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METHODS FOR DETERMINING THE FRICTION COEFFICIENT OF THE ROAD SURFACE

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Abstract. In spite of advances in aviation technology, operational procedures and weather forecasting, safe winter runway operations remain a challenge for airport operators, air traffic controllers, airlines and pilots who must coordinate their actions under rapidly-changing weather conditions. The paper analyses most popular methods for determining the friction coefficient of the road surface. Their advantages, disadvantages and comparison of their modern instruments for measuring the frictional properties of airfields is shown. Most of the information was derived from a comprehensive literature review.

Keywords: friction coefficient, measuring methods, road surface, aerodrome, surface roughness, microprofile.

Introduction

Development of methods for measuring the friction coefficient and implementing them hadrdware means is well under way from the beginning of the 1960s, the works of many scientists and engineers, including M. Pecherskiy, A. Dubovets, E. Ivanitsa, V. Glukhov, A. Bulakh, F. Andriadi, A. Kotvitskiy, A. Vasiliev, S. Kizima, A. Kaazik, V. Kane, Ya. Segal, V. Maksimovskiy, B. Elisyeyev, A. Ivantev, V. Tyrsa, I. Kelman, Yu. Lakatosh, S. Rakhubovskiy, S. Zhuravlev, G. Orlovskaya, Ya. Kossyi, A. Trankvillevskiy, V. Porubay, S. Argunov, L. Medres, A. Shestopalov, V. Scherbakov, V. Putov, V. Nizovoi, N. Petrov, V. Florman, Tomas Yager, Gösta Kullberg, Olle Nordström, Göran Palmkvist, Ottar Kollerud, Ragnar Malcus, Sven Edvin, Oddvard Johnsen, Hurson James, etc.

This section covers many of the important factors involved in friction coefficients as related to pavement surfaces and aircraft tires and brakes. Friction characteristics are primarily determined for runways through the use of a variety of measuring equipment.

Complicating the winter weather picture is the fact that criteria for safe operations on a given runway snow/wetness condition differ between airports and countries (Rado & Wambold, 2014).

The expenditure of states, counties, cities and towns in the United States on snow and ice control for their roadways reaches approximately $1.5 billion in direct costs and $5.0 billion in indirect costs annually in 1997 (Al-Qadi et al., 2002).

The direct costs arise from such maintenance activities asplowing, salting, and sanding road surfaces. The higher indirect costs stem from accidents, travel delays and related lost economic opportunity, infrastructure degradation, environmental damage to vegetation and water supply sources, and vehicle corrosion (California Department…, 1999).

Since the main objective of a snow and ice control operation is to return the road surface to a safe state for the driving public within a reasonable period of time, the development of new techniques that increase the efficiency and effectiveness of this operation could reduce costs, increase safety, and improve mobility of the driving public. More specifically, the development of inexpensive, reliable, and easy-to-use technology that allows snowplow operators to use friction indicators can produce these desirable results (Henry, 2006).

For example, regular measurement of the friction coefficient and prevention of only ice formation on airfields of class A provides savings of up to 250–300 tons of anti-icing chemicals per year.

1. World experience of measuring the friction coefficient

The efficiency of friction coefficient measuring (Perova et al., 2016):

1. Increase of combat readiness of aviation units (duty forces) to (20–30)% due to operational cooperation of the aircraft crew – the team of control tower – engineering airfield services.
2. The accuracy of qualitative and objective assessment of frictional properties of airfield pavements and the airfield in accordance with the current requirements and standards of the International Civil Aviation Organization and providing measurement results to the command tower and airfield services in real time.
3. Practical elimination of the need to stop the airport operation at peak weather conditions by calculating the coefficient of friction with an error less than 0.02 units.
4. Reduction of costs for chemicals (30–40%) due to their rational dispensing to bring the runway in compliance with the rules of airworthiness under different weather conditions (snow, ice, rain, fog, etc.).
5. The opportunity to form a centralized information and statistical data bank of the state of the airports runway on the basis of the digital data bank of the airfield.
6. Timely adoption of organizational and technical measures for carrying out capital or preventive maintenance both individual sections and the entire surface of the runway as a whole, guided by quality diagnostics of the runway condition and other airfield pavements based on the digital information aerodrome databank.
7. Determination of the residual life of the runway.

