EVALUATION OF AIRCRAFT BRAKING PERFORMANCE BASED ON OPERATIONAL FLIGHT DATA

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Abstract

This paper presents a method to quantify the braking capability of an aircraft during its deceleration phase on the runway, which is essential for both landing and rejected take-off. A model is developed to describe the aircraft's behavior as well as the interaction with the runway. The results can be used to determine the remaining safety margin for the aircraft to decelerate on the runway when comparing the maximum braking capability to the actual deceleration which is extracted from recorded flight data. A model-based approach is used which will be presented in this paper.

1 Introduction

The capability, which is the ability of the aircraft to decelerate, is essential during both landing and take-off phase of each flight. While the aircraft has to be slown down on the remaining part of the runway after touchdown to safely vacate the runway, the same task during take-off can be even more critical in case of a rejected take-off (RTO) as the aircraft is typically heavier and the remaining runway distance, particularly when the aircraft is already close to the decision speed V_1, is shorter. The inability to stop the aircraft on the runway or to control the aircraft due to braking capability deterioration could lead to runway excursions (RE), which is the most common type of accident in commercial aviation, accounting for 19 % of all accidents in 2016 [5].

Based on recorded flight data from the Flight Data Monitoring (FDM) system, the braking performance can be assessed. Particularly with regards to runway overrun accidents, i.e. when the aircraft unintentionally exits the runway at the far end, it is often difficult to determine directly the landing distance that the aircraft actually needed from operational flight data simply because the aircraft usually does not come to a full stop on the runway. Instead of only looking at the landing distance, one could consider the maximum braking capability of the aircraft regardless of whether it was fully demanded [4]. If the deceleration required to come to a full stop on the remaining runway, no matter whether after the landing or after the aborted take-off, is greater than the braking capability that can be achieved, an overrun cannot be avoided. The core objective of this work is, therefore, to assess the braking performance by computing the maximum achievable friction coefficient between the tire and te runway surface for each particular flight. The difference between the achievable and the actual braking performance can be considered as a safety margin. If it decreases below zero, an accident is destined to occur. In order to determine the maximum achievable friction coefficient, a model describing the interaction between the wheel and the runway is developed. A mathematical description has already been developed [3] as well as experiments on different runway surfaces [7].

In section 2, the data that is used in this work is described. Section 3 presents the modeling methods, including a way to describe the forces acting between the tire and the runway. In order to use this method, the groundspeed of each wheel has to be obtained, section 3.2 presents a way to estimate the groundspeed based on the available data. Finally, the results for a sample flight is shown in section 4.

2 Data Source

The data used in this work consists of recorded flights from the Airbus A320 throughout the network of a single airline. They were obtained from scheduled revenue flights. In total, about 700 continuously recorded parameters are available in each dataset. They contain kinematic parameters of the aircraft, such as speed, position and attitude, system parameters such as hydraulic and braking pressure as well as command inputs and control surface deflection. The four wheel speeds on both main landing gear are also recorded. The recording frequency of the parameters range from 0.25 Hz for slowly changing parameters, such as the aircraft's mass to up to 8 Hz for highly dynamic parameters, such as the acceleration.

In addition, weather data at the time of landing in the form of Meteorological Aerodrome Report (METAR) is available. This information is used to determine the runway condition (dry or wet) at the time of landing.

3 Friction and Runway Modeling

3.1 Pacejka's Formula

The braking force resulting from the tire friction can be described as any friction force using the friction coefficient μ. The braking force F_B can be described as follows:

$$F_B = \mu \cdot F_N \tag{1}$$

where F_N is the normal force acting between the tire and the runway surface.

The braking force that can be applied is often limited by the state of the runway surface as well as the tire. The tread of the tire as well as its depth have influence on the friction characteristics. The wear of the tire also heavily influences the interaction with the runway, causing braking performance to change over the lifetime of a tire. The maximum friction coefficient that can be achieved decreases significantly with deteriorating runway conditions, e.g. when the runway is wet, or even covered with water, slush, snow or ice. It is also influenced by the groundspeed of the aircraft as well as the pressure inside the tire.

