

# Torque of Rotating Device Prior an Airplane Landing

Abdurhman.A.Al roqi<sup>1</sup>, Dr. Weiji Wang<sup>2</sup>

<sup>1</sup>Department of Engineering and Design, University of Sussex, UK

<sup>2</sup> Department of Engineering and Design, University of Sussex, UK

Email- aa-alroqi@hotmail.com

**ABSTRACT** - This papers focuses on the calculations to understand the torque required to spin the wheel of an airplane before it touches the runway. This measure is part of a proposed solution that is expected to eliminate the smoke generated by the airplane as it lands. The landing smoke is the result of high velocity difference between the landing gear wheels and the runway. Therefore, a slip occurs and causes serve grinding between the tyre and the runway where the tyre happens to be the softer surface. The calculations are based on the assumption that there is a turbine is installed on the side of the wheel.

## Keywords

Airplane Wheel ; Landing smoke; Torque; Landing gear;side wind turbine; Translational drag; Rotational drag.

## NOMENCLATURE

$T_{\text{turbine}}$	torque required to spin the wheel
$T_{\text{Dt}}$	translational drag torque
$T_{\text{Dr}}$	rotational drag torque
$T_{\text{shaft}}$	rotating shaft torque
$F_{\text{Dt}}$	translational drag force
$F_{\text{Dr}}$	rotational drag force
$F_r$	total rotating force
$F_w$	wheel weight force
$I$	wheel moment of inertia
$I_t$	tire moment of inertia
$I_r$	rim moment of inertia
$\omega$	wheel angular speed
$t$	time required to spin the wheel
$A_f$	wheel front area against the wind – rectangle shape
$A_s$	wheel side area – tow sides and circumference
$\rho$	air density at sea level
$C_{\text{Dt}}$	translational drag coefficient
$C_{\text{Dr}}$	rotational drag coefficient

$C_r$  rolling friction coefficient

$R_s$  shaft radius

## INTRODUCTION

The friction provided by the ground at the airplane touches the runway is always limited and the wheel with inertia needs time to accelerate to the landing speed. Therefore, a slip takes place and higher temperature and smoke are generated. The process of aircraft landing can be identified as one which has a considerable number of effects on the surrounding environment. These range from environmental pollution to other direct impacts on the airport itself. The environmental pollution that results encompasses not just air, and noise but water pollution (Luther, 2007)[1]. Air pollution from aircrafts is caused by two crucial sources of exhaust gases and landing smoke. This paper focuses on the imminent effects of air pollution with regard to the smoke generated during aircraft landing. The aircraft landing procedure causes pollution through a burning of tyres as result of impact of landing and the friction between tyres and the runway surface. The landing effects generate moderately high levels of air pollution (Tomita, 1964)[2]. During aircraft landing, the main wheels are the first to make contact with the ground and spin up; the nose wheel then drops to the runway and the brakes are applied to bring the aircraft to a stop. Visible landing smoke is mainly due to the wheel spin up and subsequently, due to the release of fine aerosol from brake abrasion. Thus, landing smoke is primarily a result of brake and tire wear (Cadle & Williams, 1978)[3]. However, the proposed solution deals with designing side wind turbines. This turbine should be able to spin the airplane's rear wheel before it touches the runway in order to eliminate the landing smoke. Our example for this study is the rear wheel of the Boeing 747-400. The wheel data and the airplane landing speed have been used in this study and the calculations are aimed at knowing how much torque is required to spin the airplane's rear wheel. As the wheel has a symmetric shape, it is imperative that there be a side wind turbine to spin it with.

## CALCULATIONS

The wheel is moving through the air with anticlockwise rotation about its axel and zero angle of attack. The forces acting on the wheel and angular direction are shown in figure-1. The torque required from the turbine are anticlockwise direction while the air and shaft torque are clockwise direction. The air flow velocity considered as the airplane landing speed. The air drag force is the source of the side wind turbine torque which depends on the wind.