Pre-landing measurement of adhesion properties of surface coatings with the wheels of aircrafts is currently being implemented at airports all over the world by rolling with a constant skidding of measuring wheels, using mobile (self-propelled or towed) installations. The world leader in the measurement of the coefficient of friction on airfield pavements is the Swedish company "Airport Surface Friction Tester" (ASFT). All ASFT units contain an electro-hydraulic hoist device of the measuring wheel with a system that ensures its constant downward pressure to the surface. Mobile units of this company are used by more than 200 airports in Europe and America (Perova et al., 2016).

A new technique for measuring friction at the International Airport Baltimore/Washington named after Targuda Marshall appeared thanks to the initiative of the Federal Aviation Administration (FAA). In 2008, the FAA issued advisory circular 150/5200-30C, describing the two main types of equipment for measurement of friction coefficient on runways in winter time: continuous friction measuring equipment (CFME) for measuring the constant friction coefficient and decelerometers.

Continuous measurement of the coefficient of friction device with all its advantages have two major drawbacks (Sacharov et al., 2017):

1. The need for manual instruction set measurement speed (for modern types of devices is 60–70 km/h), which limits the length of the measurement site due to the need of the vehicle acceleration and deceleration.
2. Small service life of the structural element, namely a special measuring wheel. The tread wears and the wheel needs to be changed regularly for new. Thus, this special measuring wheel has a high value, i.e. to use the aforementioned brake carts require significant expenditure.

These shortcomings make inappropriate (and in some cases impossible) their operation on the airfields with runways up to 1000–1200 m, as well as on all the airfields in hot and dry climates because in the absence of rainfall and the maximum value of the coupling coefficient hardly changes, and the procedure of the measurement is formal and is made for registration of the reporting on the availability of material airfield to aircraft operation. Thus wear special measuring wheel (the tread surface of erasing) will be maximized due to the thermal "softening" of rubber and high friction surface (Sacharov et al., 2017).

The second group includes various decelerometers. Of the prior art known decelerometers Bowmonk Brakemeter-Dynometer (UK). Basis device – pendulum balanced accurately responsive to any change of speed or angle, which by means of a sector gear transmission rotates the arrow around the dial. The apparatus is filled with a special liquid, which dampens vibration of the whole (Sacharov et al., 2017).

The FAA recommends that airports should use desselerometers if the forced runway downtime for testing the friction coefficient is acceptable and oftentimes preferred – when it is difficult to get access to the full length of the runway, for example, at the intersection of the other runway. Like its mechanical predecessor, the new equipment measures the coefficient of friction when the aircraft slows down on the runway and engages the brakes to a complete wheel lock.

Decelerometer scale is graduated in units of acceleration from 0 to 8 m/s^2 in increments of 1 m/s^2, so that for determining the friction coefficient necessary values shown on the scale, multiplied by a factor of 0.1 (Sacharov et al., 2017).

But instead of having to manually record information about the state of the runway and the coefficient of adhesion, new desselerometers automatically process data and store the results. After calibration of the desselerometer, it is installed on the level and along the line of travel of the vehicle. The operator moves along the runway at a speed of 32 km/h, applies the brakes to a complete stop, after which the device outputs the result of measurement of adhesion to be accepted or rejected. The operator then presses the "next test" button and the process is repeated.

In addition to electronic desselometers Baltimore Airport / Washington also purchased equipment for meas-

urement (CFME) manufactured by Neubert Aero Corp., Martin Airport purchased dynamic friction tester (DFT) – device for measuring the dynamic friction coefficient that can be used under various weather conditions and in contrast to the previous system for measurement the constant friction coefficient it is compatible with more than 80 vehicles servicing the airport (Figure 1).