In order to describe the friction coefficient μ, a common way is to use the *Magic formula* introduced by Pacejka [3]:

$$\mu = D \cdot \sin\left(C \cdot \arctan\left(B \cdot (1-E) \cdot s + E \cdot \arctan\left(B \cdot s\right)\right)\right) \tag{2}$$

where s is the slip ratio defined as follows:

$$s = \frac{V_{GS} - V_W}{V_{GS}} \tag{3}$$

V_{GS} is the groundspeed of the aircraft whereas V_W represents the wheel speed. The coefficients B, C, D and E have to be obtained empirically as they depend on both the runway and the tire condition as well as the speed. Two curves of the friction coefficient depending on the slip can be seen in figure 1 using different values for the coefficient B, which changes the corresponding slip value at which the maximum friction coefficient is reached. From the mathematical description in (2), one can see that the coefficient D directly influences the maximum achieveable friction coefficient. Depending on the influencing factors described above, the slip to friction curve will look differently for different conditions.

Starting from the origin, the friction coefficient increases significantly with increasing slip, but reaches a maximum at a certain slip value and decreases afterwards. In the area close to the origin, the relationship is almost linear. A small offset can be added to the curve in order to account for roll friction, i.e. the friction coefficient when the slip is zero. The friction coefficient that results with locking wheels (i.e. $s = 1$) is

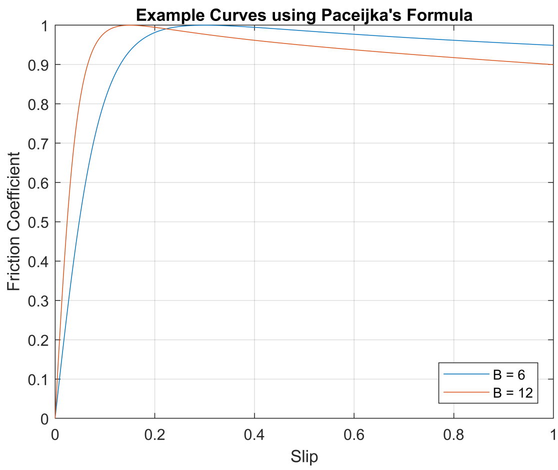

Fig. 1 Slip-friction curves according to Pacejka's formula

smaller than the maximum, making anti-skid systems necessary for both aircraft as well as ground vehicles. For automotive applications, the curve is used in the interval for $s \in [-1, 1]$ as the wheels can be powered. In our case, the negative range for s is not considered because this would imply that the wheel speed is faster than the groundspeed, which can only happen if the wheel is powered. That, however, is relevant for automotive applications, but not in our case.

By taking into account the torque M_B applied by the brake disc on the wheel, a simple equation of motion describing each individual wheel can be derived:

$$J\dot{\omega} = -r_T \cdot F_B + M_B \tag{4}$$

where J is the moment of inertia of the wheel, r_T is the outer radius of the tire, ω is the rotational wheel speed and F_B is the friction force applied on the wheel. One has to be aware of the fact that the braking process of the aircraft should only make use of the part of the curve before it reaches its maximum. If higher slip values are reached, an increase of slip will lead to a decrease of the friction coefficient, thus further reducing the wheel's speed if the same amount of braking torque is applied. A lower speed will lead to a further increase of the slip, thus leading to an unstable behavior in which the wheel stops and starts skidding instantaneously when the slip increases beyond the slip with maximum friction coefficient. The maximum braking capability of a wheel is, therefore, limited by the smaller of the two parameters: (1) The maximum friction coefficient enabled by the contact between tire and runway surface and (2) the maximum friction coefficient that can be achieved with maximum pressure on the braking disc.

As already mentioned above, the coefficients of Pacejka's formula are heavily influenced by several factors, including the aircraft's speed. This implies that the coefficients and subsequently the slip to friction curve only represent a description of the instantaneous behavior. Even if the runway surface, runway condition and the tire wear do not change, which can be assumed for a single landing, the aircraft's groundspeed is constantly changing and, therefore, continuously changing the coefficients in equation (2).

3.2 Groundspeed Estimation

As seen in equation (3), in order to model the braking process using the slip, both the wheel speed and the groundspeed are required. The wheel speed is directly measured and recorded for all four wheels on both main landing gears. The recorded groundspeed, however, is obtained from the Global Navigation Satellite System (GNSS) with precision suitable for in-flight navigation, but not for the application at hand. Therefore, an alternative method has to be used to obtain a more precise estimate of the groundspeed. Similar works have already been done in the automotive industry, such as in [9] using a fuzzy controller to adjust the covariance matrices of a Kalman filter that is used to estimate the groundspeed from wheel speed and acceleration measurements. However, the implementation of this method for the current application delivered heavily depend on the choice of the rules for the fuzzy controller, which is not a trivial task to perform.

Besides, the application in aerospace is somewhat simpler than in automotive because the wheels are not powered. One can, therefore, assume that the wheel speed is always equal to or smaller than the actual ground speed. Based on this assumption, we developed algorithm 1 for groundspeed estimation.

