Sliding Power in Aircraft Landing

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***Abstract*—This paper addresses what happens during the acceleration period of undercarriage wheels after aircraft touchdown on the runway. In this acceleration period, a sliding between the wheel tyre and runway surface takes place. The sliding friction causes high temperature which emits pollution smoke and produces excessive tyre wear. A model based on mechanical dynamics is established for analysing the high temperature, heat transfer rate to tyre and concrete runway. The effect of designing a pre-rotation device is also included in order to lower the temperature and reduce the tyre wear. The width of tyre is shown also having effect on the raised temperature. A blackened runway is believed to have changed the heat conduction therefore affecting the landing quality.**

***Index Terms*—aircraft landing, landing smoke, landing heat and wear, sliding power, sliding heat transfer**

I. Introduction

Significant high tyre temperature rise takes place when aircraft is in landing, particularly in the touchdown moment. The sudden acceleration of wheels is accompanied by wear and smoke, not just emitting pollution particles to air but depositing rubber on the runway. The high temperature weakens the tyre strength, even melts the rubber and brings about more rubber losses. With the number of landing increases, the touchdown area on the runway is usually severely blackened with deteriorated surface friction and heat dissipation properties. Normal practice is to use torch to burn off the rubber in scheduled intervals, which incurs extra airport operating cost and reduces airport operating efficiency. On the other hand, the tyre life is reduced due to such successive wear, bringing other additional costs from high frequency of changing tyres.

A number of designs for pre-rotating aircraft landing wheels have been proposed since mid of 20th century, which promisingly solves such problem effectively [1], [2]. The power source for spinning the wheel has been proposed from side wind turbines, electric motors and so on. However, the real application has to be looked forwarded into the future. Recently, the science and technology behind the pre-rotation have been investigated and developed [3]-[8].

With current static wheel in landing, the ground friction has to spin the wheel to match the linear landing speed. The limited friction is always below the demand of instant acceleration, therefore a sliding takes place, which grinds rubber away from softened tyre surface worsened by high temperature at the touch area. The reported research in the references [3]-[8] has covered finding the effectiveness of the technique of pre-spinning the wheel to reduce the tyre tread heat and wear, and choosing the initial wheel rotation speed that prevent the tread rubber from melting temperature. For achieving this, a coupled structural – thermal transient analysis in well-known software package ANSYS has been used to model a single wheel main landing gear as a mass-spring system. This model has been chosen to analyse the wheel's dynamic behaviour and tyre tread temperature and wear during the short period from static to a matching free-rolling velocity in which the wheel is forced to accelerate by the friction between the tyre and ground. The tyre contact surface temperature and wear have been calculated for both the initially static and pre-spun wheels in order to compare the temperature and wear levels for different initial rotation speeds. The required torque to spin the aircraft wheel to the required angular speed at approaching speed has been calculated using ANSYS CFX, which is used to determine the wheel aerodynamic forces developed by simulation of fluid flows in a virtual environment. Several types of side wind turbines have been simulated using ANSYS CFX in order to optimize with regard to the geometry, target rotation speed, and required acceleration.

This paper is addressing the effect of sliding power. The heat due to sliding is transferred both to tyre and concrete ground. Relatively higher heat conductivity of runway can actually ease the high temperature. Both the wheel and runway play the role in conducting and absorbing the heat during the acceleration period of undercarriage wheels.

II. Friction Power in Wheel's Acceleration Period

For modern aircraft, instantly after the landing gear touches the runway, it is for the ground friction to provide a torque to accelerate the static wheel to match the landing speed within between a fraction of a second and a couple of seconds. The acceleration time is depending on the wheel inertia and geometry, ground friction and other resistance. The runway is normally a concrete rough surface. No matter how great the friction can be provided, the torque by the ground friction is always limited. It needs some time to accelerate the wheel. During the

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acceleration, the tyre has to slide before reaching the linear landing speed.

