Conceptual design of a new experimental setup to simulate aircraft tyre spin-up dynamics

Saeed Mahjouri, *PhD., Department of Mechanical Engineering, Faculty of Engineering, Urmia University, Urmia, Iran, Email: saeed.mahjouri.sm@gmail.com*

Rasoul Shabani, *Corresponding author. Professor, Department of Mechanical Engineering, Faculty of Engineering, Urmia University, Urmia, Iran, Email: r.shabani@urmia.ac.ir; ras.shabani@gmail.com*

Martin Skote, *Professor, School of Aerospace, Transport and Manufacturing. Cranfield University, Cranfield, MK43 0AL, United Kingdom, Email: M.Skote@cranfield.ac.uk*

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Abstract:

Purpose- The first touchdown moment of aircraft tyres on a runway is the critical phase where maximum of the vertical and horizontal ground loads is produced. Some valuable drop tests have been performed at Langley research center to simulate the touchdown and the spin-up dynamics. However, a long impact basin and a huge power source to accelerate and decelerate the landing gear mechanism have been used. Based on a centrifugal mechanism, this paper proposes the conceptual design of a new experimental setup to simulate the tyre spin-up dynamics.

Design/methodology/approach- A Schematic view of the proposed mechanism is presented and its components are introduced. Operating condition of the system and the test procedure are discussed in detail. Finally, tyre spin-up dynamics of Boeing 747 is considered as a case study, and operating condition of the system and the related test parameters are extracted.

Findings- It is shown that the aircraft tyre spin-up dynamics can be simulated in a limited laboratory space with low energy consumption. The proposed setup enables the approach velocity, sink rate, and vertical ground load to be adjusted by low power actuators. Hence, the proposed mechanism can be employed to simulate the tyre spin-up dynamics of different types of aircraft.

Research limitations/implications- It is important to note that more details of the setup, including the braking and actuating mechanisms together with their control procedures should be clarified in practice. In addition, the curved path introduced as the runway will cause errors in the results. Hence, a compromise should be made between the tyre pressure, path curvature, the induced error, and the cost of the experimental setup.

Practical implications- The proposed experimental setup could be constructed in a limited space and at a relatively low cost. Low power actuators are used in the proposed system. Hence, in addition to the performance tests, fatigue tests of the landing gear mechanism will also be possible.

Originality/value- Based on a centrifugal mechanism, the conceptual design of a new experimental setup is presented for simulating the tyre spin-up dynamics of aircraft. Considering that the drag load developed during tyre spin-up following initial touchdown is an important factor governing the design of the landing gear mechanism and aircraft

structure, we hope this paper encourage engineers to continuously make efforts to increase the transparency of the touchdown process, enabling optimization of landing gear design.

***Keywords**:* Aircraft landing; tyre spin-up dynamics; experimental setup; ground loads.

1. Introduction

Before touchdown of an aircraft wheels with the runway, they are in a stationary condition. Therefore, due to the high approaching speed of heavy aircraft, an abrasive skidding between the aircraft tyres and the runway surfaces occurs immediately after touchdown (Padovan *et al*., 1991). In a fraction of second known as spin-up period, the skidding changes to fully rolling motion as the wheels accelerate to match the forward speed of the aircraft. For civil jet aircraft the approaching speed at the touchdown moment is in the range of 55 to 83 *m/s* and vertical velocity or sink rate usually fluctuates between 1.5 and 3.5 *m/s* (Li and Jiao, 2013). Hence, the generated landing impact or vertical and drag loads during touchdown are very important and decisive in cantilevered design of landing gear mechanism and fuselage (Besselink, 2000). Due to complexity of the spin-up dynamics and the high cost of providing laboratory equipment for the spin-up or drop tests, few articles and reports are devoted to the touchdown ground forces, loss of tyre, and temperature control during the spin-up period. A series of important and valuable experiments have been done at Langley Research Center with very high costs.