Algorithm 1 Groundspeed Estimation Algorithm

1: *loop*: For each timestep t
2: Compute new groundspeed $\hat{V}_{GS}(t)$ from previous groundspeed $V_{GS}(t-1)$ and previous longitudinal acceleration $a_x(t-1)$
3: Obtain new wheel speed $V_{WHL}(t)$ from measurement
4: **if** $\hat{V}_{GS}(t) < V_{WHL}(t)$ **then**
5: Set $V_{GS}(t) = V_{WHL}(t)$.
6: **else**
7: Set $V_{GS}(t) = \hat{V}_{GS}(t)$.

During touchdown, the wheel speed quickly increases from zero. Braking must not be applied during this short period of time to avoid bursting tires. Therefore, it can be assumed that the tire speed is equal to the groundspeed shortly after touchdown and before brake application.

However, the error of this method increases as the aircraft rotates around its yaw axis during ground roll. As the lateral distance between the main gear tires and the center of gravity is typically several meters for typical aircraft configurations, even small rotation rates will affect the groundspeed $V_{GS,WHL}$ of the individual tires.

The groundspeed of each individual tire i can be expressed by

$$V_{GS,WHL,i} = V_{GS} + \dot{\Psi} \cdot y_{CGGear,i} \quad (5)$$

where $\dot{\Psi}$ is the change of heading of the aircraft and y_{CGGear} is the lateral distance between the center of gravity and each individual landing gear i. It is preferable to use acceleration as well as rotational rates measurement since these parameters typically have high sampling rates. The distances can be obtained from the manuals provided by the aircraft's manufacturer in figure 2.

The obtained wheel groundspeed is shown in figure 3 and compared with the wheel speed for a sample flight.

Another way also explored during this work to estimate the groundspeed is to use the lateral

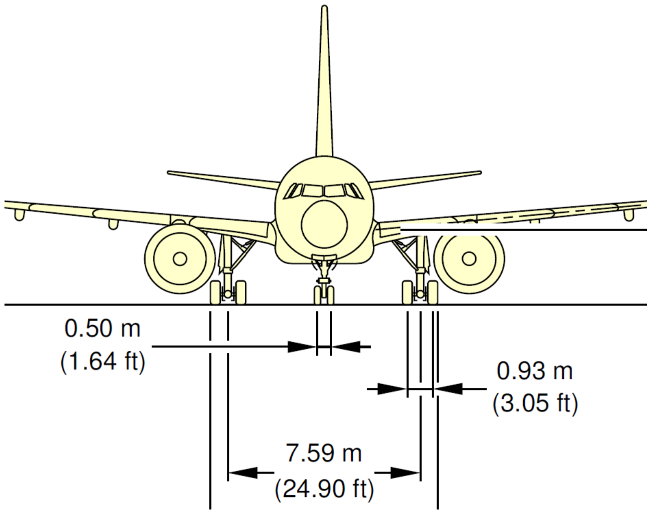

Fig. 2 Landing gear distance on the Airbus A320 [1]

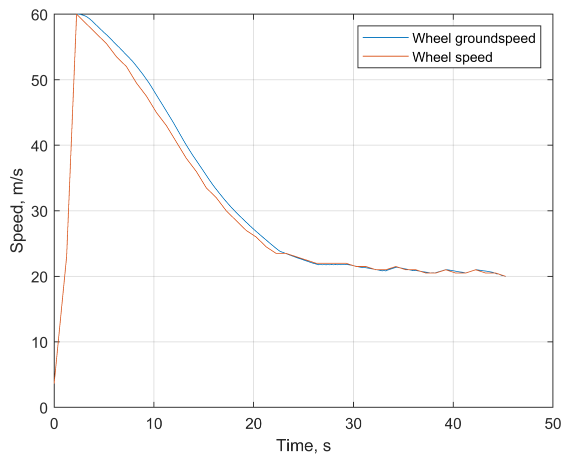

Fig. 3 Wheel speed and wheel ground speed for a sample flight

acceleration, which is essentially the centripetal force during turns and the yaw rate. The centripetal force F_c is defined as follows:

$$F_c = \frac{mV^2}{r} \tag{6}$$

Dividing by the mass and substituting $r = \frac{V}{\dot{\Psi}}$, one obtains:

$$V = \frac{a_y}{\dot{\Psi}} \tag{7}$$

However, this method is only feasible if large yaw rates occur, which is not typical for the braking phase. However, it returns very promising results for phases in which this is the case, such as taxiing in curves on the ground.