Let v be the aircraft speed and ω the angular speed of the landing gear wheel. For a landing speed $v = v_0$, when acceleration is completed after touchdown, the tangential speed of wheel at touch point becomes also $v_0 = r\omega_0$. Assuming the friction provided by the runway ground $F = \mu W$, where μ is the sliding friction coefficient, depending on type of tyre, contact area and runway condition, assumed to be constant for simplicity; W is the vertical force share on the wheel shaft due to weight of aircraft, which normally has multiple wheels, as shown in Fig. 1.

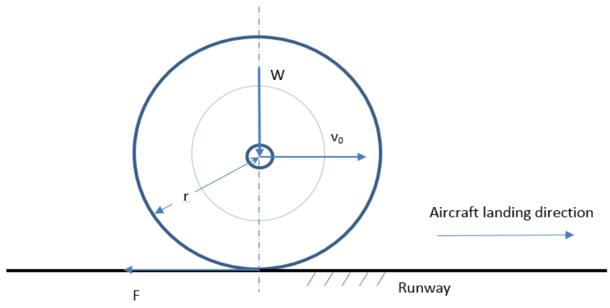

Figure 1. Aircraft wheel at landing.

After the touch instant, using the classical Newton's second law of motion for rotational circumstances, with a resistance torque T_r which includes those in shaft, air viscosity and ground rolling resistances, the equation can be described as

$$F\,r - T_r = I\frac{d\omega}{dt} \tag{1}$$

where I is the moment of inertia of the whole wheel, r is the radius. This radius is regarded as the effective radius, having taken into account of tyre deflection. Letting ε be the pre-rotation ratio, i.e., the percentage of landing speed v_0 being pre-rotated by a whatsoever pre-rotation device, and letting t_s be the required acceleration time, also assuming the angular acceleration is uniform from static or a slow spinning speed, to the matching landing speed $v_0 = r\omega_0$, therefore,

$$\frac{d\omega}{dt} = \frac{(1-\varepsilon)v_0}{rt_s}. \tag{2}$$

It is the friction between the concrete runway and rubber tyre that accelerates the wheel to a landing rotational speed within t_s by limited torque $F \cdot r$. During this acceleration time, sliding exists as at the beginning the wheel is static. In the late stage of acceleration, sliding approaches 0 as the wheel is matching the aircraft speed. The wheel needs a period of time to accelerate to ω_0 as the ground can only provide a limited, not unlimited, friction F. Therefore, a sliding is inevitable. The sliding time t_s = 0 only if the ground can provide infinitive friction to generate an infinitive acceleration from static or slow speed to ω_0, which is impossible. During this acceleration period with part wheel sliding can be assumed to be accelerated uniformly for simplicity. Several types of devices have been proposed for pre-rotation. For example, a side wind turbine is suggested as in the patents to fit on the wheel, on which an air dynamic torque is generated to accelerate the wheel to achieve a tangential speed before the touchdown. After the touchdown, no energy or just smaller energy (depending on the pre-rotation ratio) is required to accelerate the wheel to the matching speed $v_0 = r\omega_0$. A high temperature which might cause rubber melting or burning off can be avoided. From Eqs.(1) and (2) , the application of Newton's law becomes

$$F\,r - T_r = I\frac{(1-\varepsilon)v_0}{rt_s} \tag{3}$$

Therefore, the required wheel acceleration time is

$$t_s = \frac{(1-\varepsilon)v_0 I}{r(Fr - T_r)} \tag{4}$$

If the pre-rotation level $\varepsilon = 0$, $t_s = \dfrac{v_0 I}{r(Fr - T_r)}$; if $\varepsilon = 1$, $t_s = 0$. i.e. no acceleration time is needed, no sliding exists nor heat and smoke will be generated. The acceleration distance, or aircraft travelled distance during sliding is

$$s_s = v_0 t_s = \frac{(1-\varepsilon)v_0^2 I}{r(Fr - T_r)} \tag{5}$$

The acceleration distance s_s contains sliding as the wheel is gradually increasing its speed. Since the wheel is in the state of sliding, the actual tangential displacement of wheel at contact point pushed by ground friction, s_r, is less than the acceleration distance s_s. With the average speed during the acceleration $\dfrac{(1+\varepsilon)v_0}{2}$, it can be obtained:

$$s_r = \frac{(1+\varepsilon)v_0}{2}t_s = \frac{(1-\varepsilon^2)v_0^2 I}{2r(Fr - T_r)} \tag{6}$$