The equipment it chose – four Dynamic Friction Decelerometers (DFDs) from Neubert Aero Corp. – are touch-screen units designed to comply with FAA regulations exclusively for winter operations. Much like its mechanical predecessor, the DFD measures deceleration, or the forward motion to the braking point, when a vehicle drives down the runway and brakes to lock the wheels. But rather than manually report runway condition readings and braking action reports, the new DFDs automatically compute results from acceleration data (Nelson, 2009).

Decelerometers disadvantages described above are:
1. The ability to measure the current acceleration along only one axis;
2. A substantial measurement error;
3. The complexity of processing and recording the measurement results due to the fact that for each vehicle to be adapted formula for calculating the friction coefficient, which are related to motion parameters and specificity vehicle (speed, type / class, particularly in braking, tire wear, and etc.), and the data calculations, coordinate binding points at which measurements were made, and analysis of the obtained values are performed manually by the operator (Sacharov et al., 2017).

Working in tandem, the system DFD and DFT at Baltimore Airport/Washington cover a wide range of needs. In winter, the airport can detect and monitor changes in the state of the surface of runways using equipment for measuring constant friction, while the decelerometer can effectively carry out spot checks of changing conditions without the use of towing devices and repeated measurements.

Measurement of the friction coefficient in the Russian Federation is carried out by special devices:
– Measuring the friction coefficient AT-EM (Figure 2);
– Aerodrome truck brake ATT-2 (Figure 3).

Figure 1. Dynamic Friction Tester (DFT)

Figure 2. Friction coefficient measuring device AT-EM

Figure 3. Aerodrome brake trolly ATT-2

Friction coefficient measuring device AT-EM is used for (Perova et al., 2016):
– determination of friction properties of the runway with artificial pavement according to the friction coefficient value, calculated as the average arithmetic value of the ratio of measured values of the longitudinal traction force to the normal reaction, acting at each of the two measuring wheels when electromechanical braking occurs for each of the two MW;
– calculated as the ratio of the measured values of the longitudinal traction force to the normal reaction at each of the two measuring wheels when the electromechanical braking occurs;
– binding of measuring indicators of the friction coefficient to a particular point of measurement on artificial airfield pavements;
– creating an archive of measurement results of the friction coefficient;
– transfer of measurement parameters via a secure radio link to the command and control center.

The friction coefficient on runways shall be measured by use of the aerodrome braking cart ATT-2 (Figure 3). The values of friction coefficient measured by ATT-2 completely correspond to the values of friction coefficient by SFT for the same pavement conditions. Braking action will be measured on every third of runway, 5 to 10 metres on either side of the centre line. The amount of measurements on each part is not less than 8 (4 to the right and 4 to the left of centre line).

ATT-2 is a kit consisting of a measuring trolley and remote unit visual recording apparatus. The measuring carriage is a single-axis two-wheeled trailer comprising: a frame mounted fixedly on a measuring and driving wheels; central and lateral thrust of the drawbar; propshaft; lockup clutch; the guide rod with measuring

parallelogram; a protective casing; hitch; arm switching the lockup clutch; the cover of the measuring chamber; cover manhole; tether. The guide rod mounted in sliding bearings and through the measuring parallelogram connects the bogie frame with a side pull the drawbar. Measuring parallelogram is equipped with parallel-connected discharge bar and the measuring sensor. Acting on the load sensor changes the supply voltage of the sensor, which, through a flexible electric cable is fed into registration unit mounted in the towing vehicle-cabin (Sacharov et al., 2017).

Strain values of the friction coefficient in ATT-2 are amplified and displayed by a galvanometer and registered by the operator who checks the readings. Obviously, such a setting does not currently meet the international standards; it is obsolete and requires replacement. In many countries, aircraft crews do not use the normative friction coefficient calculated by the aerodrome brake truck ATT-2 (Bogoyavlenskiy & Bokov, 2012).