3.3 Friction Curve Setup

Braking performance assessment has been extensively carried out in [7] experimentally. The data can be obtained for different types of runway surfaces, runway conditions (dry or wet), different speeds as well as tire pressures. For each use-case, the maximum friction coefficient μ_{max} as well as the skidding friction coefficient μ_{skid} is provided. The goal is to describe the slip to friction coefficient curve using equation (2), fulfilling the values provided in [7].

As the slip curve also depends on the groundspeed of the wheel, the measurements are grouped by groundspeed in intervals of 10 $\frac{m}{s}$ width. For each interval, we assume that the coefficients are constant within each interval.

As only the total acceleration of the aircraft is measured, the forces acting have to be separated in order to identify the contribution of the brakes. The total acceleration a_x is composed of the braking forces F_B, aerodynamic (drag) forces F_A and propulsion (thrust reverse) forces F_P:

$$-m \cdot a_x = F_B + F_A + F_P \tag{8}$$

These forces can further be specified:

$$\begin{aligned} F_B &= \mu(s) \cdot \left(mg - \frac{1}{2}\rho V^2 S C_L\right) && (9)\\ F_A &= \frac{1}{2}\rho V^2 S C_D && (10)\\ F_P &= F_P\left(\dot{m}_{air}\right) = F_P\left(\rho \dot{V}_{air}\right) && (11)\\ &= k_P \cdot \rho \cdot \omega_{N1} && (12) \end{aligned}$$

where ρ is the air density and S is the reference wing area of the aircraft. C_L and C_D are the lift and drag coefficient, respectively. As the thrust force is more difficult to model, it is assumed that the thrust is proportional to the mass flow of the air through the engine $\dot{m}_{air}$, which is directly proportional to the air density and the rotational speed of the low pressure shaft ω_{N1}. A constant parameter k_P is introduced to account for this relationship. As we only consider the landing phase of the aircraft after the deployment of spoilers and thrust reverser, the configuration of the aircraft does not change, the lift and drag coefficient can, therefore, be considered to be constant.

It is assumed that the runway slope is zero, therefore, the gravitation forces do not affect the longitudinal motion. As the accelerations are measured in the body-fixed coordinate frame, they have to be transformed to the local navigation frame which is defined as the x axis pointing into the direction of the aircraft's kinematic velocity and the z axis pointing down, perpendicular to the earth's surface.

Based on the recorded data, a nonlinear regression is performed for each recorded flight and groundspeed intervals in order to determine the parameters C_L, C_D, k_P, the tire pressure p_{tire}, the roll friction coefficient μ_0 as well as the four coefficients of Pacejka's formula, B, C, D and E. The following constraints must be fulfilled to determine the slip-friction curve:

1. For $s = 0$, the roll friction coefficient must be obtained.
2. For $s = 1$, the skidding friction coefficient provided in [7] must be obtained.

3. The maximum friction coefficient, as provided in [7], must be obtained for $0.12 \leq s \leq 0.3$

The last constraint is based on the fact that the antiskid system on the Airbus A320 limits the slip to a maximum of 0.13 [2], independent of the state of the runway. The maximum friction has to be located right of this value in order to avoid being in the unstable region. These aforementioned three constraints are introduced into the nonlinear regression process to ensure that the obtained curves are compliant.

4 Analysis and Results

This method described above was applied on several landings of the Airbus A320 aircraft on the same runway at the same airport. Besides, the data available from [7] differentiate between different runway conditions. Dry runway condition was selected as both data is available and comparison between the flights is eased. An unweighted Root Mean Square Error (RMSE) is computed to fit the model developed in the previous section to the available data. As the friction curve is different for different values of groundspeed, the data was clustered by groundspeed, using intervals of 10 m/s of range. Data within each interval is grouped and analyzed.

4.1 Results and Analysis for a Sample Flight

The figures 4, 5 and 6 show the fitted curves for one single flight for the different speed ranges 30 to 40 m/s, 40 to 50 m/s and 50 to 60 m/s, respectively. For the other speed ranges, no sufficient data could be obtained.

In each plot, both the data and the fitted curve are shown. One can clearly seen the tendency that higher slip values will also lead to higher friction coefficients. As data with only small slip values exist, one can also see the linear relationship between the parameters. For the lower speeds as shown in 4, not many sample points can be obtained. For the higher speeds, the linear relationship is visible more clearly.