Therefore, the work contributed to the wheel rotation is $Fs_r = \dfrac{(1-\varepsilon^2)v_0^2 IF}{2r(Fr - T_r)}$. In the case of friction torque $T_r = 0$, the work is $\dfrac{1}{2}(1-\varepsilon^2)I\left(\dfrac{v_0}{r}\right)^2$, i.e. the final kinetic energy gained by the wheel. Without full pre-rotation, $s_r < s_s$. The acceleration displacement caused by the forces acted on the touch point during the whole period ($0 \le t \le t_s$)

is $s = \varepsilon v_0 t + \frac{d\omega}{dt} rt^2 = \varepsilon v_0 t + \frac{(1-\varepsilon)v_0}{2t_s} t^2$. The work done by the ground sliding friction is $\Delta E_w = Fs = F\left(\varepsilon v_0 t + \frac{d\omega}{dt} rt^2\right) = F\left(\varepsilon v_0 t + \frac{(1-\varepsilon)v_0}{2t_s} t^2\right)$ and the rate of work done by the ground friction is $\Delta \dot{E}_w = F\frac{ds}{dt} = F\left(\varepsilon v_0 + \frac{(1-\varepsilon)v_0}{t_s} t\right)$. During the acceleration period ($0 \le t \le t_s$), the aircraft displacement at time t is $v_0 t$, and the tangential displacement of wheel is the average speed multiplied by the time, i.e. $\frac{(1+\varepsilon)v_0}{2} t$. The average tangential velocity of wheel is $v_w = \frac{(1+\varepsilon)v_0}{2}$. Therefore, the sliding displacement is $s = v_0 t - \frac{(1+\varepsilon)v_0}{2t} t = \frac{1-\varepsilon}{2} v_0 t$. The sliding velocity then is $\frac{ds}{dt} = \frac{1-\varepsilon}{2} v_0$. The sliding power can be obtained as

$$\Delta \dot{E}_g = F\frac{(1-\varepsilon)v_0}{2} \tag{7}$$

On the other hand, combining Eqs. (5) and (6), the sliding work at the touch point is $\Delta E_g = F(s_s - s_r)$, thus the sliding energy is

$$\Delta E_g = \frac{(1-\varepsilon)^2 v_0^2 IF}{2r(Fr - T_r)} \tag{8}$$

The sliding power can also be obtained by $\Delta \dot{E}_g = \Delta E_g / t_s$. This part of energy remains on the touch point, generating heat, smoke, and tyre wear. During the sliding period, the wheel has gained kinetic energy from the ground friction as

$$\Delta E_w = \frac{1}{2}\left(1-\varepsilon^2\right) I \left(\frac{v_0}{r}\right)^2 \tag{9}$$

In the case of zero pre-rotation, $E_w = \frac{1}{2} I \left(\frac{v_0}{r}\right)^2$. After the acceleration period, this energy will be eventually dissipated in the subsequent aircraft braking or in air and runway frictions in the late stage of landing, which is outside this topic. The total work done by ground friction force in the acceleration period is

$$\Delta E = \frac{(1-\varepsilon)^2 v_0^2 IF}{2r(Fr - T_r)} + \frac{1}{2}\left(1-\varepsilon^2\right) I \left(\frac{v_0}{r}\right)^2 \tag{10}$$

If without pre-rotation, $\varepsilon = 0$, the total energy will be $\Delta E = \frac{v_0^2 IF}{2r(Fr - T_r)} + \frac{1}{2} I \left(\frac{v_0}{r}\right)^2$. In the case that T_r is small and can be ignored, $\Delta E = I\left(\frac{v_0}{r}\right)^2$. i.e. in this case, the work done by the ground friction is the twice of the kinetic energy gained by the wheel during the acceleration period. In Eq. (10), only the first term, i.e. the energy in Eq. (8) causes the high temperature problem.

