A COMPARISON OF AIRCRAFT TIRE SKID WITH INITIAL WHEEL ROTATIONAL SPEED USING ANSYS TRANSIENT SIMULATION

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Abstract- Based on heavy aircraft main landing gear tires touchdown skidding process, patents have been registered since the 1940s to improve tire safety, decrease the substantial wear and smoke that results from every landing by spinning the rear wheels before touchdown. A single wheel has been modeled as a mass-spring-damper system using ANSYS mechanical transient simulation to analyze static and pre-rotating wheels behavior during a short period between touchdown and skidding, to spin-up to reach the equivalent of the aircraft ground speed. In this paper, a case study is presented of a Boeing 747-400 main landing gear wheel to compare the skidding distance and time between initially static and pre-spun wheels.

Keywords- Aircraft Touchdown, Landing Smoke, Tire Skidding Distance, Spin-Up Time, Pre-Rotating Wheel.

I. INTRODUCTION

The approach speed of heavy aircraft on landing is high because of weight limitations; and leads to skidding on its main landing gear tires, caused by the high slip ratio between the tires and the runway surface, as the landing system does not provide tire spin-up before touchdown. The heat generated by high slip tires at touchdown is enough to melt the thin layer of rubber and adhere it to the runway surface [1]. During the tire skidding phase, the tire tread temperature rises immediately to reach critical temperature. At critical temperature, the tread rubber material bonds break; and then wear occurs easily by friction force. Therefore, the skidding process produces tire wear as rubber burns off and tire material is worn away while the tires accelerate to match the forward speed of the aircraft along the runway [2]. A proportion of rubber particles burn off under the skidding wheel and evaporate in the form of smoke ($\approx 32\%$), while the remaining proportion stays on the runway to be removed later[3]. Few studies were found to have simulated tire dynamics during landing. Padovan, Kazempour and Kim (1990) built an energy-balance model of the space-shuttle single wheel to compute the rate of work due to interfacial friction between tire and runway. In this study, the distance of fully locked wheels were varied between 0.101 to 0.241 depending on the constant friction coefficients of 0.7 and 0.3 respectively [4]. Besselink (2000) simulated 'shimmy' oscillation in the main landing gear of a Boeing 747-400 aircraft. Some experimental data was recorded, including the wheel speed time during landing [5]. Useful data to validate our model was presented by Khapane (2004), who showed that aircraft tires accelerated from zero rotational speed to a free-rolling velocity within about 0.1 seconds from touchdown, which agreed with Basselink's results [6]. Some patents were suggested by Beazley (1947) and others, to pre-spin the main landing gear wheel before touchdown by wind energy, in order to avoid high wheel slip ratio and prevent aircraft landing smoke [7]. However, the majority of tire wear occurs at fully locked wheel, when the slip has maximum value. In this paper, a comparison between static and pre-rotation wheels has been carried out to estimate how much reduction of the full skid wheel distance can be achieved. The Boeing 747-400 data are used as a case study in this simulation, divided by the number of rear wheels (16), to be valid for single wheel model.

II. SIMULATION MODEL

To simplify the model, and because the comparison involves making the same assumption for all wheel statuses, we used the following assumptions supported with references:

•The pilot does not use brakes immediately after touchdown to avoid locked wheels, which increases skidding [8]. Therefore, a constant horizontal speed was used in this simulation.

• The aircraft will touchdown with all of the main wheels and zero wing lift [9] [10]. So, maximum aircraft landing weigh is used.

•The nose wheel will touch the ground approximately two seconds after the main wheels touchdown [11]. Therefore, the aircraft weight divided by the number of rear wheels only.

2.1 Landing Gear Dynamics

The simple mass-spring-damper is modelled using the ANSYS transient as shown in Figure 1, F_y represents the downward force created by the landing gear structure, and it is equal to the weight applied on the shock absorber [12][13].

Balancing forces are vertical to present oscillation of vehicle mass:

$$F_y = m\ddot{y} + c\dot{y} + ky \quad (1)$$

Where, m is the vehicle mass, c is the shock absorber damping coefficient (Ns/m), k is the landing gear linear stiffness (N/m), and y is the lumped

massvertical displacement (m) with an initial value equal to zero. $\dot{y}$ is the vertical velocity (m/s), and $\ddot{y}$ is the vertical acceleration (m/s^2).