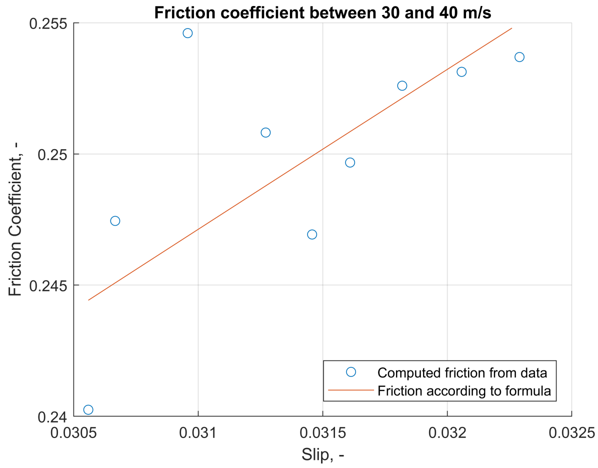

Fig. 4 Fitted curve for one flight, speed between 30 and 40 m/s

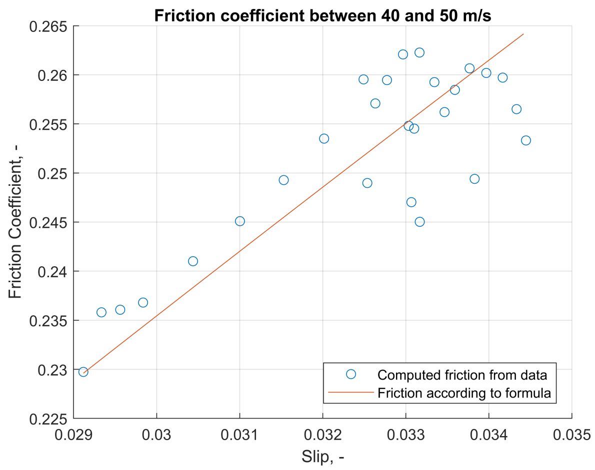

Fig. 5 Fitted curve for one flight, speed between 40 and 50 m/s

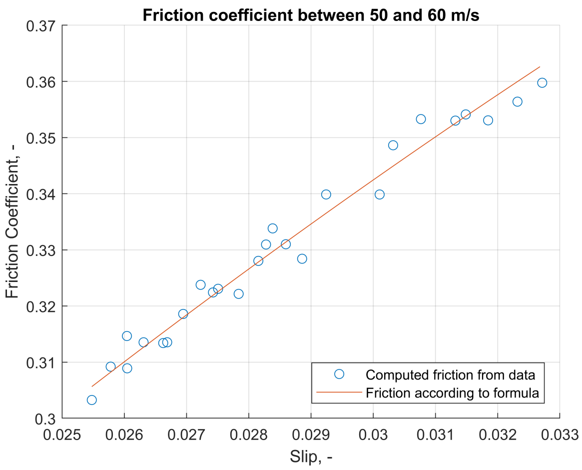

Fig. 6 Fitted curve for one flight, speed between 50 and 60 m/s

From the fitted curves, the Pacejka's coefficients are also obtained and subsequently the slip to friction curve. The maximum possble friction coefficient is obtained. By comparing this value with the friction coefficient obtained during the actual landing recorded in the data, it is possible to make statements about the remaining safety margin when attempting to stop the aircraft on the remaining runway length. For the three speed intervals analyzed, the highest achieved slip values are 0.0323, 0.0344 and 0.0327, respectively. The corresponding friction coefficients are 0.255, 0.264 and 0.363. When looking at the maximum friction coefficient, assuming the maximum allowed slip value by the antiskid system of 0.13, the correspondong friction coefficients are 0.569, 0.618 and 0.524. One can see that for this particular landing, the remaining braking capability was sufficient to double the braking deceleration in almost all of the three intervals.

However, one has to keep in mind that out of all the flights considered, the curves that are not always considerably well fitted as in this case.

5 Conclusion and Outlook

This paper presented a method to assess the braking capability of and aircraft during landing in order to obtain the safety margin when comparing to the actual braking that was performed. For the aircraft, a model incorporating reverse thrust, aerodynamic drag as well as braking forces is used. For the interaction between the tires and the runway, the slip to friction curved developed by Pacejka was used along with data measured by the Engineering Science Data Unit. The results were demonstrated using a sample flight.

Some effects are currently not fully taken into account and should be further investigated:

- The change of the tire pressure during the braking process is not considered. As the tire heats up due to braking, the pressure should increase in time, subsequently also changing the braking behavior of the tire.
- The difference between each tire caused by different normal force on each landing gear is currently not considered. This effect could be significant if the runway surfaces is banked, which is desired due to the simple drainage of water on the runway.

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