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A TEST METHOD FOR EVALUATION AND CLASSIFICATION OF UNSURFACED AIRFIELDS

METODA OCENY I KLASYFIKACJI GRUNTOWYCH NAWIERZCHNI LOTNISKOWYCH*

The study presents a project of a method for testing, evaluation and classification of unsurfaced airfields, with respect to wheel-soil interactions analysis. Basic theoretical considerations have been included in this study, together with a review of existing methods as well as instrumentation, which will be applied in the presented method. It is supposed the method to be advantageous for a better utilization of grassy, unsurfaced airfields in Poland and other EU countries, mainly through improving the safety level of airfield operations.

***Keywords**: airfield operations, general aviation aircrafts, unsurfaced airfiels, airstrips, test methods.*

W pracy przedstawiono projekt metody oceny gruntowych nawierzchni lotniskowych w aspekcie warunków współpracy kół podwozia samolotu z nawierzchnią. Zawarto podstawy teoretyczne, dostępne metody pomiarowe możliwe do zastosowania w projektowanej metodzie a także opisano projektowane rozwiązania. Przewiduje się, że przygotowywana do wdrożenia metoda może przynieść znaczne korzyści w zakresie lepszego wykorzystania licznych lotnisk trawiastych w Polsce, także w aspekcie bezpieczeństwa operacji lotniczych.

***Słowa kluczowe**: naziemne operacje lotnicze, lotnictwo ogólne, samoloty, lotniska gruntowe i darniowe, metody badań.*

1. Introduction

Aircraft ground performance on grassy airfields is weakened and depends upon a number of factors that we are unable to control. Safe take-offs and landings on an airfield require that the pilot know how the actual conditions may affect take-off or landing distance. Deformability of a soft surface affects rolling friction and traction of aircraft wheels. Moreover, there is a significant and poorly predicted effect of meteorological conditions upon the latter. Thus, the safety of aircraft operations on unsurfaced airfields requires the knowledge of their actual conditions with regard to a given aircraft.

For testing and classification of paved airfields, the ICAO has adopted two methods: the LCN (***L**oad **C**lassification **N**umber*) method, which is currently out of use and an ACN-PCN system [4], introduced between 1980 and 1983. This system uses two values: ACN – aircraft classification number and PCN, pavement classification number. The value of ACN is dependent upon airplane mass, center of gravity location, wheel base, and tire inflation pressure. Various experimental methods can be used to determine PCN. Moreover, airfield test methods include friction testers, i.e. ASFT (***A**irport **S**urface **F**riction **T**ester*) or SARSYS Friction Tester [1, 10, 17] as well as the use of specially designed, instrumented vehicles (for example the *CRREL Insrumented Vehicle* [18]). In these methods, braking friction is determined and the methods are widely used in northern hemisphere and cold regions, where runways are often covered by ice or snow. The presented methods are mainly applied for rigid surfaces, not for soft grassy airfields. They utilize models of wheel-surface interactions based on Boussinesque or Westergaard theories [9], which may perform not exactly in cases of moist surface and for a variety of soils. Consequently these methods do not ensure the required level of accuracy with their predictions. From the above mentioned, an introduction of a new method, especially designed for soft, unsufraced airfields is reasonable.

An increase of air transport is one of the priorities in new EU countries, like Poland. The utilization of unsurfaced airfields for general aviation operations may include such activities as crop dusting, fire fighting, personal transport on demand (the so called “air taxi”), medical or rescue flights, sport aviation, etc. There are lots of small and medium, unsurfaced airfields in the EU countries and they are important elements of ATM (***A**ir **T**raffic **M**anagement*), mainly for general aviation. Expected effects of utilization of the presented methods could be very advantageous since the GA community forms a strong complementation for the “big” air transport industry.

2. An idea of the proposed method

Authors’ idea was to propose an integrated method which would enable to evaluate the surface of an airfield, giving a precise information for pilots or airfield operators about the actual surface conditions. The purpose of the method is determination of important parameters, describing wheel-soil interactions and influencing the resulting aircraft ground performance:

- takeoff distance;
- ground roll distance;

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

– passenger comfort.