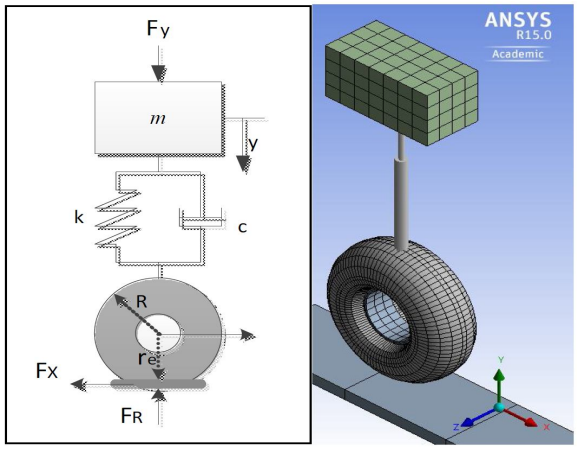


Fig.1. Mass-spring-damper system shown (left) and ANSYS model (right)

However, from inspection of the system in Figure 1 and equation (1), the reaction force over the tire contact patches is:

$$F_R = c\dot{y} + ky \quad (2)$$

And the friction force $F_x = \mu F_R$ has an assumed constant friction coefficient ($\mu = 0.65$). At touchdown, the tire is deflected under the vertical load force to an acceptable deflection level; as it is supported by its inflation pressure and the stiffness of the material. In this case, the effective tire radius should be used, which can be calculated using the radial tires deflection formula[14]:

$$r_e = R - \frac{\delta}{3} \quad (3)$$

Where R is the wheel radius(m), and δ is the tire deflection (m).

2.2. Slip (skidding) distance

The wheel may spin-up to be over the free-rolling level and then spin-down. Therefore, the longitudinal wheel slip ratio λ is defined as:

$$\lambda = \frac{v - r_e\omega}{v} \quad \text{if} r_e\omega \le v$$
$$\lambda = \frac{r_e\omega - v}{v} \text{ if } \quad r_e\omega > v,$$

Where, v is the aircraft forward speed (m/s), and ω is the wheel angular velocity (rad/sec). The upper part of the slip formula is the relative (skidding) speed between a point tangential to the outer tire surface and the forward speed of the aircraft along the runway. At the beginning of spin-up or fullywheel skid,$r_e\omega \le v$ this can be written as:

$$v_{skid} = v - r_e\omega \quad \text{and if } r_e\omega > v, \text{ then}$$
$$v_{skid} = r_e\omega - v$$

The wheel angular velocity can be calculated as:

$$\omega = \int \dot{\omega} + \omega_i$$

Where,ω_i is the initial wheel velocity, and $\dot{\omega}$ is the wheel angular acceleration which can be defined as:

$$\dot{\omega} = \frac{F_X r_e}{I}$$

Where, I is the wheel moment of inertia (kgm^2).
When $\lambda = 1$, the wheel is fully locked, and the spin-up ends at $\lambda = 0$. In the process of tire spin-up or when fully locked, the skid distance can be defined as:

$$L = \int v_{skid}\ dt \quad (4)$$

From equation (4), v_{skid} is function of wheel angular velocity, and when $\omega = 0$, the wheel is fully locked, $v_{skid} = v$. Because v is constant, so once we calculate the distance, L, simply the skidding time is:

$$t = \frac{L}{v}$$

III. SIMULATION METHODOLOGY

The simulation framework has been developed to evaluate the tire dynamics in the virtual environment. The Boeing 474-400 tire (H49x19.0-22) geometry is developed using the ANSYS design modeler with its data as shown in table 1 [15][16]:

Table 1: Wheel data

	Weight (kg)	Radius (m)	Width (m)
tire	110	0.622	482.6
rim	74.4	0.255	---

The tire is modeled as rubber material only, half of the cross-section of the 3D tire model and rim was constructed and shown in Figure2, with enough thickness because only the dynamic behavior is required. Based on the standard model material available in ANSYS, the rubber is represented as a hyper-elastic material, the runway material is asphalt and 75m long; and the other parts: rim and weight box are aluminum alloy with different densities. A suitable Mooney-Rivlin material model is used for the tire with a suitable Poisson's Ratio.Table 2 shows some of the rubber material properties[17]:

Table 2. Tire material properties

Parameters	Tire
Density (Kg/m3)	1200
Mooney-Rivlin constant	$C_{10} = 0.1186x10^6$ $C_{01} = -0.718x10^5$
Poisson's Ratio	0.49