### Data

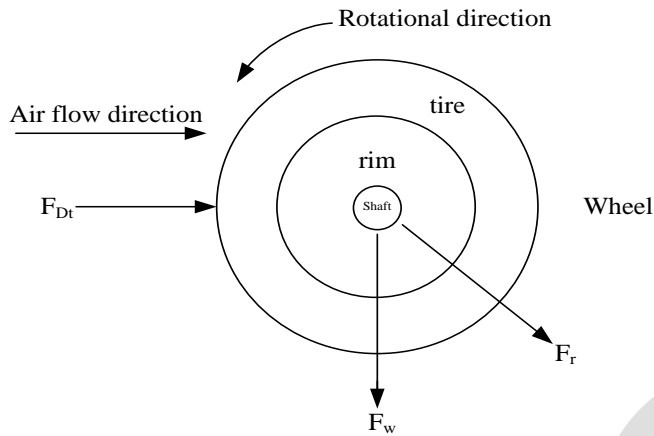
Airplane approach speed ( $V$ ) = 157 knots = 80.768 m/s [4]

Time ( $t$ ) = 30 sec (time is assume to be enough to spin the wheel).

Table-1, shows the tire and rim data.

**Table-1 tire and rim data**

	Weight (kg)	Radius (m)	Width (m)
Tire [5]	110	0.622	0.5588
Rim [5]	74.4	0.255	-----
Wheel axel shaft [6]	-----	0.065	-----



**Figure-1 Forces on an Airplane Wheel while landing**

The relation for the torque on wheel is given by torque and Newton's Second Law for Rotation. In our example, the main equation for solution is:

$$T_{\text{turbine}} - T_{\text{air}} - T_{\text{shaft}} = T_{\text{wheel}}$$

Where,

$T_{\text{turbine}}$  torque required to rotate the wheel (Nm)

$T_{\text{air}}$  air resistance torque (Nm). This torque is two types:  $T_{\text{air}} = T_{D \text{ translational}} + T_{D \text{ rotational}}$  [7]

$T_{\text{shaft}}$  wheel shaft torque (Nm)

$T_{\text{wheel}}$  wheel torque (Nm)

### 1-Wheel Torque

The solution comprises of following working formulae,

$$\omega = \alpha t$$

Where,

$\omega$  wheel angular speed (rad /sec)

$\alpha$  angular acceleration, (rad/sec<sup>2</sup>)

$$T_{\text{wheel}} = \alpha I = I \frac{\partial \omega}{\partial t} \quad [8]$$

We first have to calculate angular acceleration ( $\alpha$ ) and moment of inertia (I). here, we have to mention that the side wind turbine weight is not consider. So, the designer have to find the weight of the turbine and then re-calculate the equations. Here, the mass moment of inertia of rim (thin plate and circular ring) is given by [9],

$$I_r = \frac{mR_r^2}{2} \text{ for thin plate, and } I_r = m r^2 \text{ for circular ring}$$

Assume the weight of the ring is  $m_1 + m_2 = 74.4 \text{ Kg}$ ,  $m_1 = m_2 = 37.2 \text{ Kg}$

Where,  $m_1$  is the weight of the rim flat plate part and  $m_2$  is the weight of the rim circular ring part. Incorporation of values gives us the required moment of inertia of rim.

$$I_r = m_1 \frac{r^2}{2} + m_2 r^2 = \frac{37.2}{2} (0.255)^2 + 37.2 (0.255)^2 = 3.628 \text{ kg-m}^2$$

### Moment of Inertia for Tire

By using circular ring equation;  $I_t = m r^2$

$$I_t = 110 (0.622)^2 = 42.56 \text{ kg-m}^2$$

Total wheel moment of inertia,  $I = I_r + I_t = 3.628 + 42.56 = 46.19 \text{ kg-m}^2$

In order to find angular velocity ( $\omega$ ), we have the following relation [8],

$$V = r \omega$$

Rearranging the equation for  $\omega$ , we get

$$\omega = \frac{V}{r} = \frac{80.768}{0.622} = 129.85 \text{ rad/sec (1239.98rpm)}$$

Similarly, the angular acceleration,

$$\alpha = \frac{\partial \omega}{\partial t} = \frac{\omega_f - \omega_i}{t} = \frac{129.85 - 0}{30} = 4.328 \text{ rad/sec}^2$$

$$T_{\text{wheel}} = I_{\text{wheel}} \alpha$$

$$T_{\text{wheel}} = 46.19 \times 4.33$$

$$T_{\text{wheel}} = 0.2 \text{ kN.m}$$

## 2-Air Resistance Torque

There are two types of aerodynamic drag forces acting on the wheel. The component of these forces gives the total aerodynamic drag on the wheel. The two types are translational and rotational drag.