Milwitzky *et al*. (1955) employed Langley impact basin and experimentally investigated the vertical and horizontal ground loads and variations of the coefficient of friction between the tyre and the runway during the wheel spin-up period. Due to limited length of the test basin and power source to accelerate the carriage, their tests have been performed with horizontal velocity up to 25 *m/s*. Some other experiments were also conducted at the Langley landing-loads track to investigate many different facets of the landing and ground-handling problems of aircraft (Joyner and Horne, 1954). The landing-loads track included a large hydraulic water-jet catapult which accelerated an 18-meter-long test carriage to speeds up to 62 *m/s* (Joyner *et al*., 1963). With close control of test parameters such as forward velocity, sink rate, vertical load, and runway surface conditions the landing gear and tyre performance were investigated. Wet-runway tests have also been conducted at the Langley landing-loads track in which smooth and dimple-tread tyres were used to represent completely worn tyres (Trafford *et al*., 1965). Another experimental investigation of the space shuttle orbiter main gear tyre spin-up processes has been conducted at the NASA Langley research center ‘Aircraft Landing Dynamic Facility ALDF’ (Daugherty *et al*., 1988). The facility included of a set of rails 850 *m* long on which a 49-ton carriage travels. The carriage was propelled at speeds up to 80 *m/s* using a high pressure water jet directed at a turning bucket mounted on the carriage. Arrestment was achieved using a set of water turbines connected by nylon tapes and steel cables that were engaged by a nose block on the front of the carriage (Daugherty *et al*., 1988; Horne, 1965). In another test in the same research center (Trafford and Glenn, 1965b), the hydraulic water-jet catapult system accelerated a 45ton carriage to top speed 62 m/sec in about 3 seconds, over a distance of 90-120 meter. It means that an average power of about 30,000 Kw was utilized in the 850-meter-long test track, where some portion of the energy was wasted due to aerodynamic of the carriage. This extremely high power was due to the limitation of the track and time to reach the desired velocity. Internationally published papers and reports show that the Langley facility has been in use since 1945 and the last available report is related to 1988.

Experimental results and field observations have revealed that during spin-up time, the aircraft tyre burns, its frictional characteristics change effectively (Waddad *et. al*., 2019; Gschwandl, *et al*. 2019), and significant asymmetric wear occurs. Hence, mathematical or even numerical modeling of the spin-up tyre-runway contact dynamics would be very complex. Therefore, only a small number of articles have been published on the modeling of spin-up dynamics, where each of them has its own limitations and should be verified experimentally (Padovan *et al*. 1991; Alroqi *et al*., 2017). Recently, based on wet landing during the spin-up period, the authors (Mahjouri *et al*. 2022) proposed a new strategy to reduce tyre temperature and ground loads. They claimed that reducing the coefficient of friction during the tyre spin-up reduces the ground horizontal drag force, resulting in increased fatigue life and improved the frequency response of the landing mechanism (Chaudhary, 2021). However, their claim should also be quantified experimentally. Hence, experimental test results are essential to study the tyre spin-up dynamics and landing gear system.

It should be noted that the material properties of the aircraft tyres are also essential in the tyre spin-up period and braking phase of an aircraft. However, testing a tyre on a real runway or straight Langley landing- load track still remains very expensive and difficult task, especially at high velocity. Therefore, drum-tyre machines represent a suitable alternative where tyres could be tested in contact with the inner or the outer surface of the drum. The internal contact drum test was frequently used to investigate the influence of the tread pattern, tread groove, cornering and braking force capability of the tyres (Rosu *et al*., 2018). However, simulating the runway material conditions (concrete or asphalt) on the drum surface, especially in outer drum cases should be very complex (Rosu *et al*., 2018).

The presented literature review shows that the valuable experimental research, related to the tyre spin-up dynamics, have been done at the Langley research center with very long tracks, high power consumption, and consequently high cost (Trafford and Glenn, 1965b). In addition, some relatively cost effective tests related to the aircraft tyre's material have been done in drum-tyre machines. However, direction of the energy flow in the drum tests (from the drum to the wheel) is different from what is happening in the real conditions. This paper proposes a vertical circular path with a rotating arm to simulate tyre spin-up dynamics. The arm is rotated with a low power source and carries two tyres to be tested. Two radial actuators are installed on the rotating arm and closely control the radial movement of the wheels. The sink rate, linear or tangential velocity, and vertical or radial load are controlled with the velocity control of the rotating arm and the radial actuators. Layout of the proposed mechanism and test procedure is discussed in detail. Boeing 747 is considered as a case study and its vertical dynamics are derived. The wheel center displacement history is extracted and employed as the command value for the radial actuators. Radial dynamics of the actuators are derived and the power consumption of the actuators during the spin-up are depicted. It is revealed that to control or replicate the radial or vertical ground force there is no need to inject more energy by the actuators. However, during the touchdown moment it is necessary that significant energy is taken from the system by a separate braking mechanism. In other words, the radial actuators will be used to inject energy into the system and the braking mechanism will be used to take energy from the system. The simulation results are discussed in detail.