The "AvtoVAZ" company made an attempt to master the arisen domestic niche, developing a friction coefficient measuring device "Lada-Aero", mounted on the reinforced VAZ-2108 motor car, but its serial production failed to be implemented.

Of all the devices of this kind the most perfect is the "Mu-meter", designed and manufactured in England, Finnish runway friction testing trailer "Skiddometer BV11" and French automatic skid resistance measurement device for runways "IMAG" (Figure 4). It is a three-wheeled trailer weighing about 400 kg, designed for towing vehicles. Load on measuring wheel 180 kg. The braking effect is created by the movement of the middle measuring wheel with a constant slippage of about 15–17% under all states of coatings. This allows obtaining the values of friction coefficients proximately to their limit values.

Patented in 1991, IMAG is currently used in operational conditions on several French airports such as Roissy-Charles de Gaulle, Orly, Strasbourg, Metz-Nancy-Lorraine and Europort Vatry. On these airports, the IMAG is used during the winter period to measure runway surface friction and to inform pilots about runway conditions (Civil Aviation..., 2012).

The measured friction coefficients are continuously recorded by the recorder, the paper tape of which is stretched
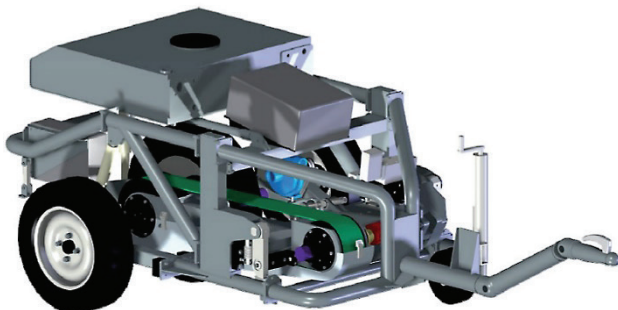

Figure 5. Illustration of Mu-Meter Trailer Unit
(Highway Continuous..., 2007)

in proportion to the distance traveled. Simultaneously, the integrator automatically calculates mean values of the coefficients for distances predetermined in the device software, and prints them on the paper tape indicating the direction of movement of the trolley (the direction of the runway), the date and time of measurement.

Mu-meter is a three-wheeled trailer, used for towing cars (Figure 5). Unlike the skiddometer, the braking effect in it is created by the installation of two wheels with a slip angle. The third wheel is used to measure the distance traveled. The resultant in the course of motion force of the side clutch is measured by a hydraulic sensor, and the ratio obtained in such a way is adopted as the longitudinal coefficient of coupling. This principle of truck operation is less successful, because it allows you to evaluate the lateral grip of tires and does not meet the conditions of hindered movement of the wheel (Perova et al., 2016).

At present, at airports assessment of braking conditions on the runway, using dynamometric trolleys, measurements are performed by means of two driveways of the trolley at the speed of 60 km/h on the runway at a distance of about 10 m from the center line. Based on the data obtained they calculate the average values of friction coefficients for each third part of the length and the entire runway. Imperfection of the existing state of the fleet of vehicles for continuous control of frictional properties of airfield and road coatings is also partly due to the common and necessary for both foreign and national products requirement, impairing their access to the country market - mandatory state certification (Bogoyavlenskiy, 2013).

2. Methods of determining the friction coefficient of the road surface

Due to the fact that all previous methods present the availability of instruments for measuring the friction coefficient that significantly increases the cost of measurement, the State Enterprise "ROSDORNII" obtained a patent for the method of determining the friction coefficient of the road surface. The authors are N. Lushnikov, P. Lushnikov, Yu. Gvozdkov. The method consists in measuring the parameters of the road surface and calculation of the friction coefficient. Initially, it is measured the ordinates of the microprofile of the coating surface, according to