The important parameters are rolling and braking friction as well as surface roughness. The users of the method will be operators of airports and pilots of general aviation aircrafts. Knowing the actual values of the parameters, it would be possible to determine ground performance of a given airplane. The method consists of the following elements:

– braking friction measurement, performed with the use of a wheel tester;
– rolling friction measurement, very important for soft surface airfields, not included in other known methods;
– surface roughness measurement with the use of LIDAR method (***Li**ght **D**etection **a**nd **R**anging*);
– a mobile application, which will be an end-user toll of the method, enabling the calculation of ground performance of a given aircraft, knowing the measured parameters of the surface.

This paper covers the background of the method together with details of instrumentation used in the method.

3. Theoretical background of the method

3.1. Rolling friction of a wheel

Rolling friction of an aircraft wheel on an unsurfaced airfield affects ground performance of a given aircraft significantly. Stinton [15], gives values of rolling friction coefficient for a grassy airfield: 0,05 and 0,08, for short and long grass, respectively as well as 0,13 for long wet grass. The effect of high rolling friction on grassy surfaces is a significant increase of takeoff distance, typically by 10 to 25% when compared to paved runways. It is of great importance in the case of numerous private and casual airstrips, which are short or sometimes surrounded by trees or other obstacles. Filippone [8] gives simplified formulas to calculate takeoff ground roll l_r and landing roll l_d as functions of rolling friction, f_{RF} and braking friction, μ:

$$l_r = \frac{mV^2}{2\frac{\eta P}{V} - \frac{1}{4}\rho A C_D V^2 - f_{RF} mg} \qquad (1)$$

$$l_d = \frac{1}{2g\left(\mu + f_{RF}\right)} \ln\left(\frac{1}{2}\rho A\left(C_D - f_{RF} C_L\right)V^2 + mg\left(\mu + f_{RF}\right)\right) \qquad (2)$$

where: m – aircraft mass, V – touchdown speed, η – propeller efficiency, P – engine rating power, A – wing area, C_D – aerodynamic drag coefficient, C_L – lift coefficient, ρ – air density, g – Earth's gravity.

Rolling friction on paved runway is easy to determine. Frequently used methods include pull test or coast down procedure. On soft, deformable surfaces at lower speed, rolling friction of aircraft wheels can be measured with the use of pull test method or an indirect method, in which a rut depth is measured and this parameter is used for further calculations of rolling drag.

Some problems arise by higher speed, 10 m/s and more. Dynamics of soil deformation result in additional phenomena, such as the so called „spray effect" besides the wheel, with soil granules ejected outside with a relative high kinetic energy. Traditional methods of rolling friction measurements fail in such situations and only special instrumentation enables to fix the methodological problems. It is a method with the use of an instrumented vehicle, equipped with the so called "fifth wheel" or a trailer, enabling the determination of rolling friction at high speed. Also, a multi-channel rotating wheel dynamometer, installed in a test vehicle could be a good solution here.

Measuring the wheel forces and moments with the use of a rotating dynamometer was introduced and practically applied for testing wheel performance on a grassy airfield by the present authors in the cited work [13]. In this method, wheel forces and moments measured during a test ride can be recalculated into rolling friction coefficient. The following measures have to be known or determined during a test run:

– M_y – driving or braking moment on a test wheel;
– F_v – vertical load on a test wheel;
– r_d – dynamical radius of the tyre.

Rolling friction coefficient can be calculated from the equation below:

$$f_{RF} = \frac{M_y}{r_d} \times \frac{1}{F_v} \qquad (3)$$

Preliminary tests with the use of an instrumented vehicle with a rotating wheel dynamometer were conducted on a grassy airfield, what is shown in figure 1. Riding at 3 m/s forward speed, braking moment on the measuring wheel has been measured together with vertical load on this wheel. The rotating dynamometer was installed in the right front wheel and it was in rolling mode (not driven) during the test. Measured data has been averaged for a chosen range, where the values of measured forces tend not to oscillate. A sample set of data for the rolling friction force, F_{RF}, calculated from measured braking moment, M_y is shown in figure 2. It is to point out that the method enabled to determine of rolling friction for a given tyre, which, in the case of the tests performed in the cited work, wasn't any typical aircraft tyre. Therefore, an additional wheel trailer has been designed and a typical aircraft tyre is a part of this measuring device.