2. Proposed mechanism

The proposed setup is similar to a centrifugal mechanism which includes a circular vertical wall as the runway'Fig.1'. An arm carries two aircraft wheels and is rotated by an electric servomotor. For decreasing or even eliminating the shaking forces on the supporting column of the rotating arm, two wheels are symmetrically installed on the arm. The circular velocity of the wheels carrier arm is controlled so that the tangential velocity of the tyres reach the aircraft landing speed. It should be pointed out that due to lack of any time limit in reaching the approach velocity, and also unlimited track or runway length, a low power source could be used to drive the wheels carrier arm. In other words, there is no dead load or equivalent aircraft load to be accelerated, and the wheels carrier arm could be accelerated in a reasonable period (about 5-10 min), like the duration considered in centrifuge mechanisms, especially in structural engineering (Broekman et al., 2020). Therefore, as the acceleration time increases, the required power will decrease. Two radial actuators such as servomotors with a ball screw or power screw mechanism or even a servo hydraulic actuator are installed on the rotating arm and employed to closely control of the wheels in the radial direction. Due to high approach velocity or high centrifugal acceleration of the wheels, only tyre and its rim masses could produce a large share of the pushing or vertical touchdown force. In other words, at the first moment of the touchdown, the centrifugal force is much more than the desired force, and therefore a separate braking system (not shown in Fig. 1) must prevent the increase in displacement and force.

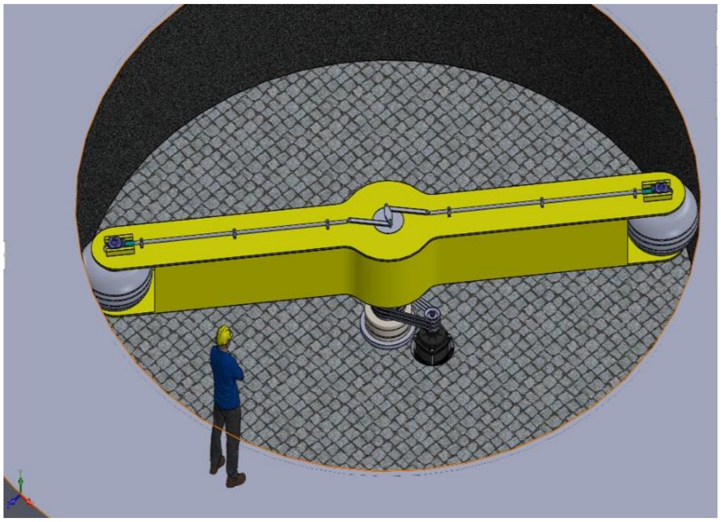

Fig.1 Schematic view of the proposed experimental setup.

3. Test procedure

Before each simulated spin-up run, the artificial runway surface 'vertical wall surface' should be cleaned and its condition of wetness or dryness noted. Employing appropriate water spray mechanism, wet or damp condition of the tyres and the runway surface could be easily simulated during each test. A test starts with rotating the wheel's carrier arm. During a real touch down, the forward velocity and the sink rate of aircraft can be assumed constant. Hence, angular accelerating the arm is not critical while its final angular velocity or tangential velocities of the wheels are important for replicating a realistic landing scenario. Consequently, a low power electrical actuator could be used to drive the carrier arm. A locking mechanism prevent the radial movement or touchdown of the wheels during the acceleration of the arm. The locking system is released when the arm reaches the desired angular velocity or the tangential speed of the wheels reaches the desired landing speed. At that moment, the driving power of the arm is turned off and closely control of the radial actuators and the braking system simultaneously, could control the radial movement of the wheels and consequently their vertical wheel-wall normal load. Some experimental data related to the tyre-runway loads, during the spin-up time, are available in some technical reports (Milwitzky *et al*., 1955). These data or simulation results of the vertical dynamics on a real runway could be used as desired trajectories in control process of the radial actuators and the braking system. To measure the appropriated variables such as drag or tangential load, friction coefficient, wheels angular velocity, tyre surface temperature, and other variables a variety of high frequency or fast time history instrumentation should be employed.

