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EXPERIMENTAL ANALYSIS OF ULTRALIGHT AIRCRAFT TYRE BEHAVIOUR UNDER AIRCRAFT LANDING PHASE

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Abstract. The aim of the research described in this paper is analysis of the deformation of the aircraft tyre subjected to static load. Based on the results of experimental tests with a different value of inflation pressure, favorable pressure conditions for use in the tyre of an ultralight aircraft were determined. The deflection characteristics of the tyre depending on the nominal pressure was determined using the digital image correlation technique. In the range of loads not leading to excessive tyre deflection, quite linear relation between vertical deflection and vertical force is observed. The safe minimum pressure in tyre loaded with a force of 12 kN is 2.5 bar. The experimental results will be used to select a shock absorber for a 600 kg ultralight, light sport aircraft commercialised by the company Ekolot (Krosno, Poland).

Keywords: digital image correlation, landing impact, light sport aircraft, tyre, tyre deflection, touchdown.

Introduction

The landing gear of the aircraft is an extremely important element of its structure, which is mainly aimed at minimizing the impact of dynamic load on the airframe structure during touchdown. Suitable design of the landing gear requires consideration of many factors, not only related to the mass of the aircraft, but also the conditions under which it operates. The landing gear operating conditions include the quality of the landing strip and the overloads that may occur during landing. The proper selection of landing gear parameters is important both for operational reasons and for the comfort of pilots and passengers (Currey, 1988; Biot & Bisplinghoff, 1944).

The landing gear of an airplane is in direct contact with the ground during parking and taxiing. It is also the part of the aircraft that carries all ground forces during take-off run and touchdown. Therefore, it must meet a number of requirements (Temple, 1945; Franz, 1937). The undercarriage have to ensure sufficient stability of the airplane and directional maneuverability. It should also prevent an aircraft from overturning during braking. In the latter case, a phenomenon called turnover may occur, which is a common cause of accidents during landing of ultralight planes (Daughetee, 1974).

A number of researchers have dealt with the problem of loads affecting the aircraft structure during landing (Flugge, 1952; Ghiringhelli, 2000). Dubey et al. (2015) provided an overview of a simple landing-gear structures with energy absorb systems. The authors also presented the results of finite element-based numerical modeling of the load of a landing system. Hać and From (2008) simulated a nose wheel landing gear mechanism of a light airplane. Results show that the finite element model can be used for analysis of dynamics and kinematics of landing gear. Arif et al. (2018) studied an innovative light aircraft landing gear with brush tyre. The numerical model of the undercarriage was verified on the basis of the drop test results. Alroqi and Wang (2015) investigated landing impact of an aircraft using physical model of a single wheel. The principal aim of this study was to analyze the tyre wear at the instant of touchdown. Chester (2000) investigated aircraft landing impact with emphasis on nose gear landing. It was found that vertical load is linearly dependent on the sinking speed. However, there is variation in kinetic energy absorbed. The influence of aircraft weight on the tyre behaviour during aircraft landing phase was investigated by Essienubong et al. (2018). The authors concluded that overloaded airplanes may negatively affect the aircraft tyre

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during the landing phase of the aircraft in terms of stress deformations and build up.

The analysis of the properties of aircraft landing gear and design conditions resulting from operational processes of aircrafts has been carried out by Conway (1958) and Currey (1988). A comprehensive analysis of the dynamic loads acting on the aircraft structure during both touchdown and taxiing was analyzed by Flugge (1952). Milwitzky and Cook (1953) presented the analytical dynamic analysis of the hydro-pneumatic undercarriage during landing. Due to various landing conditions and different conditions of the aircraft structure load, active (Luong et al., 2020; Yazici & Sever, 2018) or semi-active (Wu et al., 2007; Batterbee et al., 2007a, 2007b) suspensions are widely used. Currently, intensive investigations are carried out on systems with a controlled damping force using magnetorheological fluids, which may be an effective alternative to traditional passive damping systems (Lee et al., 2009).

This article presents the results of experimental tests aimed at determining the behaviour of an ultralight aircraft tyre. The test results were useful in the process of designing the landing gear of 600 kg ultralight aircraft, including the selection of shock absorber properties.

The test results will be used in the process of designing the main landing gear of the aircraft, including the selection of shock absorber properties. The precise characteristics of the tyre at different operating pressures are to enable the proper selection of damping parameters by the shock absorber so that it can adequately absorb kinetic energy during landing in the range of tyre pressures that may occur during operation.

Therefore, the results of the tests described in the paper will be used only for the design of the future landing gear, while for its production, destructive static and dynamic tests will be carried out.