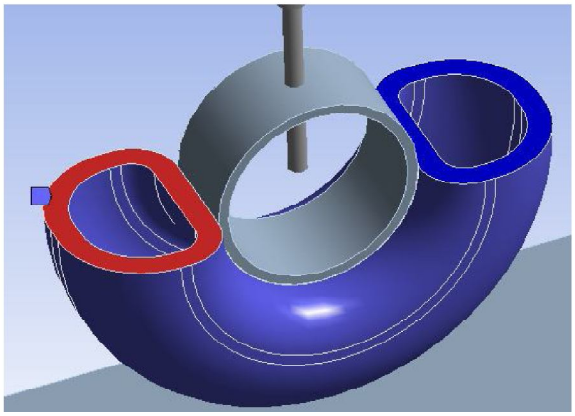


Fig.2.Half of the cross-section of the 3D tire model & rim

The shock absorber connected to the wheel axle has a combined spring constant of $3.125x10^5$ N/m, and damping coefficient of $3.42x10^5$ Ns/m [9]. It is also connected to the weight box (18,484 kg) which is the proportion for a single wheel calculated from the maximum landing weight of the aircraft, and the input speed, $v = 75.6m/s$ is based on the approach speed (80.77 m/s) minus 5.14 from flare deceleration, and the vertical sink rate is set to be 3m/s [18][19]. The pressure set inside the tire is 215 Psi, as proposed by Boeing and FAA [20]. However, the simulation result was for 1 sec after landing impact, and the ANSYS code (OMGZ) is used to calculate the tire rotation around the z-axis.

IV. RESULTS AND DISCUSSION

From first simulation with $\omega_i = 0$, we obtained the tire deflection and the tire free- rolling to set the 50% pre-rotation for the 2nd and 3rd simulations. The effective radius can be simply calculated using equation (3). However, Figure 3 shows the moment of touchdown, and Figure 4 shows the wheel angular velocity (the negative sign represents –z axis).

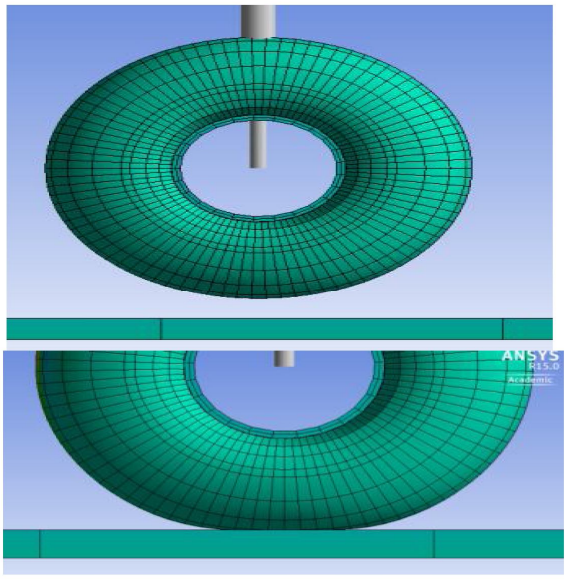


Fig.3.Transient tire touchdown



Fig.4. Static wheel angular velocity

The results of the static wheel touchdown are shown in Figure 5. The tire was fully locked for 0.03 sec with a distance of 2.27 m; and then started to spin-up for 9.1 m for 0.12 sec, which agreed with the literature. The curve shows the wheel spin-up is more than the free-rolling level, and then wavers to spin-down to reach a steady state ($v = \omega r_e$). From this relation with $r_e = 0.619\,m$ (calculated from equation 3), free rolling velocity,$\omega = 122rad/sec$; therefore, 50% pre-rotation will be 61 rad/sec.

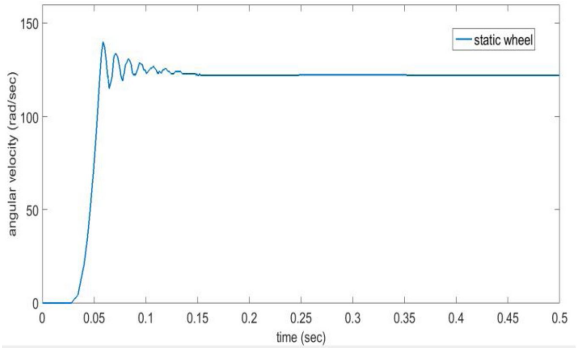


Fig.5. Static wheel angular velocity vs. time

The 2nd and 3rd simulation results for 50% and 100% pre-rotation are shown in Figures 6 & 7 respectively. For 50% pre-rotation, the wheel velocity dropped to 1.8 rad/sec immediately, losing about 97% and then recovering to waver for 0.07 second to spin-up and reaching 142 rad/sec to waver again for 0.13 seconds before reaching a steady state.