Figure 4. Illustration of IMAG (© VECTRA)
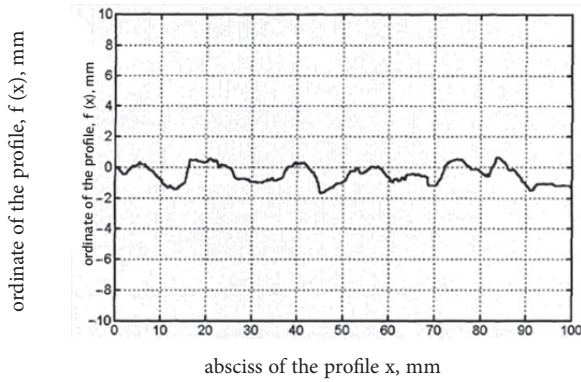(Civil Aviation..., 2012)

Figure 6. Example of the profile

which determined the dependence $y = f(x)$, describing the microprofile at a fixed interval (Figure 6). Using this dependence, it is determined the length of the curve of the microprofile and parameters K_i of the roughness of the road surface by calculating formulas. The invention makes it possible to simplify and reduce the cost of the measurement method, as well as eliminate the need for wetting the coating (Perova et al., 2016).

This invention relates to the field of transport, to be exact – to the construction of road surfaces, airfields, etc., machinery and auxiliary equipment for control of geometric characteristics of coatings in the construction and repair, and it can also be used to determine the coupling properties of road surface.

In the proposed method of determining the friction coefficient of coating they measure the geometric parameters of roughness of the dry or wet coating; these parameters are displayed on the display device; according to these parameters they calculate the roughness indexes of the coating by obtaining the implementation of the surface profile (or a series of profiles), calculation the length of the implementation of this profile (lengths of implementations) or a derivative of this implementation (of these implementations); they calculate the values of the friction coefficient according to the regression curve and the obtained friction coefficients obtained are displayed on the indicator.

The essence of this method lies in the fact that, for example, using the profilometer with the step x they measure the parameters of the surface roughness – the ordinate y. On the interval $[l_1, l_2]$ they determine the dependence $y = f(x)$, describing the microprofile, where l_1, l_2 – the coordinates of the beginning and end of the interval. The length of the curve L of the microprofile is also specified. Further, the parameters of roughness are determined according to one of the two options (Perova et al., 2016):

1. Parameter K_1 is determined as a function of the length of curve L of the microprofile:

$$K_1 = \frac{L}{(l_2 - l_1)},$$ (1)

where the length of the curve of the microprofile is:

$$L = \int_{l_1}^{1} \sqrt{1 + \left(f'(x)\right)^2} \, dx .$$ (2)

2. Parameter K_2 is determined as a function of the derivative of the microprofile:

$$K_2 = \frac{\sqrt{\int_{l_1}^{1} \left(f'(x)\right)^2 dx}}{(l_2 - l_1)}.$$ (3)

3. Determining one of the roughness parameters, friction coefficient φ_{fric} is calculated by the following formula:

$$K_i = b_i + a_i \times \varphi_{fric} \times i = 1,2 ,$$ (4)

where a_i, b_i - constant regression coefficients;

$0.1 = \varphi_{fric} \, i = 0.5$.

4. The empirical coefficients a_i, b_i are determined according to experimentally known relationship φ_{fric} (K_i) by the method of least squares. The coefficients are satisfied to the following constraints: $|a_i| < 0.5$; $1 < b_i < 1.3$.
5. This method can be used to determine the mean coefficient of friction area. For this purpose, the ratio of the area of the examined surface to the area of its projection is used as parameter K. Further calculations are carried out similarly 1–4.

The subject method has been implemented using a scanning profiler, allowing determining the profile ordinates with accuracy of 0.05 mm and a step of 0.05 mm. As a result there were obtained the regression curves, described by formulas (4) ($i = 1.2$), relating the values of obtained from the experiment microprofile parameters with the friction coefficient, obtained by the PPK-MADI-VNIIBD device.

3. Method of determining the coefficient of wheel coupling with the surface of artificial coating

The invention relates to measurement methods and is used to assess the state of the surface of the airfield runway, but can also be used to determine the coefficient of friction of road coatings.

