Dynamics of an Airplane Wheel at Touchdown

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Abstract  The dynamics of tire skidding and wear of a commercial airplane during touchdown is discussed, and a simple analytical model is presented. It is suggested that prespinning of the wheels prior to touchdown is not only possible but also practical to prevent tire wear and damage to the runway and the ensuing environmental issues.

Keywords  airplane, tire, wheel, prespinning, wear, landing, skid, smoke, runway

INTRODUCTION

During the landing of an airplane, a small cloud of smoke is generated shortly after touchdown. Microplastics are released when the tires smoke, negatively impacting the environment. The smoke is caused by the burning of the tires, which are made from natural rubber in commercial airplanes (Hunter, 1977), as a result of friction between the tires and the runway. This friction is the result of a mismatch between the rotational speed of the wheels and the translational speed of the airplane (Cadle & Williams, 1978). The heat that causes the smoke continues to be generated while the wheels are rotationally accelerating until the rotational speed of the wheels matches the translational speed of the airplane. This results in excessive wear of the tires and damage to the runway as well as other issues.

Although many articles have been published regarding tire wear as a result of skidding, investigations have mainly been carried out in the automotive area. In addition,
some investigations also involve simulation of the phenomenon using various models (Padovan et al., 1990; Li & Jiao, 2013; Alroqi & Wang, 2015). A comprehensive literature review of these studies appears in Alroqi and Wang (2015); therefore, we do not duplicate those studies here. However, to the best of our knowledge, no analytical model has been provided in the literature. The goal of this article is therefore to develop such a model, the results of which are in agreement with those obtained by other methods.

Based on the available statistics (Andy, 2021), a commercial airliner takes off and lands up to four times per day. In addition, each such airplane has a large number of wheels. For example, a Boeing 747 has 18 wheels (16 of which are the main landing wheels) (Flying Staff, 2022; Bodell, 2021), with a price per tire of about $2,000 (Emoji Cut, n.d.). Since the tires should be replaced after every 200–300 landings (Krasner, 2023), the tires alone would cost roughly about $18,000 per month. This is in addition to the labor cost for the tires to be replaced and the eventual cost of repairing the runway due to damage, not to mention the associated environmental issues that go back to as early as the 1940s (Beazley, 1947). In fact, each day there are about 100,000 airplane landings worldwide, out of which 90,000 are commercial planes (Trip.com, 2023). The toxic smoke produced as a result of tire skidding in these landings can certainly contribute to atmospheric pollution, at least in the long term. Consequently, if there is a way to prevent the wearing of the tires and damage to the runway, these issues are worth looking into.

A possible solution to preventing tire wear and damage to the runway is prespinning the main landing tires prior to touchdown. Although this has been discussed in some literature (Alroqi & Wang, 2015), it is generally perceived that doing so poses complex engineering challenges and/or that the implementation of the design would not be cost-effective.

In this article, we briefly discuss the dynamics of an airplane wheel during touchdown and suggest a solution to prevent the wearing of the tires. In doing so, with Alroqi and Wang (2015), we base our analysis on the Boeing 747 aircraft.

DYNAMICS OF AN AIRPLANE WHEEL DURING LANDING

Consider an airplane wheel shortly after touchdown with a translational speed \( v \) while the tire is skidding on the runway, shown in Figure 1.

Let the radius of the wheel be \( R \). According to Newton’s second law in rotational motion, we have

\[
\mu_kNR = I\alpha
\]  

(1)
where $\mu_k$ is the coefficient of kinetic friction, $N$ is the normal force on the wheel from the runway, $\alpha$ is the wheel's angular acceleration, and $I$ is its rotational inertia. From equilibrium of the forces in the vertical direction, we have $N = \frac{Mg}{n}$, where $M$ is the total mass of the airplane and $n$ is the number of main wheels that touch down, which is normally 16 (Alroqi & Wang, 2015). Furthermore, since the friction force is constant, the angular acceleration is also a constant, therefore, we have

$$\omega = \alpha t \tag{2}$$

where $\omega$ is the angular speed of the wheel, and $t$ is time. Therefore, Equation 1 becomes

$$\frac{\mu_k MgR}{n} = \frac{I \omega}{t} \tag{3}$$

This equation continues to apply during the entire skid period, and $t$ is the time duration of this period, which hereafter is denoted by $t_s$.

At the moment when skidding stops and the rotational speed of the wheel matches the translational speed of the wheel, which is the same as the speed of the airplane $v$, we also have $v = R\omega$. Substituting for $\omega$ in Equation 3, we get

$$\frac{\mu_k MgR}{n} = \frac{Iv}{R t_s} \tag{4}$$

Since $t_s$ is time during which the wheel skids, the distance that the airplane travels while its wheels skid is given as $d_s = vt_s$, in which we are making the reasonable assumption that the speed of the airplane during the skid period is constant. Therefore, Equation 4 reduces to
Furthermore, the rotational inertia of a round solid has the form

\[ I = \gamma mR^2 \]  \hspace{1cm} (6)

where \( \gamma \) is a number between 0 and 1 that depends on the geometry of the solid, as shown in Table 1 (Halliday et al., 2011, p. 255).

Therefore, Equation 5 reduces to

\[ d = \frac{\gamma nmv^2}{\mu_k MgR^2} \]  \hspace{1cm} (7)

where \( m \) is the mass of one of the main wheels of the airplane.