Fig. 1. A rotating wheel dynamometer installed on a test vehicle, during a test ride on a grassy surface. Braking moment MY¬ of a wheel is being measured

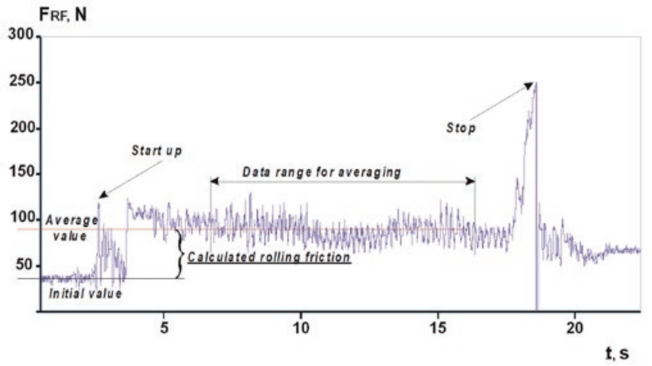

Fig. 2. Sample data of rolling friction force, calculated from measured braking moment, MY¬ of a wheel on a grassy surface with pre-calculation analysis

The effect of speed on rolling friction is significant. Mitschke [12] has shown the components of the rolling friction of a passenger car on a bitumen surface as follows:

$$f_{RF} = k_{R0} + k_{R1}\frac{V}{100} + k_{R4}\left(\frac{V}{100}\right)^4 \tag{4}$$

with: k_{R0}, k_{R1}, k_{R4} – factors for the sub-ranges of forward velocity: 0 – 30 km/h, 30 – 120 km/h and above120 km/h respectively, determined experimentally.

The relationships between rolling friction coefficient and aircraft ground speed (see references[13] and [14]), shown in figure 3, proofs that taking speed into account is of highest importance also for soft, deformable surfaces like grassy airfields. The use of wheel trailer, pulled by a test vehicle will enable to determine wheel rolling friction for a wide range of forward speed, with no necessity of rather difficult and expensive flight tests. Also, identification of rolling friction components, showed in the equation (4), can be performed.

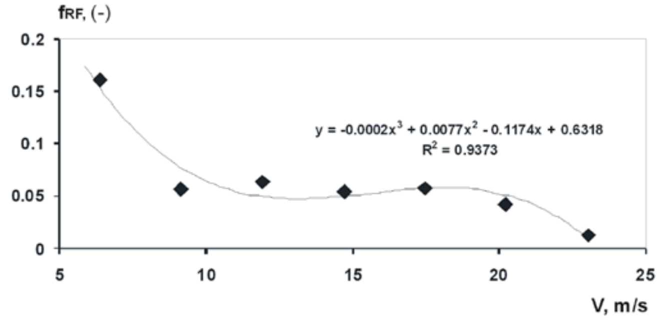

Fig. 3. Effect of forward speed upon rolling friction coefficient, fRF for an aircraft tyre on a grassy surface, determined in a flight test

3.2. Braking friction of a wheel

Let's consider a wheel rolling over a surface. Two general modes of operation are possible:

- free rolling, without any driving moment;
- driving or braking, which is caused by an external moment applied to the wheel.

In a contact area there exists a horizontal component of surface reaction to wheel loads. This force has a longitudinal direction and its value may be expressed by a well known Amontons law of friction:

$$X = F_v \mu \tag{5}$$

with: F_v – vertical load on the wheel and μ – correlation factor, known as a braking friction coefficient or simply traction.

Braking friction coefficient is of a fundamental importance for safe landings, especially, when an airplane is of huge mass and at high landing speeds. In such cases, extensive ose of braking during rollout is mandatory. But even a very powerful brakes don't help if a sufficient braking friction hasn't employed. For a grassy, unsurfaced airfield, braking friction is important because of two facts. Firstly, grass, especially when wet, doesn't ensure high braking friction. Secondly, surface unhomogenity and roughness act as additional factors decreasing braking efficiency. Finally, wheel-surface friction is strongly affected by weather, yet more on natural, soft fields [1, 3].