The issue was carried out in terms of the currently implemented ultra-light aircraft (Figure 1) commercialised by the company Ekolot (Krosno, Poland).

Figure 1. 600 kg ultralight, light sport aircraft with retractable undercarriage

1. Materials and methods

Ultralight aircrafts are subjected to much less restrictive aviation regulations than commercial aircrafts weighing more than 600 kg. The specificity of non-commercial aviation entails a great deal of freedom in the operation of airframes. These airplanes can be operated over a wide range of tyre pressure. Hence, the research described in the paper focuses on the tyre's characteristics depending on the nominal pressure. A typical dynamic model of an aircraft landing gear is shown in Figure 2. The landing gear consists of undercarriage legs, a shock absorber with a specific spring constant k_1 and damping coefficient c, and a wheel whose tyre is characterized by the spring constant k_2.

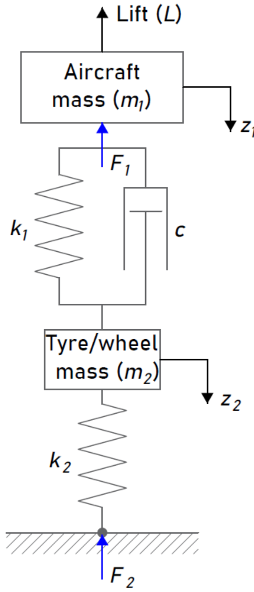


Figure 2. Typical dynamic model of the main aircraft landing gear

In order to properly select the parameters of the landing gear shock absorption, it is necessary to determine the values of the forces acting on the landing gear leg. It is also important to determine the value of tyre deflection under the influence of the maximum forces that may occur during landing. Due to the cooperation of two elastic elements (tyre and shock absorber) working in series arrangement, two forces should be considered in this analysis.

The first one is the force F_1 acting on the structure of the aircraft in the place where the landing gear is attached. The value of this force depends on the mass of the airplane and the aerodynamic lift, and the degree of damping and springback of the shock absorber. The second of considered force F_2 is the value of the pressure force acting on the ground, which is additionally related to the deflection of the tyre. Values of these forces may be determined from the formula (Sivakumar & Haran, 2015):

$$F_1 = m_1\ddot{z}_1 = (m_1 g - L) - F_{k1} - F_c; \quad (1)$$

$$F_{k1} = k_1 z; \quad (2)$$

$$F_c = c\dot{z}; \quad (3)$$

$$z = z_1 - z_2; \quad (4)$$

$$m_1\ddot{z}_1 + k_1(z_1 - z_2) + c(\dot{z}_1 - \dot{z}_2) = m_1 g - L; \quad (5)$$

$$F_2 = m_2\ddot{z}_2 = F_{k1} + F_c - F_{k2}; \quad (6)$$

$$m_2\ddot{z}_2 = k_1 z + c\dot{z} - k_2 z_2; \quad (7)$$

$$m_2\ddot{z}_2 = k_1(z_1 - z_2) + c(\dot{z}_1 - \dot{z}_2) - k_2 z_2, \quad (8)$$

where: c is shock absorber damping coefficient, F_1 is the force acting on the airplane structure at the landing gear attachment, F_2 is ground reaction force (tyre load), g is gravity, k_1 is shock absorber spring constant, k_2 is tyre spring constant, L is lift force acting on aircraft, m_1 is aircraft mass per landing gear, m_2 is sum of wheel, tyre, rim and axle mass, z_1 is vertical displacement of aircraft, z_2 is vertical displacement of wheel.

This work focuses on determining the deflection characteristics of the tyre 400×6' MITAS (14x4) 6 Ply, depending on the nominal pressure and vertical load. The parameters of tyre analysed are as follows: diameter 340 mm, width 110 mm, max. speed 120 km/h, load capacity 300 kg, max. pressure 4.25 bar, number of plies 6, weight 1.28 kg.

Figure 3 shows the stand used in the static tests in the Zwick/Roell Z100 testing machine. A three-dimensional Digital Image Correlation (DIC) system Aramis® (GOM, a Zeiss Company) was used to continuously measure tyre deformation during the tests. The tyre surface was covered with white, matt varnish, and then graphite measuring points were applied to the tyre surface. The tyre was subjected to static loads with the force F_2 up to a value of 12 kN. The guidelines of the Polish Civil Aviation Authority regarding the design of ultralight aircraft impose that when designing the main landing gear, it should be assumed that the load should correspond to the overload of 4G, hence, with the mass of the plane equal to 600 kg, there is 1200 kg per one wheel of the main landing gear. However, with lower tyre pressures, the maximum load was reduced to avoid damaging the wheel rim. The tests were carried out for different values of the pressure p_1 in the tyre in the range between 1.00 and 4.25 bar. The maximum allowable pressure is specified by the tyre manufacturer.