During the tyre spin-up period, the ground drag load depends on the vertical load and the friction coefficient. In addition, the friction coefficient will depend on the slip ratio, tire temperature, inflation pressure, runway texture, and contact path area (Wang et al., 2022). At the same normal load and inflation pressure p_f, the contact path in the proposed system will be higher than that of the flat surface 'Fig.2', which results higher drag load. To compensate this difference, the inflation pressure must increase until the same contact patch area is reached (inflation pressure P_c). Of course, with the same contact path area, the higher inflation pressure will produce lower drag load. Hence, again, the pressure should be slightly reduced to reach an almost equal drag force (p_f <p< P_c). However, tuning of these parameters should be done experimentally. Therefore, a compromise should be made between the path curvature, the induced error, and the cost of the experimental setup. Nevertheless, as the radius of the test path increases, the test results get closer to a real landing.

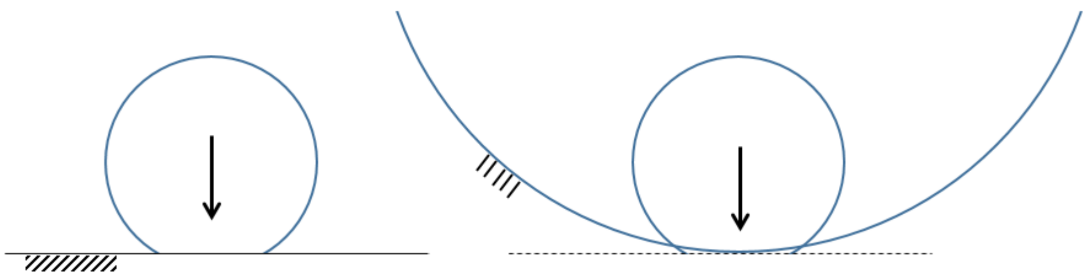

Fig.2 Schematic of a tyre interacted with flat and circular path.

4. Case study and discussion

As a case study, the spin-up dynamics of Boeing 747 with specifications depicted in Table 1 is considered to simulate in the proposed experimental setup.

Table 1. System parameters and spin-up conditions (Alroqi *et al*., 2017)

Properties	Values
Tyre diameter, d	1244.6 (mm)
Aircraft mass on each tyre, m_a	17×10^3 (kg)
Tyre and its rim mass, m_t	185 (kg)
Landing speed, V	75 (m/s)
Sink rate, V_s	2 (m/s)
Suspension stiffness associated each wheel, k_s	3.12×10^5 (N/m)
Radial Stiffness of each tyre, k_t	1.7×10^6 (N/m)
Suspension damping of each wheel, c_s	3.42×10^5 (N.s/m)
Suspension damping of each wheel, c_t	175 (N.s/m)

At first step, the vertical dynamics of the aircraft and its wheel center fluctuations should be identified on a real runway. A two DOF mass-spring-damper system depicted in Fig. 3 could be used to simulate the vertical dynamics (Padovan, 1991).

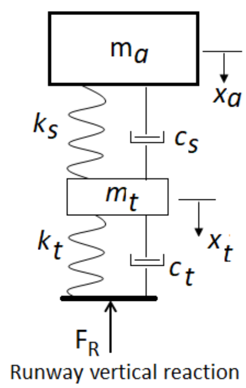

Fig. 3 Vertical suspension model of the aircraft.