### A-Translational Torque

The translational torque is result of translational drag force multiply by the wheel radius. The translational drag is aerodynamic force facing the wheel when it moving during the air. However, the torque in this case can be determined by this equation:

$$T_{Dt} = F_{Dt} r$$

Where,

$F_{Dt}$  translational drag force

To find translational torque, we have to determine the translational force:

$$F_{Dt} = \frac{1}{2} \rho C_{Dt} A_f V^2 [7]$$

Where,

$$C_{Dt} = 1.98 \text{ as flat plate against the wind } 90^\circ [12]$$

Wheel frontal area,  $A_f = 2r * t_w = 0.5588 \text{ m} \times 1.244 \text{ m} = 0.695 \text{ m}^2$ . Here, we use the wheel facing area which is rectangle shape.

Air Density  $\rho_{\text{air}} = 1.225 \text{ kg/m}^3$

Air velocity (Airplane approach speed)  $V = 80.768 \text{ m/s}$

Hence,

$$F_{Dr} = \frac{1}{2} * 1.98 * 0.695 * 1.225 * (80.768)^2$$

$$F_{Dr} = 5.498 \text{ KN}$$

And,

$$T_{D \text{ translational}} = 0.622 * 5.498 = 3.42 \text{ KN.m}$$

### **B- Rotational Drag Torque**

Rotational drag torque is result of rotational drag force multiply by wheel radues. rotational drag force is result of rotating wheel through the air about its axel. Rotational drag force can be calculated by:

$$F_{Dr} = \frac{1}{2} \rho C_{Dr} A_s r^2 \omega^2 [7]$$

Where,

$A_s$  Area of Wheel side (two sides and circumference wheel area)

$$A_s = 2\pi r^2 + 2\pi r t_w = 2\pi r (r + t_w) = 2 * 3.1416^2 (0.622 + 0.5588)$$

$$A_s = 23.31 \text{ m}^2$$

Air Density  $\rho_{\text{air}} = 1.225 \text{ kg/m}^3$

$C_{Dr}$  rotational drag coefficient

Some previews studies have been done to estimate the drag coefficient by experiments. The researchers found that the distribution of pressure force on a wheel is different when it is at stationary or when it rotates. An experiment was done on a racing car wheel by Fackrell and Harvey[10]; they found that the pressure distribution is more when the wheel rotating compared with the same wheel at stationary position. In addition, the coefficients of rotational drag increases to an approximate 10% of the total rotational wheel drag. This is according to wind tunnel experiment on the wheel of a racing car by Morelli.A [11].

That lead to  $C_{Dr}$  is 10% of  $C_{Dt}$  i.e.

$$C_{Dr} = 0.1 * 1.98 = 0.198$$

Hence,

$$F_{Dr} = \frac{1}{2} * 1.225 * 0.198 * 23.31 * (0.622)^2 (129.85)^2$$

$$F_{Dr} = 18.44 \text{ KN}$$

And,

$$T_{Dr} = 11.47 \text{ kN.m}$$

$$T_{\text{air}} = T_{Dt} + T_{Dr} = 3.42 + 11.47 = 14.89 \text{ kN.m}$$

### 3-Torque for Shaft Rotation

The forces acting on the wheel are shown in figure-2. The translational drag and wheel weight forces are acting on the axel shaft. Here, we can calculate the rolling force and then determine the rolling torque:

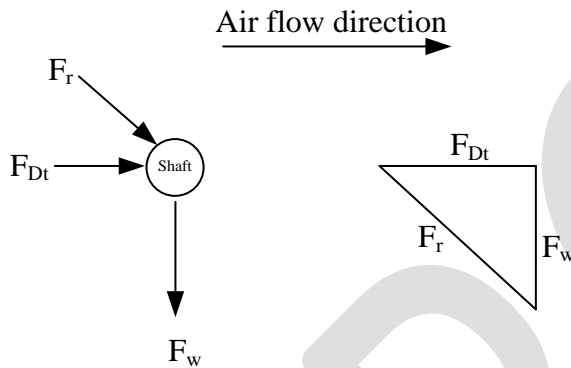
$$T_{\text{rolling}} = C_r * F_r * R_s \quad [12]$$

Where,

$C_r$  rolling coefficient friction = 0.001 (assumption as steel to steel)[13]

$R_s$  wheel axel shaft radius = 0.065m

$F_r$  rolling force, can be calculate as:



**Figure-2 Diagram of forces acting on wheel shaft**

$$F_w = 184.4 * 9.81 = 1.81 \text{ KN}, \quad F_{Dt} = 5.498 \text{ KN}$$

Hence,

$$F_r = \sqrt{F_{Dt}^2 + F_w^2} = \sqrt{(5.498)^2 + (1.81)^2} = 5.788 \text{ KN}$$