The aim of the method offered lies in increasing the accuracy of measurement of friction coefficient of the wheel with the road surface by registering the maximum braking force $R_{break.max}$ between the measuring wheel and the surface of the coating, according to which they calculate the rate of wheel friction with the surface of the artificial pavement with no slip of the measuring wheel.

Solution of the goal set concerning "The method of determining the coefficient of friction of the wheel with the surface of the artificial pavement" is achieved by the fact that using this method the coefficient of wheel friction with the surface of the artificial pavement is determined by the method of braking, when they roll the measuring wheel on the surface of the artificial pavement, the brakes being applied in accordance with the state of the coating surface, wherein the normal force F of the measuring wheel load onto the coating surface is determined.

The use of this method during its implementation will make it possible to increase the safety of aircraft landing by improving the accuracy of determining the coefficient of friction of the landing gear with the surface of the runway, as well as determine more accurately the state of highways.

The essence of the proposed method of determining the coefficient of friction of the wheel with the surface of the artificial pavement is illustrated by drawings, which show in Figure 7.

In the inventive method, regardless of the speed of movement they further determine the braking torque (M) generated by the electromagnetic brake and the friction torque (M_g) of the measuring wheel with the surface of coating (Figure 8). Thereafter, the equality of points in the braking force (M) and the moment of traction M_g $(M = M_g)$ are constantly maintained. At the same time, the maximum braking force $R_{break.max}$, which is equal to the force of friction R_{fric} of the measuring wheel with the surface coating, is obtained between the measuring wheel and the surface of the pavement ($R_{break.max} = R_{fric}$, $R_{fric} = RK_{fric}$). The coefficient of friction is calculated by the following formula (Lukanov, 2012):

$$K_{fric} = \frac{M_g}{P \times R}, \qquad (5)$$

where K_{fric} – coefficient of friction of the measuring wheel with the surface of pavement;

M – braking torque, generated by the electromagnetic brake or other braking device, Nm;

M_g – friction torque of the measuring wheel with the coating surface, Nm;

P – normal load of the measuring wheel on the surface of coating, N;

R_{fric} – friction force of the measuring wheel with the coating surface, N;

$R_{break.max}$ – maximum braking force between the measuring wheel and the surface of the coating, N;

R – radius of the measuring wheel, m.

Algorithm for implementation of the proposed method of determining the coefficient of friction is shown in Figure 9.
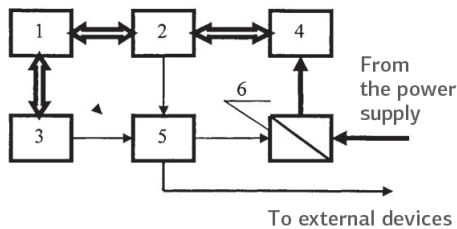

Figure 7. Structural diagram of the device, which implements the proposed method of determining the coefficient of friction (Lukanov, 2012)