During touchdown, the pilot interaction balances the aerodynamic lift and weight of the aircraft and consequently the touchdown takes with constant vertical velocity or sink rate (Padovan, 1991). As soon as the spin-up is finished, the spoilers are deployed and the weight of the aircraft is gradually transferred to the wheels (Mahjouri et al., 2022). Therefore, the governing vertical tyre-suspension-aircraft equations take the following form

$$m_a\ddot{x}_a + k_s(x_a - x_t) + c_s(\dot{x}_a - \dot{x}_t) = \beta m_a g \quad (1)$$

$$m_t\ddot{x}_t - k_s(x_a - x_t) - c_s(\dot{x}_a - \dot{x}_t) + k_t x_t + c_t \dot{x}_t = \beta m_t g$$

where m_a represents the aircraft mass share on each tyre, m_t is the mass of a tyre and its rim, k_s is the stiffness of landing gear suspension associated to each wheel, k_t is the tyre stiffness, c_s is the damping coefficient of the landing gear's shock absorber, and c_t is the damping coefficient of each tyre. In Eq. (1), transferring of the aircraft weight over the wheels is depicted as β where its value is zero during the spin-up time, and it will be one during the rollout and breaking phases where the weight of the aircraft is completely transferred to the wheels. Of course, according to the dynamics of the spoilers and aerodynamic response of the aircraft, it can be assumed that the value of β will change linearly during the transition phase. The aircraft and tyre displacements x_a and x_t are initialized with a value of zero at the touchdown moment and their velocities are initialized with the vertical velocity of the aircraft or sink rate ($\dot{x}_a(0) = \dot{x}_t(0) = V_s$). Solving Eq.(1) for x_a and x_t, using the mentioned initial conditions, would give a solution that could be used as the command value in the proposed experimental setup.

It is worth noting that by using the variable or even average constant coefficient of friction (between 0.3 and 0.7) and calculating the angular velocity of the wheel, it can be found that the spin-up time will be about 0.15 (Padovan *et al*. 1991; Alroqi *et al*., 2017; Milwitzky *et al*. 1955) and maximum value of the tyre deflection and vertical runway-tyre load will occur during the spin-up phase. According to the data in Table1 and linear variation of $0< \beta <1$ in the time interval $0.15<t<0.2$ seconds, the wheel center and aircraft body displacements are shown in Fig. 4. It can be seen that the maximum deformation of the tyre '0.14*m*' happened in the spin-up phase and it finally converges to its static value '0.1 *m*'. The displacement of the aircraft body tends to its final value '0.6 *m*' after a local overshoot '0.23 *m*' in the spin-up phase.

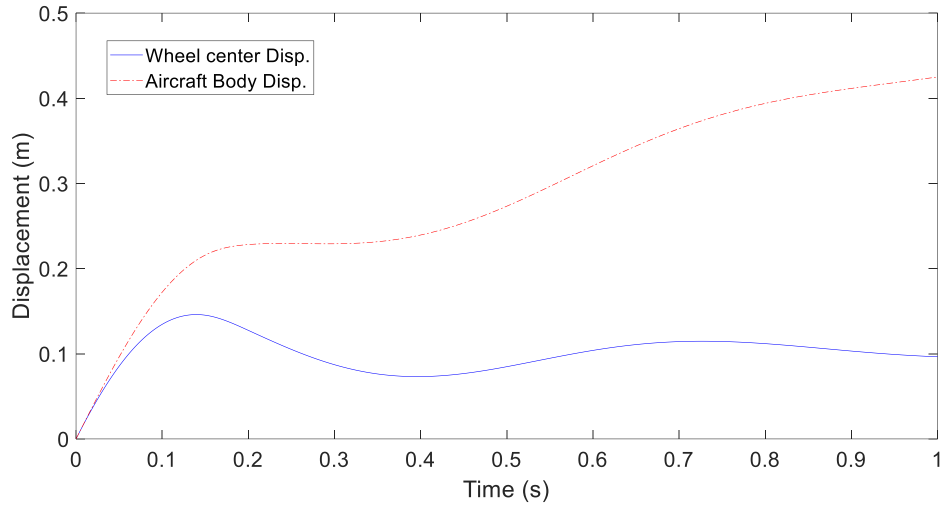

Fig. 4 Variations of the wheel center and aircraft body displacements.

Fig. 5 depicts the variation of the runway vertical force. It is revealed that, due to presence of the sink rate, the maximum values of the vertical force '250 KN' in spin-up time is much more than its static value '170 KN'.