And

$$T_{\text{shaft}} = 0.001 * 0.065 * 5.788 = 0.376 \text{ KN.m}$$

Now the overall torque required by the side wind turbine to spin the wheel during 30 seconds could be given as,

$$\begin{aligned} T_{\text{turbine}} &= T_{\text{wheel}} + T_{\text{air}} + T_{\text{shaft}} \\ &= 0.2 + 14.89 + 0.376 \end{aligned}$$

$$T_{\text{turbine}} = 15.47 \text{ kN.m}$$

### RESULTS AND DISCUSSIONS

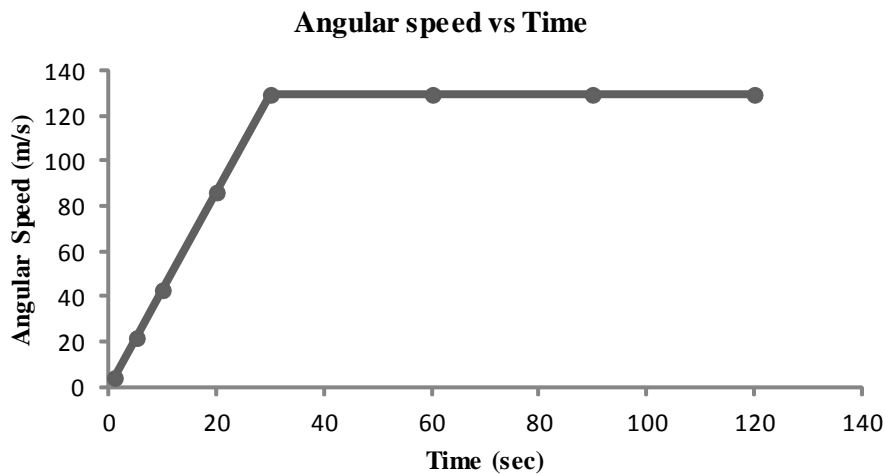
The above listed calculations give us a maximum value of 15.84 kNm for the torque required to rotate an airplane wheel after a time lapse of 30 seconds. The table-2 gives the values of required torque (turbine torque), air torque, wheel torque and angular speed at different times.

**Table-2 Variation of angular speed and torques with time**

Time (seconds)	Angular speed (rad/sec)	T <sub>wheel</sub> (kN.m)	T <sub>air</sub> (kN.m)	T <sub>turbine</sub> (kN.m)
1	4.328	0.20	3.43	4.38
5	21.642	0.20	3.74	4.69
10	43.280	0.20	4.69	5.64
20	86.560	0.20	11.62	12.19
30	129.850	0.20	14.89	15.84
60	129.850	0.10	14.89	15.74
90	129.850	0.07	14.89	15.33
120	129.850	0.05	14.89	15.32

A graphical representation of the tabulated values and discussion on the obtained curves is given here. The figure-3 shows that angular speed increases until it reaches a maximum at 129.85 rad/sec by acceleration at 4.328 rad/sec<sup>2</sup> and then it becomes constant. We get a straight line at a wheel torque of 0.2 kNm during the time range of 0 to 30 seconds as shown in figure-4. Here the curve descends after 30 seconds due to the reason that the angular speed becomes constant after this duration of time. The relation between angular speed and time ( $\frac{\partial \omega}{\partial t}$ ) describes clearly the descent in wheel torque reason.

The variation of torque of air with time is shown in figure-5. Here the air torque curve rises to 14.89 kNm and then becomes constant as it is a function of angular speed. The air torque is the summation of translational and rotational torques. It is rising during the 30 seconds as the rotational torque is a function of angular speed. Therefore, when the angular speed becomes constant the air torque turns into steady value. The required torque (turbine torque) is shown in figure-6; it rises until 30 seconds and then becomes almost stable as the wheel continues to rotate with a constant speed. The slight descent in the curve shows decrease in the required torque as it effects by the wheel torque reduction.