Measuring of braking friction of aircraft wheels rolling over a paved runway is performed by means of a friction tester, which is typically a fifth wheel attached to a service vehicle that allows to gather friction data at a range of speed. This measuring wheel can be loaded vertically to reconstruct real conditions of a given aircraft undercarriage. During a test run, the wheel is braked until full stop and the resulting friction force is measured with a load cell. Measured data are then used to calculate friction coefficient, which are published in a form of NOTAM (***No****tice* ***t****o* ***A****ir****m****en*).

The use of rotating wheel dynamometers, described in [15] is naturally advantageous, since this device enables to measure all variables needed to determine friction coefficient and it can be installed on a wheel. A basic measure required to determine wheel braking friction is braking moment on a wheel, M_Y. The relationship between longitudinal force, X, acting on a contact surface and the M_Y can be expressed by the equation below:

$$\vec{M}_Y = \vec{r} \times \vec{X} \tag{6}$$

where $\vec{r}$ is the radius of the longitudinal force (wheel dynamical radius).
Finally, braking friction can be determined with the following equation:

$$\mu = \frac{M_y}{r F_z} \tag{7}$$

Neglecting the effect of tyre vertical deflection due to wheel load will not affect the accuracy of the method when tyre stiffness is much higher than surface. This is not true for low pressure, baloon tyres. In this case, tyre dynamics should be taken into account. Another simplification is that we neglect tyre longitudinal deflection as a result of wheel-surface traction. We simply determine braking friction as a function of kinematical wheel slip.

3.3. Surface uneveness and roughness

The surface of paved runways is usually well maintained, so the uneveness or roughness do not affect wheel performance. Typically, statistical methods are used to describe tarmac or bitumen pavement profile, as is often used in highway construction and maintenance. The surface profile is described as a two-dimensional, homogenous and isotropic, stochastic process [5]. A synthetic measure of hard surface roughness is performed by means of power spectrum density function and typical values of uneveness belong to the range between 0,001 – 0,04 m. The surface of grassy, natural airfield is characterized by its roughness, which depends on the type of soil, its activity with time, the presence of small animals and plants. Typical natural surface uneveness is about 0,01 – 0,2 m and similar analytical methods can be used to describe its profile. For the presented method for evaluation and classification of unsurfaced airfields, it was important to develop a simple, durable and precise enough technique for measuring roughness.

Among a number of methods possible, a non-contact remote measurements with the use of LIDAR may provide a good solution. LIDAR is an optoelectronic device that uses nanosecond impulse mode of a laser. Very short but of high energy laser impulses are being sent toward a measuring surface and after they are backscattered and come to a selective detector integrated with the laser. An analyzer determines spectra of laser impulses and this analysis forms a background for obtaining the so called point clouds. Assuming, LIDAR would be used as a very precise and fast range meter, which determines the time of laser impulse travel, to and from the surface. A certain disadvantage of this method is its sensitivity to aerosols and contamination in the atmosphere. This can be fixed or minimized when scanning would be performed from a low passing airplane.

4. Applied methods

4.1. Single wheel tester

We have designed and developed a single wheel tester, towed behind a SUV. The main frame of the tester is joined with the base vehicle and the movable frame with the test wheel is connected by means of two rotating joints. This allows to apply various loads on the test wheel as well as compensation of vertical movements when rolling over rough surfaces. The test wheel is from a PZL 104 Wilga multipurpose aircraft and is used with the complete suspension. The entire construction of the tester allows to reconstruct loads and kinematics of the main undercarriage of the aircraft. A schematic of the tester is shown in figure 4.