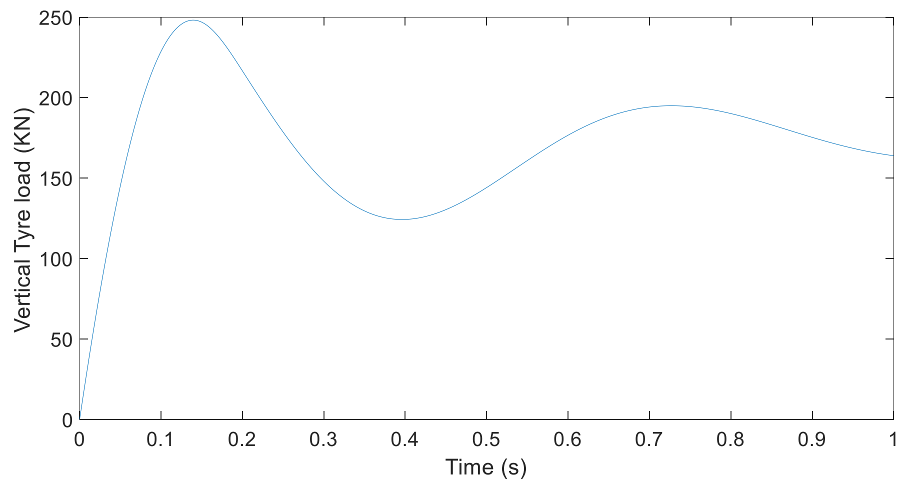

Fig. 5 Variations of the vertical ground force versus time.

During the landing simulation, in addition the desired sink rate 2*m/s*, the wheel center displacement x_t (Fig.4) and consequently the vertical tyre load (Fig.5) should be extracted. In the proposed mechanism the aircraft mass is not present and the wheel center displacement and the reaction force should be produced by the centrifugal force and closely controlled of the radial actuators and the braking mechanism. Assuming horizontal touchdown speed as 75 *m/s* and the path radius as 5 meters, the circular velocity of the arm should be 15 *rad/s* before touchdown. Hence, considering tyre radius as 0.622 *m*, the radial acceleration at the center of the wheels will be about 1000 m/s^2. Therefore, the desired radial force F_r and the associated required power P_r could be calculated as

$$F_r = m_t(\ddot{r} - r\omega^2) + k_t x_t + c_t \dot{x}_t$$
$$P_r = F_r \dot{r} \tag{2}$$

In Eq. (2), the values of $\ddot{r}$ and $\dot{r}$ should be replaced by $\ddot{x}_t$ and $\dot{x}_t$, respectively. In addition, the value of r is replaced by ($\underline{R}+x_t$) where R is the radial wheel center location. Considering the assumed path radius as R=4.38 *m* and substituting the simulation results in Eq. (2) leads the desired radial force, which is depicted in Fig. 6. It is clear that as soon as the test starts, a negative radial force about 175 *KN* and an overshoot about 50 *KN* will be needed during the spin-up phase. In the steady state or rollout phase, a negative force about 15 *KN* should also be maintained in the radial direction.

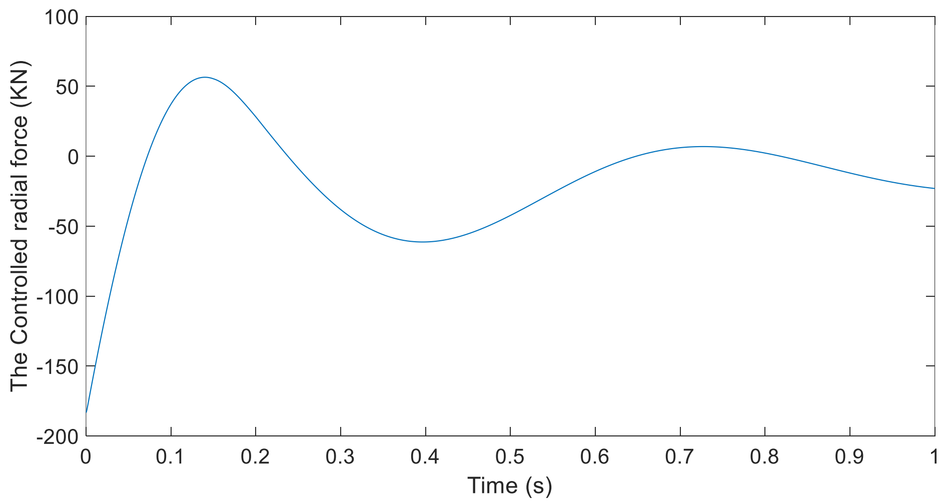

Fig.6 Desired radial force should be replicated by the proposed setup.