III. Heat on the Tyre and Runway

Sliding friction is a complicated subject. Two surfaces of bodies are interacting with physical and chemical processes. In the interfacial media, tribo-chemical reaction, such as smoke in the intensive cases such as the landing, takes place and tribo-particulates are also generated. In the adjacent solids of two contacted bodies, there exist deformation, fatigue and fracture [9]. In aircraft landing cases, due to high speed, the sliding friction causes high temperature, smoke and excessive tyre wear. The sliding friction originally causes substance losses but the high temperature intensifies such losses, partly burned off as smoke and partly torn off as powder sticking on the runway. The rubber is a low heat transferred material, the rapid change of contact point on tyre gives too short time to transfer heat to deeper tyre body. On the other hand, the heat also dissipates to the runway, normally made of concrete with a higher heat transfer coefficient.

Assuming the width and length of contact area are *a* and width *b*, where *b* is regarded as the tyre width. The contact time for this contact area is a short period as $t_{pr} = a / v_w$ for the tyre and $t_{pc} = a / v_0$ for the runway concrete. t_{pr} is longer than t_{pc} as tyre is in sliding. The sliding work applied on the contacted area is part of the ground friction work. From the energy in Eq.(8), the energy for heating the contact area is

$$\frac{t_{pr}}{t_s} \Delta E_g = \frac{(1-\varepsilon)^2 v_0^2 IF}{2r(Fr - T_r)} \frac{t_{pr}}{t_s}. \tag{11}$$

According to energy conservatory law, it is also the heat energy received during the contact by the rubber and concrete of contact area, i.e.

$$Q = \frac{(1-\varepsilon)^2 v_0^2 IF}{2r(Fr - T_r)} \frac{t_{pr}}{t_s} \tag{12}$$

This heat will give a significant temperature rise to both tyre rubber and runway concrete. The heat transfers to the rubber and to runway of contact area are, respectively [11],

$$\frac{Q_r}{t_{pr}} = k_r \frac{T_h - T_0}{\delta_r} \tag{13a}$$

$$\frac{Q_c}{t_{pc}} = k_c \frac{T_h - T_0}{\delta_c} \tag{13b}$$

where k_r and k_c are the heat conduction coefficients of rubber and concrete respectively. T_h and T_0 are the final raised temperature and initial temperature. It is also the surrounding temperature. δ_r and δ_c are the thickness of the heat transferred in the contact area. The heat Q is shared by the tyre rubber and runway concrete with the effect of increasing the internal energy:

$$Q = m_r c_r (T_h - T_0) + m_c c_c (T_h - T_0) \tag{14}$$

where for the contact area, $m_r = ab\delta_r \rho_r$ and $m_c = ab\delta_c \rho_c$ are the heated rubber mass and concrete mass of the contact area. $Q_r + Q_c = Q$. Using Eq.(13a) and (13b) the heated depths for the rubber tyre and concrete runway are respectively,

$$\delta_r = k_r \frac{T_h - T_0}{Q_r} t_{pr} \tag{15a}$$

$$\delta_c = 2k_c \frac{T_h - T_0}{Q_c} t_{pc} \tag{15b}$$

If assuming $Q_r = Q_c = Q/2$, it can be arrived $\delta_c = \frac{k_c}{k_r}\delta_r$. Since the thermal conductivity of concrete is about twice as much as the rubber, the heated depth of concrete is double of the rubber. The number of revolution during the sliding is $s_r/(2\pi\ r)$. Therefore, the heated rubber mass is

$$\Delta m_r = \frac{t_s}{t_{pr}} m_r \cdot \tag{16}$$

Δm_r is the heated rubber and in high temperature, part of which are likely to be melt or burned off. The other part may be torn off to print on the runway.