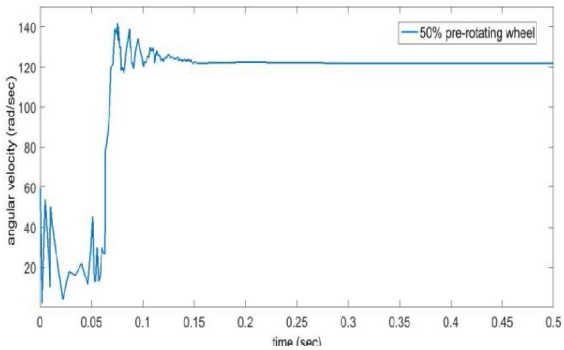


Fig.6. 50% pre-rotated wheel angular velocity vs. time

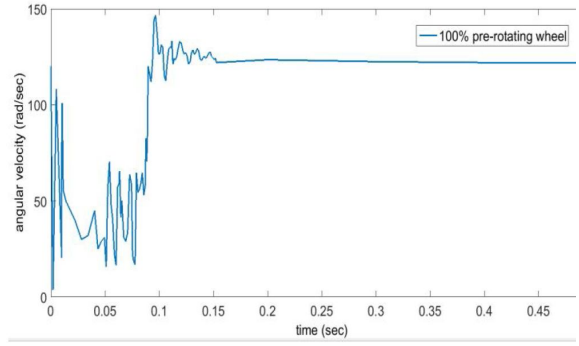


Fig.7. 100% pre-rotated wheel angular velocity vs. time

The reduction of wheel angular velocitypre-rotated 100% is about 96% of its speed at the moment of touchdown, as it reached 3.8 rad/sec and then recovered immediately with many waves to spin up after 0.08 seconds and over-shoot 146rad/sec. The rolling steady state was achieved after 0.15 seconds. Figure 8 compares the wheel angular velocity for the three stages.

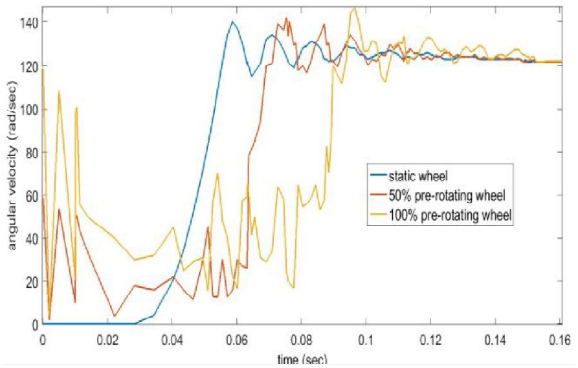


Fig.8. A Comparison of wheel angular velocity vs. time with initial rotation speeds

CONCLUSIONS

The fully locked wheel is the critical phase of aircraft tire touchdown; which melts the tread rubber and causes wear and smoke. The model shows a comparison of aircraft tire skid distance at the moment of landing impact for static and pre-rotating wheel. The results show that the 50% of the initial wheel rotating speed before touchdown is enough to avoid full tire skid, because the rotating wheel for all speeds is lost 96-97% of its rotation at the moment of landing impact. The spinning wheel was very close to be full skid, but it recovers immediately while the static wheel is still fully locked for 0.03 seconds and 2.27 m.

However, because most of the proposed solutions to spin the wheel were to use wind turbines, 50% pre-rotation give good opportunity to use small drag turbine as the wind is high at aircraft approach speed. Moreover, full spin is required large wind turbine while its size must be small to avoid aerodynamic effect or extra weight and to be fit in aircraft undercarriage.

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REFERENCES

[1] Swatton, P.J., "Aircraft performance theory for pilots", book, Technology & Engineering, Wiley, pp.91, 2008.

[2] Saibel, E. and Tsai, C., "Tire wear by ablation", Elsevier: Wear, vol.24,pp.161-176, 1973.