According to the value and sign of the required radial force, as well the direction and value of the radial velocity, the required power is calculated and shown in Fig.7. The required negative power is related to the braking power and positive values of the power is related to condition that the radial actuator should inject some power into the system. It can be seen that the maximum power of braking or taking energy from the system 'about 350 *KW*' is much more than the power that the actuator must inject into the system 'about 21 *KW*'. In other words, at the start of the test the braking system should be closely controlled so as to prevent excessive radial touchdown force and produce the desired wheel center time history and sink rate. Of course, in some specific time intervals during the spin-up phase, there may be a need to inject some power to the system by the radial actuators 'positive power cases'. It is clear that installing a 21 KW actuator in the radial direction would be reasonable and feasible in practice. At the same time, a more braking power could be created alike such as done in automotive industry.

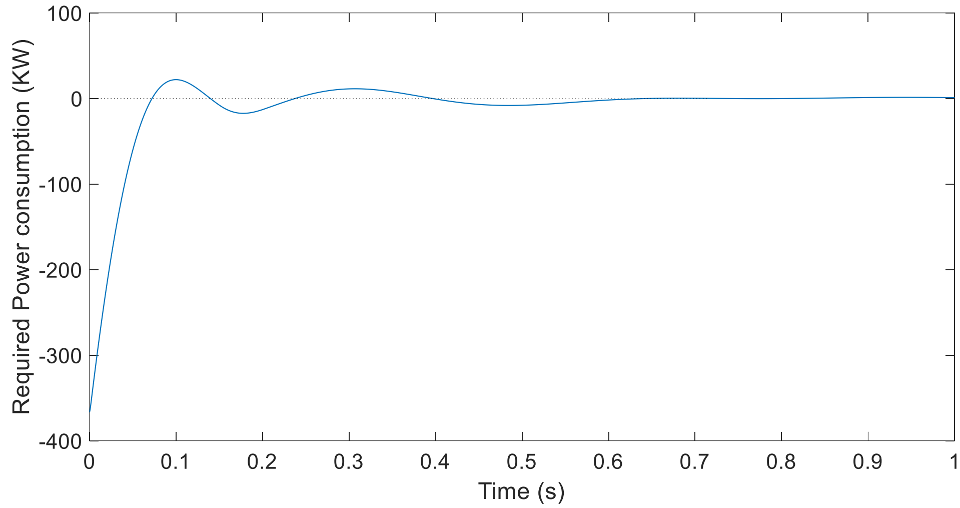

Fig. 7 Required power consumption to produce desired wheel center displacement.

It is important to note that adding some masses to the tyres, mounted on the rotating arm, can affect the braking and actuating capacity. The required power for different tyre mass values are shown in Fig.8. It reveals that by increasing the tyre mass to 200 kg, the required power of the actuator can be reduced to about 15 *KW*. However, by more increasing the mass of the tyre (220 or 250 kg), it can be seen that the required power of the actuator increases again and time of its use is moved out of the spin-up phase.