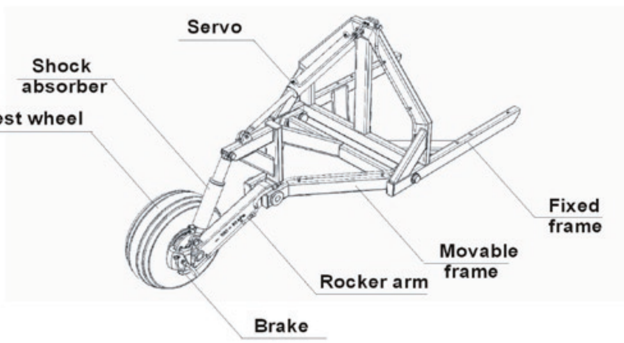

Fig. 4. A schematic of the wheel tester developed in the study

The range of applied vertical load on the test wheel is limited by the mass of the base vehicle, but when needed, the load can be extended by installation the tester on a heavier vehicle. The range of forward speed is between 0 – 60 km/h, although this can be limited for tests performed on very rough surfaces. A typical test run may include the following measuring procedures:

- free rolling – determination of rolling friction coefficient;
- braking – determination of braking friction coefficient.

The wheel tester is equipped with instrumentation, which enables the following measurements:

- measuring the vertical load and the braking moment on the wheel;
- measuring the rotation speed of the test wheel to determine wheel slip during braking action.

Description of the instrumentation follows.

4.2. A multielement rotating wheel dynamometer

The test wheel installed on the tester, is a measuring wheel, integrated with a multi-element rotating dynamometer. This device enables to perform dynamic measurements of forces and moments acting on the test wheel during test runs. The device has been built based on strain gage technology. There are two elastic elements, one is used to determine braking moment M_Y, the other one for the remaining components, F_Z, F_Y, F_Z and M_Z , M_X. The test wheel is shown in figure 5. The entire dynamometer is installed in the wheel hub together with electronics, which forms the measuring signals and allows to send them wirelessly to a portable computer for downloading and analysis.

4.3. Wireless telemetry system

This system has been built based on a portable device with Android operating system. It can be a tablet computer or even a cellular phone. A special software has been developed to communicate with the rotating dynamometer. A primary function of the software is to control the measurements performed with the use of the tester. The

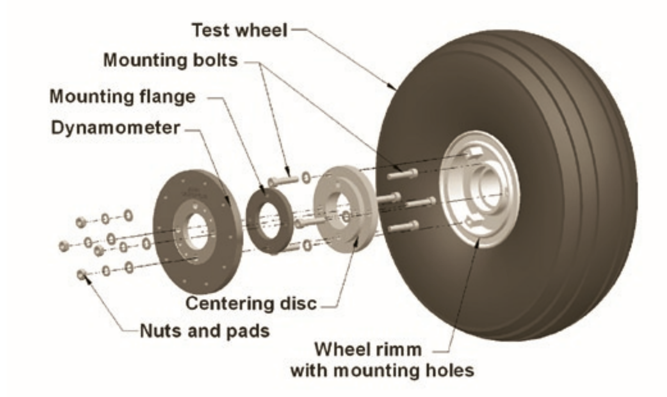

Fig. 5. The test wheel with the rotating wheel dynamometer, based on a PZL 104 Wilga undercarriage wheel

user can also transmit the measuring data wirelessly after a test run is finished. Finally, the program gives a possibility to calculate the required coefficients as well as to visualize their values or time courses if needed.

The telemetry system consists of a 16-bit, 8-channel analog-to digital converter, performing the successive approximation (SAR – ***S****uccessive* ***A****pproximation* ***R****egister*), with a highest data sampling rate of 115 ksps (*kilo samples per second*). Another subsystem in the architecture of the telemetry is a data acquisition system, based on a 32-bit controller. Finally, the measured data can be transmitted by a Bluetooth Class 2.0 module which ensures communication range of more than 600 m. The purpose of the microcontroller is managing of data acquisition, preliminary data analysis and filtering the digital data. An important advantage of the presented telemetry system is the use of a mobile device driven by the Android system. There is a possibility to add more applications, which could help in performing the measurements or in data analysis.