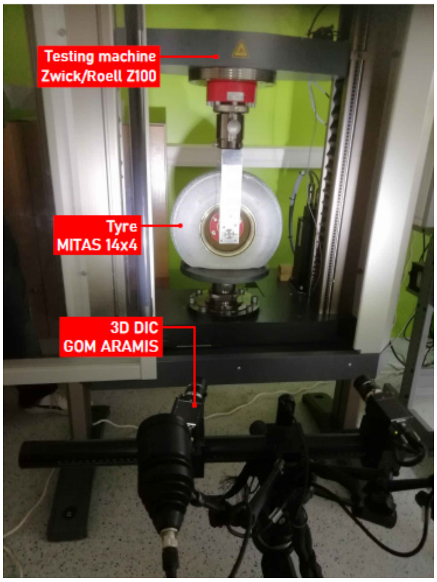


Figure 3. Stand for static aircraft tyre deformation tests

The tests were carried out at room temperature using a constant speed of the force increase equal to v_F = 50 N/s. The rate of vertical force increase was selected in such a way that the maximum value of the compressive force of the tyre was reached after t = 120 s. This time is optimal from the point of view of the accuracy of deformation measurement using DIC system.

Figure 4 presents the values measured during the static tests. Before the test, the tyre was pumped to a specific pressure p_1, and then it was loaded with a linearly increased force to the maximum value F_{2max}. During the tests the tyre deflection was continuously registered. When loaded with the maximum force, the pressure p_2 in the tyre was measured to determine the changes of this value under the load.

The tyre deflection under load is determined by the section $\overline{AC}$. The arc $\widehat{B_1AB_2}$ becomes a tyre footprint when loaded. As the wheel moves over the surface, the ground is created by the friction force $T = \mu F_R$ (μ – coefficient of friction, F_R – reaction force) directed against the direction of the aircraft's movement. From the geometrical conditions shown in Figure 5, the tyre static deflected radius r_t can be determined as the difference between the radius R and the tyre deflection $\overline{AC}$:

$$r_t = R - \overline{AC}. \quad (9)$$

It is well know that:

$$\sin\alpha = \frac{\overline{B_1C}}{R}. \quad (10)$$

To find the value of the angle α, the function in equation (10) should be inverted:

$$\arcsin(\sin\alpha) = \arcsin\left(\frac{\overline{B_1C}}{R}\right). \quad (11)$$

It is well know from trigonometry that $\arcsin(\sin\alpha) = \alpha$ and $\arcsin := \left(sin_{\left[-\frac{\pi}{2},\frac{\pi}{2}\right]}\right)^{-1}$. So eq. (10) can be rewrite as:

$$\alpha = \sin^{-1}\left(\frac{\overline{B_1C}}{R}\right), \quad (12)$$

where:

$$\overline{B_1C} = \sqrt{R^2 - r_t^2}. \quad (13)$$

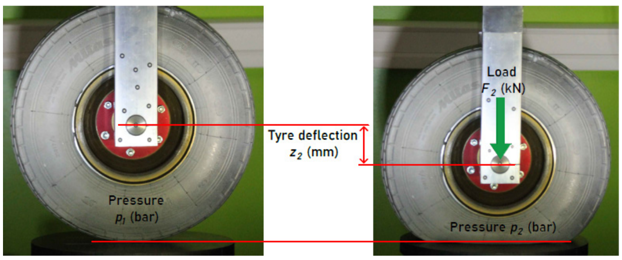


Figure 4. Quantities measured in the unloaded (left) and loaded (right) tyre static load test

Combining (12) with (13) yields the rolling radius r_r of the tyre on the ground surface ($\overline{B_1 B_2}$ in Figure 5):

$$r_r = \frac{\sqrt{R^2 - r_t^2}}{\arcsin \frac{\sqrt{R^2 - r_t^2}}{R}}. \quad (14)$$

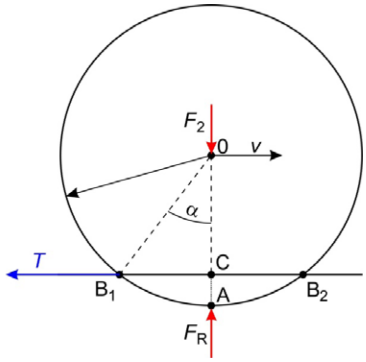


Figure 5. The geometrical parameters of the tyre in contact with ground

2. Results and discussion

For each variant of the tyre pressure value, a continuous measurement of its deformation in three directions was carried out. The results of the deformation measurements for the tyre compression tests at the operating pressure p_1 = 1.0 bar are shown in Figure 6. In the range of loads that do not lead to excessive tyre deflection, a quite linear relation between vertical deflection and vertical force is observed. The values of the greatest deformations of the tyre recorded by the DIC system (Figure 6) are in quantitative and qualitative compliance with the experimental observations.

