference and Exhibit*, 1999, p. 2528.

[2] O'Dell, R., "The Gulfstream G650 Aircraft Health and Trend Monitoring System," *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2012, p. 5682.

[3] NTSB, "Runway Overrun During Rejected Takeoff Global Exec Aviation Bombardier Learjet 60, N999LJ Columbia, South Carolina September 19, 2008," Accident investigation report, National Transportation Safety Board, Washington, DC, Aug. 2009.

[4] NTSB, "Main landing gear - Failure, Dassault Falcon 20C,XA-PCC Eagle, colorado January 8, 2010," Accident investigation report, National Transportation Safety Board, Washington, DC, Aug. 2010.

[5] BEA, "Accident on 25 July 2000 at La Patte d'Oie in Gonesse (95) to the Concorde registered F-BTSC operated by Air France," Accident investigation report, Bureau Enquêtes-Accidents, Paris, France, Aug. 2000.

[6] AAIS, “Tire Failure Resulting in Loss of a Single Hydraulic System,” Accident investigation report, Air Accident Investigation Sector, Abu Dhabi, UAE, Aug. 2018.

[7] Currey, N. S., *Aircraft landing gear design: principles and practices*, American Institute of Aeronautics and Astronautics, 1988.

[8] Roskam, J., “Airplane Design Part IV: Layout Design of Landing Gear and Systems,” *Roskam Aviation and Engineering Corporation. Ottawa, Kansas*, 1985.

[9] Zakrajsek, A. J., Naboulsi, S., Bohun, M. H., Vogel, M. G., Fiepke, B. J., Vogel, R. N., Bena, R. M., Howell, S. J., Alsobrook, C. B., and Childress, J. M., “Improved Aircraft Tire Life through Laboratory Tire Wear Testing and Computational Modeling,” *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2015, p. 1125.

[10] Castilho, I. X., “Fault prediction in aircraft tires using Bayesian Networks,” Master’s thesis, Instituto Superior Técnico, Portugal, 2015.

[11] SAE, “Aircraft Tire Wear Profile Development and Execution for Laboratory Testing,” Standard, SAE International, Warrendale, USA, Aug. 2018.

[12] Tanner, J. A., Stubbs, S. M., and Mccarty, J., “Static and yawed-rolling mechanical properties of two type 7 aircraft tires,” Tech. rep., National Aeronautics and Space Administration (NASA), 1981.

[13] Vogler, W. A., and Tanner, J. A., “Cornering characteristics of the nose-gear tire of the space shuttle orbiter,” Tech. rep., National Aeronautics and Space Administration (NASA), 1981.

[14] Daughterty, R. H., *A study of the mechanical properties of modern radial aircraft tires*, Citeseer, 2003.

[15] Krüger, W. R., and Morandini, M., “Numerical simulation of landing gear dynamics: state-of-the-art and recent developments,” *Proceedings of Limit Cycle Oscillation and Other Amplitude-Limited Self Excited Vibrations, RTO-MP-AVT-152, Loen, Norway*, 2008.

[16] Zakrajsek, A. J., Childress, J., Bohun, M. H., Naboulsi, S., Vogel, R. N., Lindsey, N. J., and Mall, S., “Aircraft Tire Spin-Up Wear Analysis through Experimental Testing and Computational Modeling,” *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2016, p. 0413.

[17] Alroqi, A. A., and Wang, W., “Comparison of aircraft tire wear with initial wheel rotational speed,” *International Journal of Aviation, Aeronautics, and Aerospace*, Vol. 2, No. 1, 2015, p. 2.

[18] Zakrajsek, A. J., and Mall, S., “The Development and use of a Digital Twin Model for Tire Touchdown Health Monitoring,” *58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2017, p. 0863.

[19] Adan, S. P., Viñas, J. E. G., Martínez, J. M. C., Pérez, A. M., and Morales, J. A. C., “Methodology for the Validation of Loads in Rational Turning Analysis,” *5th CEAS Air & Space Conference 7-11 Sept 2015 Delft University of Technology*, 2015, p. 13.

[20] “NFM Technologies,” , 2018. URL `www.nfm-technologies.com/newsletter/english/newsletter1-eng.pdf`.