IV. Numerical Results

The touchdown temperature against several parameters has been calculated based on meaningful Boeing passenger aircraft undercarriage data [5], [10]. The following figures are used:

The friction force $F=1.449\times10^4$ *N* and the landing speed $v_0=80.8$ *m/s*, the density of rubber and concrete are $\rho_r = 1185 kg/m^3$, $\rho_c = 2300 kg/m^3$, the specific heat capacities are $c_r = 480\ J/kg{\cdot}^oC$, $c_c = 1000\ J/kg{\cdot}^oC$, the heat conduction coefficients are $k_r = 0.293\ W/m{\cdot}^oC$, $k_c = 0.80\ W/m{\cdot}^oC$, $I=46.19$ *kg-m*^{2}, the tire radius $r=0.622$ *m*.

It can be obtained that the heat Q transferred to the contact area is 2898 *J* for each touch time t_{pr}. The number of revolutions during the sliding is 6.9. Because of windy circumstance, the heat of continuous rotating contact will be subject to immediate forced convection. The high temperature with wear and smoke only happens in the rotating contact area. However, the rubber loss will be accumulated with the 6.9 actual wheel revolutions. The thickness of heated tyre layer δ_r can be obtained by iteration calculation through Eqs(14), (15a) and (b). The mass of heated rubber is 234 grams, corresponding to each landing of a single wheel, part or all of which are to be grinded off to stick on the runway. The touchdown temperature against pre-rotation ratio is given in Fig. 2. It shows linearly that without pre-rotation, the highest temperature is 300 ^oC and full pre-rotation will have no temperature rise. 50% of pre-rotation is to halve the temperature which can likely control the rubber not being softened and turned off.

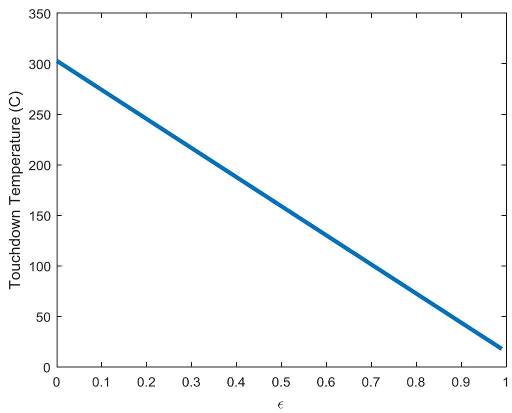

Figure 2. The touchdown temperature vs pre-rotation ratio.

The tyre width affects touchdown temperature. A narrower tyre will have higher temperature as shown in Fig. 3. Obviously, it is because the narrower the tyre, the higher the friction power density on the touch area. Based on this factor, certain tyre pressure is required to provide a good size of contact area to prevent from high temperature. However, the change is not very significant.

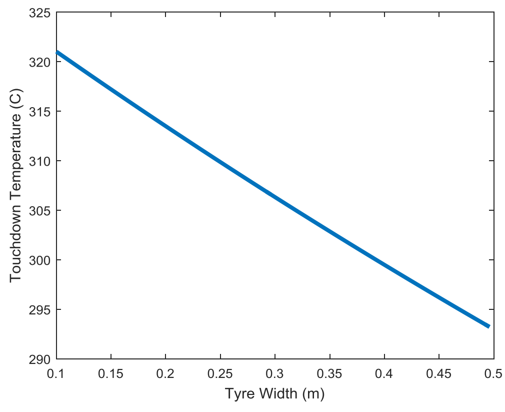

Figure 3. Tyre width affects the touchdown temperature(ε=0).