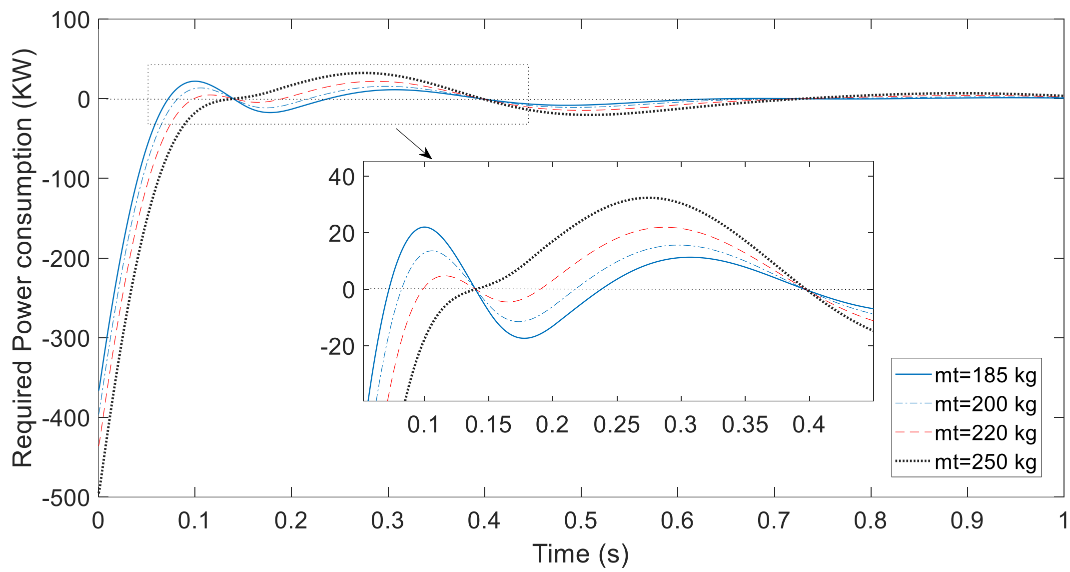

Fig. 8 Variation of the required power for different values of the tyre mass values.

By simulating the wheel center displacement time history and utilizing the axle load- deflection curve of the aircraft wheel (Moravec *et al*., 1989), the vertical force between the tyres and the curved runway can be obtained. This vertical load could be measured and compared with the present experimental results (Daugherty and Stubbs, 1988). In addition, the drag or horizontal load (circumferential load in the proposed setup) and consequently the friction coefficient could also be measured in the proposed experimental setup.

It should be noted that the extremely high-power consumption and long track in the conventional experiments were due to the equivalent aircraft mass and the very limited time to reach the desired approach velocity (Trafford and Glenn, 1965b). However, in the proposed system, which is very close to the centrifuges employed in the geotechnical engineering, a much smaller space (a circular path with a diameter of up to 10 meters) is required. In addition, by creating and angular velocity of about 150 rpm, it is possible to reach a centrifugal acceleration of about 100g. Hence, considering a wheel mass, the appropriate impact or touchdown loads can be created. Therefore, according to the rotary inertia of the wheels carrier arm, a power source up to 100 Kw can bring the system to the desired velocity in about 5 minutes, which is much less than the power employed in the conventional systems.

It is important to note that the proposed setup could also be used to simulated the rollout process (Liang *et al*., 2022). In that situation, other requirements or conditions should be considered. For instance, the rotary kinetic energy of the rotating elements must be equivalent to the linear kinetic energy of the aircraft, which is related to the two tyres in the experimental setup.

5. Conclusions

The tyre spin-up phase is the most critical transition in the landing process. This transition takes place very roughly and produces large ground-impact loads. Magnitude and variation of the vertical and drag loads developed during tyre spin-up immediately following initial touchdown are very important factors governing the design of aircraft and landing gear mechanism. Some valuable and high cost spin-up dynamic tests have been done in a straight path in Langely Research center. This paper proposed a centrifugal based mechanism to simulate the tyre spin-up dynamics. The proposed system included a rotating arm that carries two wheels of the tested aircraft. It was shown that the wheel center displacement or vertical tyre-runway load could be generated by simultaneously control of two radial actuators and a separate braking mechanism. Spin-up dynamics of Boeing 747 was considered as a case study and test procedure of it was discussed in detail. It is revealed that

- In comparison with straight path drop tests, the proposed setup requires a limited space and is subsequently cost effective.
- The desired approach velocity could be produced with a low power source.
- The desired sink rate, wheel center displacement, and tyre vertical load could be produced with simultaneously control of two radial actuators and a separate braking system.
- Wet condition of the runway can be created with a simple procedure.
- As the radius of the test path increases, the test results get closer to a real landing. Hence, a compromise should be made between the path curvature, the induced error, and the cost of the experimental setup.
- After completing each test, there is no need to use any braking system to quickly stop the rotating arm.
- Due to the relatively long acceleration time and no requirement to rapidly stop the system after completing each test, the safety of the proposed system will be better.
- Unlike drop tests, the proposed system can be used to perform wheel fatigue or endurance limit tests.

It is also noteworthy that with equating the kinetic energy of the rotating elements and linear kinetic energy of aircraft associated to two wheels, the proposed mechanism can also be used to simulate the rollout process (breaking and taxing phases). Finally, it is important to note that in constructing a real experimental setup, details of the system, including braking and actuating mechanisms, as well as their control procedures, should be clarified.

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