Figure 7 shows the compression curves for all performed tests with different operating pressures in the tyre. For the pressure p_1 in the range between 2.50 and 4.25 bar, the measurements were carried out for the maximum intended load F_{2max} = 12 kN. However, at the pressure p_1 between 1.0 and 2.0 bar, the tyre deflection was so large and there was a fear for damaging the wheel rim (Figure 8). Therefore, for the pressures p_1 between 1.0 and 2.0 bar the tyre deflection was limited to the value of d_{max} = 77.45 mm.

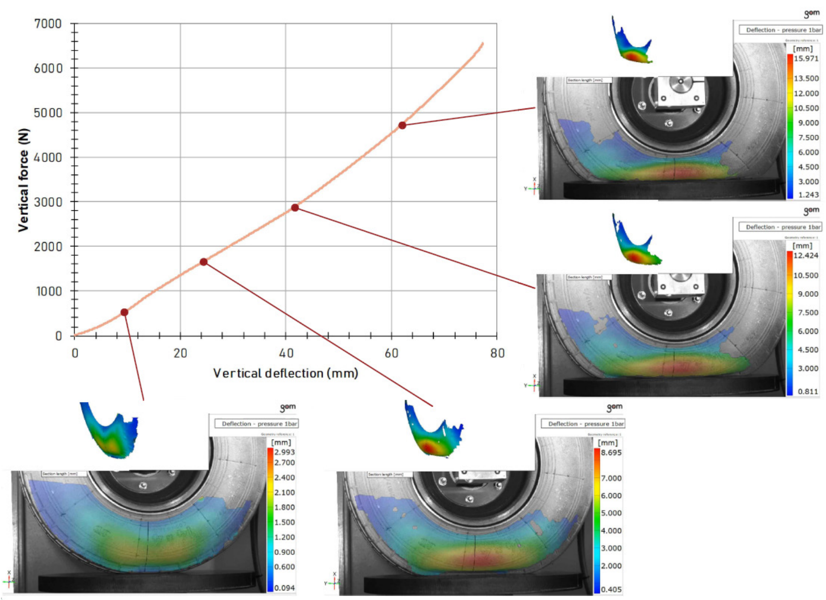


Figure 6. Example results of 3D tyre deformation measurement for the operating pressure p_1 = 1.0 bar