[3] Bennett, Michael, et al.,"Composition of smoke generated by landing aircraft", Environmental science & technology,vol.45.8,pp.3533-3538, 2011.

[4] Padovan, J., Kazempour, A., and Kim, Y. H.,"Aircraft Landing-Induced Tire Spinup", Journal of Aircraft,vol.28(12), pp.849-854. doi: 10.2514/3.46108,1990.

[5] Besselink, I.J.M., "Shimmy of Aircraft Main Landing Gears", Delft: TechnischeUniversiteit Delft. PhD thesis. Available at: http://www.tue.nl/en/publication/ep/p/d/ep-uid/227775/ [Accessed 12 March 2015]

[6] Khapane, P. D.,"Simulation of aircraft landing gear dynamics using flexible multibody dynamics methods in SIMPACK", Conference: ICAS, Yokohama, Japan. Available at: http://icas.org/ICAS_ARCHIVE/ICAS2004/PAPERS/262.PDF[accessed 21 July 2015]

[7] Beazley, R. H. (1947). Aircraft wheel spinner and control. U.S. Patent, Publication No. US2414849 A. Washington, DC: U.S. Patent and Trademark Office. Available at: http://www.google.com/patents/US2414849 [Accessed 7 March 2014]

[8] United States Air Force, "Republic F-84 Thunderjet Pilot's Flight Operating Manual", book, pp.7-11, 2007.

[9] Jingzhe, J.,"A Mixed Mode Function – Boundary Element Method for Very Large Floating Structure – Water Interaction Systems Excited by Airplane Landing Impacts", Doctoral thesis, Southampton University, 2007,Available at: http://eprints.soton.ac.uk/52018/ [Accessed 9 April 2015].

[10] Daidzic, N. E., andShrestha, J., "Airplane landing performance on contaminated runways in adverse conditions", Journal of Aircraft, vol.45(6),pp.2131-2144, 2008.

[11] FAA-H-8083-3A., "Airplane Flying Handbook. FAA Handbooks series", book, US Department of Transportation, Federal Aviation Administration. USA. Washington, DC: /r/flying Publishing Services. p.8-33.

[12] Lernbeiss, R., "Simulation of the Dynamic Behavior of an Aircraft Landing Gear during Landing",Simpack User Meeting, Vienna University of Technology. Availabel at: http://www.simpack.com/fileadmin/simpack/doc/usermeeting04/um04_tu-wien-lernb.pdf [Accessed 23 March 2015]

[13] Tanyolac, T. and Yasarcan, H.,"A Soft Landing Model and a Mass Spring Damper Based Control Heuristic", Proceedings of The 29th International System Dynamics Conference, 2011,Available at: http://www.systemdynamics.org/conferences/2011/proceed/papers/P1119.pdf [Accessed 23 March]

[14] Daugherty, R. H.,"A study of the mechanical properties of modern radial aircraft tires", 2003,Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.74.1702&rp=re&type=pdf

[15] Goodyear., "Aircraft data tire book", book, Akron, OH: The Goodyear Tire &Rubber Co, pp.32-33, 2002.

[16] Lufthansa Technik., "Aircraft tires: more than just rubber on steel", website, Available at:http://www.lufthansa-technik.com/aircraft-tires [Accessed 17 Jun 2014]

[17] Lin, Y-J., and Hwang, S-J., "Temperature prediction of rolling tires by computer simulation", Elsevier: Mathematics and Computers in Simulation. Vol.67,pp 235–249,2004.

[18] Boeing Commercial Airplane Co., "Approach speeds for Boeing airplanes",Available at: http://www.boeing.com/assets/pdf/commercial/airports/faqs/arcandapproachspeeds.pdf [Accessed 21 Jun 2014]

[19] Benjamin M., Dean C., and Dexter M.,"An experiment study of applied ground loads in landing", NACA-TR-1248, National Advisory Committee for Aeronautics. Langley Aeronautical Lab.; Langley Field, VA, United States, 1954,Available at: NASA technical reports server: http://ntrs.nasa.gov/search.jsp?R=19930092250 [Accessed 9 July 2015]

[20] Airbus Commercial Airplane Co., (2010). "High Tire Pressure Test", Technical Report, Available at: http://www.airbus.com/fileadmin/media_gallery/files/tech_data/Pavement/HTPT_final_report_Aug2010.pd[Accessed 7 September 2015]

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