Equation 7 can be used to estimate the value of the skid distance of the wheels during landing of the airplane. To do so, we use the following values for the parameters:

- For \( \gamma \) we use a value of 0.75. Some investigators, for example Alroqi and Wang (2015) and Day (2014), have divided the wheel into tire and rim with radii of 0.622 m and 0.255 m, respectively, with a total mass of 184.4 kg. They further divided the rim into a circular and a flat part. However, these decompositions are unnecessary considering the approximations involved in the calculations. Therefore, we approximate the moment of inertia of the entire wheel to be the mean value of the moment of inertia for the tire and a disk, namely \( \gamma = 0.75 \).
- The maximum landing weight (MLW) of Boeing 747-400 is 295,743 kg (FAA, 2016), and the number of main wheels is \( n = 16 \).
- For the horizontal touchdown speed of the airplane, again we use the value for Boeing 747, which is 75.6 m/s (Alroqi & Wang, 2015).
- For mass per wheel, we use \( m = 184.4 \) kg (Alroqi & Wang, 2015).
- Finally, for the coefficient of static friction between the tires and the runway, we use \( \mu_k = 0.5 \) (Alroqi & Wang, 2015).
With the above values of the parameters, Equation (7) gives a skid distance of $d_s = 8.73 \text{ m}$. Therefore, the skid time of the tires is $t_s = d_s / v = 8.73 / 75.6 = 0.115 \text{ s}$. This is in excellent agreement with the value of about $0.1 \text{ s}$ reported by Alroqi and Wang (2015) using a much more complex model and simulation as well as the measured value of about $0.1 \text{ s}$ reported in investigations by Besselink (2000) and Khapane (2004).

**DISCUSSION AND CONCLUSION**

Although materials and structural changes to tires can contribute, at least to some extent, to reducing tire wear, these changes cannot prevent tire skidding during landing of an airplane. Therefore, in this article we have focused on the dynamical aspect of the process to prevent or reduce tire skidding.

The problem of tire wear and burning during landing of an airplane, especially commercial airplanes, has been discussed in some literature. Microplastics are a main contributor to environmental pollution, and airplane tires release microplastics when skidding upon landing. These discussions are mainly based on computer simulations, such as the Simulink model to predict the forces that act on the tire during landing and the consequent tire wear. Some of the literature also involves patents (Alroqi & Wang, 2015; Day, 2014); however, there is no valid proof that the solutions suggested in these patents can eliminate landing smoke and tire wear, and apparently no aircraft industries have used these patents (Alroqi & Wang, 2015).

In this article, we have provided a new model for tire skidding and wear during landing of an airplane. This model is not based on simulation and is purely analytical and quite simple, but it produces results that are in excellent agreement with those in more complex simulations as well as measured values.

Currently, aircraft landing continues to generate smoke, excessive tire wear, and flat spots on tires, which requires the tires to be replaced periodically. In fact, each tire leaves approximately 0.7 kg of rubber on the runway after each landing (Estrada & Hayton, 2022). A solution to this problem is prespinning the wheels prior to landing of the airplane, for which simple to complex methods have been suggested. However, it is generally perceived that these solutions are mechanically too complex, too heavy, or not durable (Alroqi & Wang, 2015). Nonetheless, we believe that prespinning the wheels is feasible without being too complex or too heavy. One solution would utilize small electric motors, as explained below.

The kinetic energy of a wheel is

$$K = \frac{1}{2} I \omega^2 \quad (8)$$
where $I$ is the moment of inertia of the wheel around its axis of rotation and $\omega$ is the angular speed. When the rotational speed of the wheel matches its translational speed $v$ (free rolling), we have $\omega = v/R$. Furthermore, since $I = \gamma mR^2$ with $\gamma = 3/4$, as stated earlier, Equation 8 reduces to

$$K = \frac{3}{8}mv^2$$  \hspace{1cm} (9)

Suppose an electric motor with power $P$ is used to prespin the wheel from rest to the required rotational speed for free rolling. The time for this process is

$$t = \frac{K}{P} = \frac{3mv^2}{8P}$$  \hspace{1cm} (10)

Considering the mass of a 747 airplane wheel to be 184.4 kg as mentioned earlier, the horizontal translational speed of the wheels at touchdown of $v = 75.6$ m/s, and a power of electric motor $P = 2$ hp (1492 W), we obtain $t = 265$ s, which is only about 4.4 minutes. In fact, electric motors with specific power (power to mass ratio) of 3–4 kW/kg (4.02–5.36 hp/kg) are readily available (Ivanov et al., 2022).

A wireless electronic sensor can monitor the rotational speed of the wheel, and once the desired value is reached, the electric motor is turned off. This is quite practical for prespinning the wheels without requiring complex mechanical designs.

Yet another simple design for prespinning the wheels is by installing check valves on the outside or inside of the rim of the wheels, as shown in Figure 2. As the landing gears are lowered, the air on the lower check valves closes the valves but opens the upper ones, as shown in Figure 2. This generates a net torque on the wheel, resulting in an angular acceleration and prespinning of the wheel prior to touchdown. Again, the rotation of the wheel can be monitored by a wireless electronic sensor, and the flaps of the check valves can be locked once the desired rotational speed is obtained.

Finally, we point out that during the landing of an airplane in turbulent weather, the main wheels might not all touch the runway simultaneously. The force from the runway on wheels that touch the runway first exerts a torque on the airplane, which results in its additional instability. Prespinning the wheels would eliminate this torque, making the plane more stable at touchdown in turbulent weather.

In conclusion, commercial aircraft release microplastics into the environment, polluting the surrounding areas. When the rotational speed of the wheel matches the translational speed of the wheel, tire skidding is eliminated. The research team concluded two different methods to stop tire skidding that involve either an electric motor or air foils to prespin the tires. Prespinning wheels in a commercial aircraft prior to landing without complex designs and astronomical costs is possible, thereby
avoiding smoke during landing, excessive tire wear, damage to the runway, and the resulting environmental issues.

REFERENCES


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