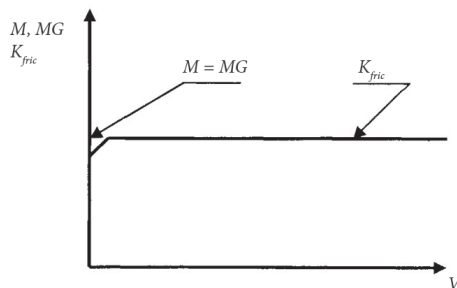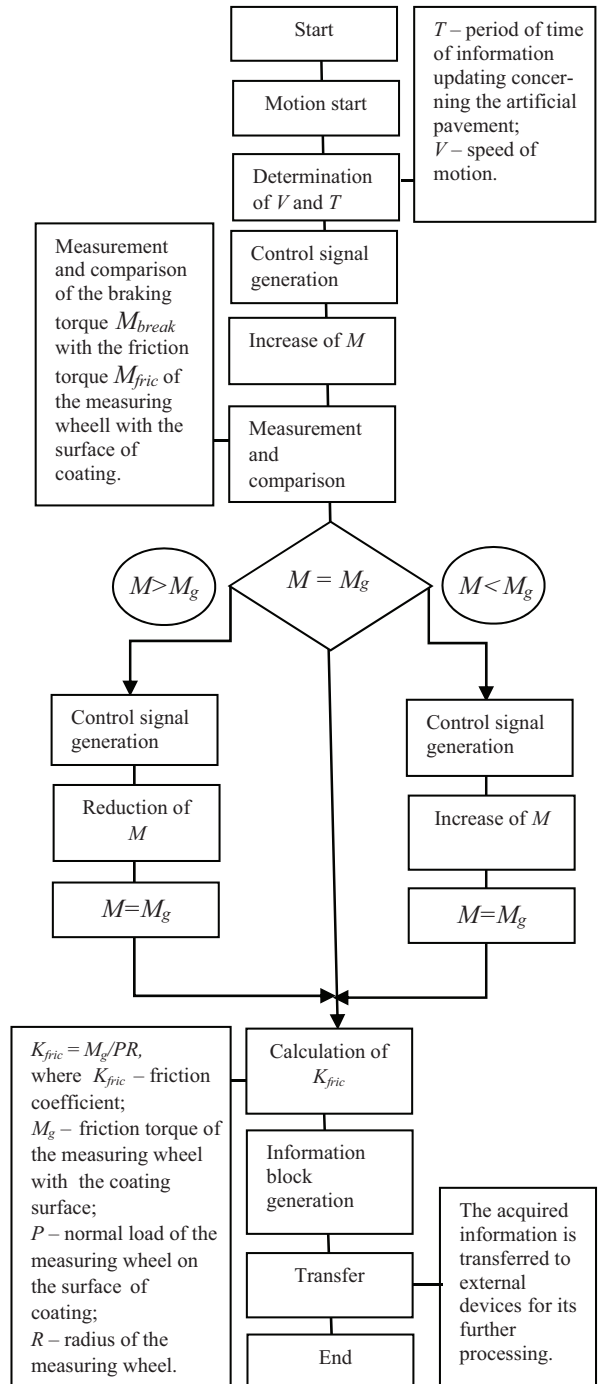Figure 8. Implementation of the proposed method of determining the coefficient of friction with the surface of coating (Lukanov, 2012)

Figure 9. Algorithm for implementation of the proposed method of determining the coefficient of friction (Lukanov, 2012)

Conclusions

Imperfection of the existing state of the fleet of vehicles for continuous control of frictional properties of airfield and coatings has lead to the need for a uniform method of determining the frictional properties of airfield pavements.

To obtain more accurate data on the friction coefficient, it is necessary to use several devices, which can cover a wider range of information.

Implementation of these methods makes it possible to determine the coefficient of friction at any speed, which allows measuring the coefficient of friction on the runway, on the aircraft parking place, when taxiing, in hangars, on the highways in use at any time (observing all the traffic rules), while maintaining or commissioning new highways, in all turns and a small extension of the coating surface.

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TRINTIES KOEFICIENTO SU KELIO DANGA NUSTATYMO METODAI

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Santrauka

Nepaisant aviacijos technologijų pažangos, operacinių procedūrų ir oro prognozių, saugios kilimo ir tūpimo tako operacijos žiemą išlieka iššūkiu oro uostų valdytojams, skrydžių vadovams, oro linijoms ir pilotams, kurie turi koordinuoti savo veiksmus sparčiai besikeičiančiomis oro sąlygomis. Straipsnyje analizuojami populiariausieji kelio dangos trinties koeficiento nustatymo metodai. Pateikiami jų privalumai, trūkumai ir lyginami jų modernūs prietaisai, skirti aerodromų trinties savybėms matuoti. Didžioji dalis informacijos buvo gauta iš išsamios literatūros apžvalgos.

Reikšminiai žodžiai: trinties koeficientas, matavimo metodai, kelio paviršius, aerodromas, paviršiaus nelygumai, mikroprofilis.