**Figure-3 Variation of Angular Speed of wheel**

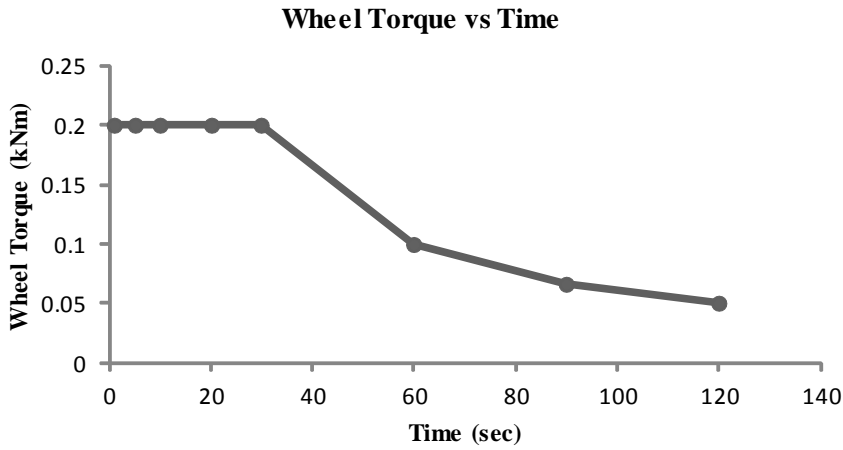


Figure-4 a graph of wheel torque against time

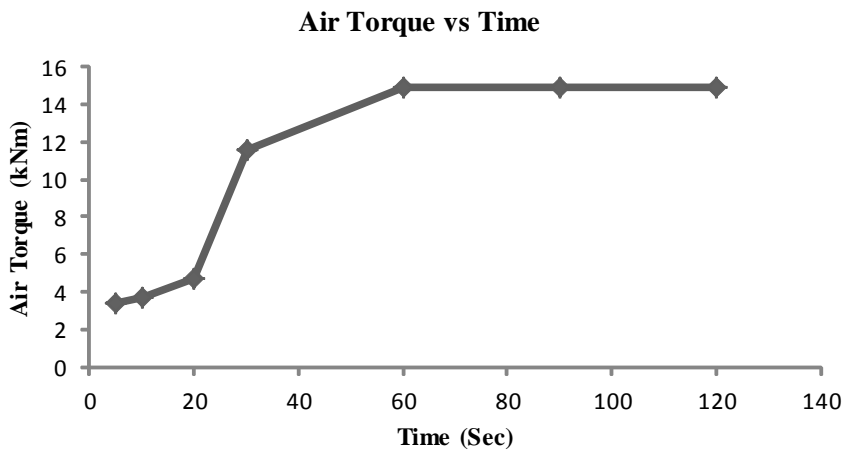


Figure-5 a plot showing variation of air torque with time

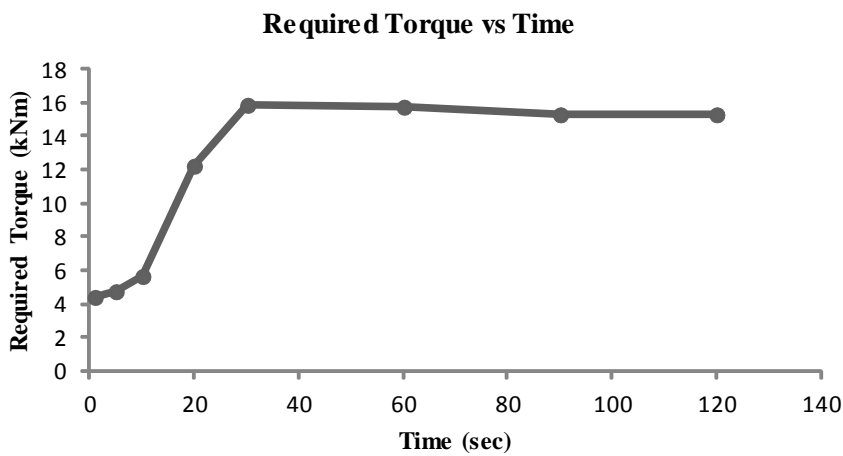


Figure-6 diagram of the required torque with time variation



## CONCLUSION

When aircraft wheels touchdown the runway skidding phenomenon is observed. If wheels do not rotate before touchdown then this skidding can lead to landing smoke, tyres failure, and rubber loss. A simple device that can avoid skidding and can be fixed to external portion of tyre rim is a Side Wind Turbine. This device will internally eliminate the landing smoke by a percentage which will depend on the angular speed of the airplane wheels. As the speed of rotation of wheels relate to the torque of side wind turbine, its designing has to be equilibrated between its efficiency and weight. An increase in the turbine weight will cause an increase in the total wheel weight and then more torque is required to spin the wheel. In addition, the shape of turbine must be suitable so that it can fit within the airplane undercarriage during retraction. Calculations made in this research paper give the basis for design of a side wind turbine and are useful for applications in aviation performance.

## ACKNOWLEDGEMENT

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