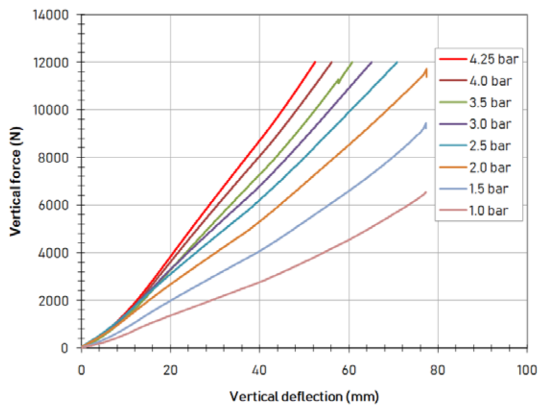


Figure 7. Summary of tyre compression curves for all pressure variants

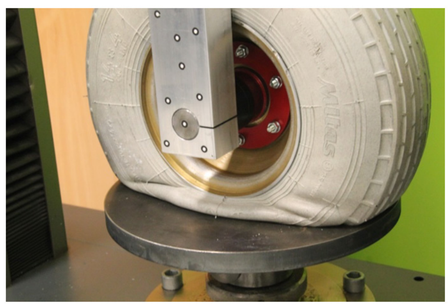


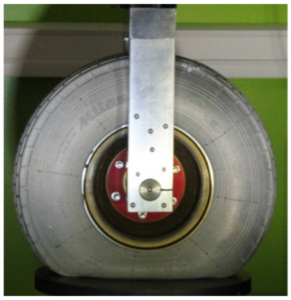
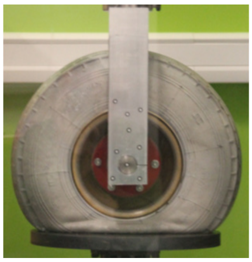
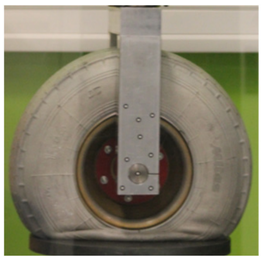
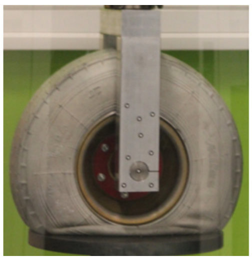
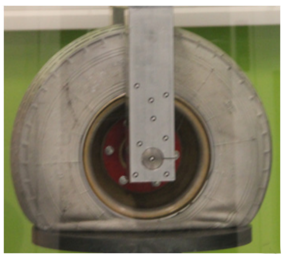
Figure 8. The deflection of the tyre with the value z_2 = 77.45 mm, which was adopted as the limit value of the safe deflection for the rim

The minimum pressure, not causing the risk of damaging the rim when loading the tyre with a force of 12 kN, is 2.5 bar. Increasing the pressure from 2.5 bar to 4 bar reduces vertical deflection of tyre by approximately 26%.

Table 1 shows the results of measurements of tyre deflection and pressure changes under load. The lower the operating pressure p_1, the smaller the increase in pressure p_2 caused by the vertical load. For the tyre inflated with the pressure p_1 = 1.0 bar, an increase in pressure was observed due to the deflection of d_{max} = 77.45 mm by 40%. However, the increase in the pressure p_2 of the tyre inflated with a pressure of p_1 = 2.0 bar is about 45%.

The phenomenon of pressure changes in the tyre is related to the reduction of its volume during compression. Although the rubber from which the tyre is made stretches to some extent, the wire reinforcement of the tyre and the fabric limit the stretching of the rubber material, hence the greater the compression deformation of the tyre, the less its volume, which leads to an increase in pressure. Generally, it should not use less pressure than recommended by the manufacturer, as significant tyre deflection may damage the rim.

Table 1. Airplane tyre load test parameters

Nominal pressure p_1 (bar): 4.25			Nominal pressure p_1 (bar): 4.00		
Pressure p_2 (bar)	4.70		Pressure p_2 (bar)	4.40	
Force F_{2max} (kN)	12.00		Force F_{2max} (kN)	12.00	
Deflection d_{max} (mm)	52.41		Deflection d_{max} (mm)	56.15	
Nominal pressure p_1 (bar): 3.50			Nominal pressure p_1 (bar): 3.00		
Pressure p_2 (bar)	4.00		Pressure p_2 (bar)	3.50	
Force F_{2max} (kN)	12.00		Force F_{2max} (kN)	12.00	
Deflection d_{max} (mm)	60.77		Deflection d_{max} (mm)	65.08	
Nominal pressure p_1 (bar): 2.50			Nominal pressure p_1 (bar): 2.00		
Pressure p_2 (bar)	3.30		Pressure p_2 (bar)	2.90	
Force F_{2max} (kN)	12.00		Force F_{2max} (kN)	11.73	
Deflection d_{max} (mm)	70.82		Deflection d_{max} (mm)	77.45	
Nominal pressure p_1 (bar): 1.50			Nominal pressure p_1 (bar): 1.00		
Pressure p_2 (bar)	2.20		Pressure p_2 (bar)	1.40	
Force F_{2max} (kN)	9.46		Force F_{2max} (kN)	6.53	
Deflection d_{max} (mm)	77.45		Deflection d_{max} (mm)	77.45	

Conclusions

The article presents the results of load tests on a 600 kg ultralight aircraft tyre. It was observed that in the range of loads not leading to excessive tyre deflection, quite linear relation between vertical deflection and vertical force is observed. The research results presented in the paper are a collection of important information that may constitute valuable data in the design of landing gear for light-sport aircraft. It is important that the characteristics of the aircraft tyre at different pressures were presented, which is intended to show the behavior of the landing gear element under various operating conditions. The safe minimum pressure in tyre loaded with a maximum allowable load of 12 kN is 2.5 bar. Depending on the operating pressure in the tyre and the deflection value, the pressure caused by load increased between 10 and about 45%. Future finite element-based numerical modeling of the tyre load may allow to better understanding of the behaviour of the landing gear operated in tyre failure conditions.

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