4.4. Determining the profile of grassy surface with the use of LIDAR

Scanning and creating of numerical charts of terrain can be performed with the use of laser technology. A practical range of laser devices used in highway construction and maintenance is about 1m. The laser is installed on an external rim and works vertically to the surface. The idea of the present authors was to examine the possibility of the use of LIDAR to scan the surface of an airfield from a flying aircraft. A schematic of the LIDAR is presented in figure 6. The laser impulse is optically formatted and sent toward the object (surface). Backscattered signal is registered by a photodetector, then analyzed. Although the subject of signal analysis in LIDAR systems is well described and mature, there are some interesting aspects, such a for example developing new algorithms to obtain required information from the so called point clouds [4].

Surface roughness of an airfield can be described with the use of quadratic mean or root mean square. If we consider the high of the elementary uneveness as a function of the linear dimension, x (in case of surface analysis, two dimensional function will be used) to be a measure of roughness, the root mean square of the roughness can be expresses as below:

$$z_{RMS} = \sqrt{\frac{1}{x}\int_{x_0}^{x_0+x_i} z^2(x)dx} \qquad (8)$$

The so called point clouds, obtained from the LIDAR scanning enable to determine the over mentioned parameters, based on known algorithms. The idea of scanning with the use of airborne equipment

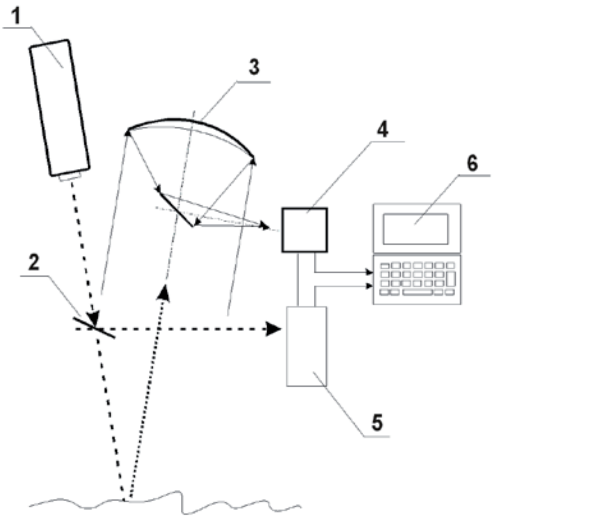

Fig. 6. A schematic of LIDAR. 1 –laser, 2 – beam splitter, 3 – telescope, 4 – photomultiplier, 5 – impulse counter, 6 – data analyzer

has the advantage over the use of vehicular scanners, that there is no need to compensate of vertical movements of the vehicle. On the other side, airborne scanners have to be characterized by much higher parameters (laser impulse power and its frequency) what is caused by higher ground speed of an airplane.

4.5. Estimation of measurements precision and the accuracy of the proposed method

The rotating wheel dynamometer is a measuring device with the class of 1, so at the full scale of the braking moment channel, the error of measurement of the rolling or braking friction is ± 0,0033 in laboratory conditions. Taking into account the effect of test conditions, the uncertainty of the measurement in realm is of the order of 0,0075. If we use equations to determine takeoff or landing roll, cited in this work, then the accuracy of the entire method may reach about 25 m and 30 m, respectively. A more precise determination of the accuracy requires the analysis of covariance of the measured and estimated values of braking moment and is expected to be as low as about 10m [2].

5. Conclusions

In the paper a description of a new method to evaluate and for classification of unsurfaced airfield is presented. The method respects parameters affecting wheel-surface interactions, especially the deformability of soft grounds and its effects on aircraft ground performance, such as takeoff roll and landing distance. Based on theoretical analysis from the literature, the following parameters have been chosen as important: rolling and braking friction coefficients, surface roughness. Instrumentation proposed to be applied in the method has also been presented in the paper. The solutions include a single wheel tester and the LIDAR for air scanning of the surface roughness. Estimated error of the method is about 10m of the takeoff or landing distance for a typical GA airplane on a grassy surface.

Prospective users of the method could be operators of the airfields and the pilots flying from them. The application of the method may have positive effects on the regional air transport through increasing of the use of unsurfaced airfields for different air operations

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