Since part of the friction heat is transferred into the runway concrete and the heat conduction of concrete is higher than the wheel rubber, the runway makes contribution in dissipating the heat generated by sliding friction. A blackened runway will tend to change the concrete runway into rubber runway. Assuming there is no major change in the friction coefficient, the heat dissipation will be reduced so that the touchdown temperature will become higher as shown in Fig.4. This can partly justify the regular removal activity for the runway.

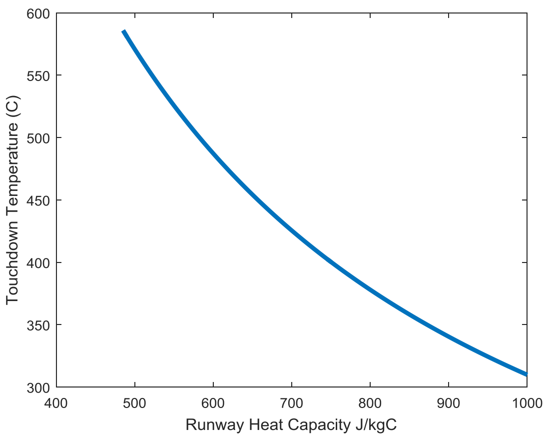

Figure 4. Touchdown temperature vs runway heat capacity.

A part of the heated mass on rubber will be lost during the touchdown by sliding friction. Fig. 5 shows it will be linearly reduced by increasing the pre-rotation ratio. Not surprised, the rubber will not be heated up and no smoke and wear exist if the pre-rotation ratio is 100%. This may be achieved by careful design of the pre-rotation torque or adaption of a feedback control. As long as a certain pre-rotation ratio is achieved, the temperature will not be high enough to generate smoke and excessive tyre wear. Obviously, a pre-rotation ratio over 100% is not necessary and can be easily avoided in practice.

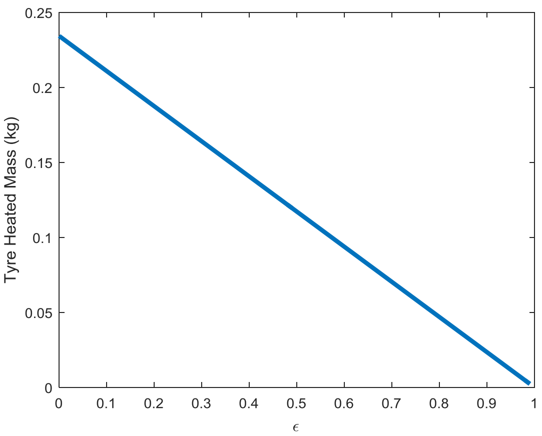

Figure 5. Tyre heated mass (kg) vs pre-rotation ratio.

V. CONCLUSION

The classical dynamic modelling of acceleration period of undercarriage wheels after aircraft touchdown has been approached and clearly developed, giving fundamental relationship between forces and motion of aircraft undercarriage. The formula for calculating sliding power flow is derived, which is generated on the touchdown area, producing heat, smoke, and causing excessive tyre wear. The analysis shows the sliding power is a part of the work done by the ground friction. During the sliding period, the wheel has also gained kinetic energy from the ground friction in order to match the landing velocity. The temperature rising formula is established based on thermodynamics. The heat transfer to both tyre and runway has been simulated. Ideally, the touchdown temperature will decrease with the increase of the pre-rotation ratio linearly as effective solution for landing smoke, tyre wear and blackened runway. The analysis also indicates the blackening of runway will change the heat conduction property of runway therefore may intensify the touchdown temperature. The tyre width will also affect the touchdown temperature. Increase of the tyre width will reduce the temperature. The new knowledge in this research unveils the mechanism of landing smoke and tyre particulate emission, hopefully can be used as a starting attempt to find the solution for the world-wide landing smoke problem. Further desirable move should be in finding out the required torque by side-wind turbine or other auxiliary power source, electrical or pneumatical, to drive the wheels in laboratory conditions. On-board experiment is most desirable but final, which will involve large scale of funding and regulatory issues, leading to significant future improvement of aircraft landing and airport operation.

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