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Load Factor Measurement in Landing Gear Tests

***Abstract**. In the presented work, author would like to present the physical and legal basis of the load factor in aviation. Possible methods of determining and methods of measuring this factor, which ensure repeatability, the required accuracy and verifiability of this very important measurement. Descriptions, data and methodologies are used during load factor tests in the Structural Test Laboratory on aircraft landing gear test stands, and are accepted by aviation regulatory authorities, both domestic and international.*

***Streszczenie.** W przedstawianej pracy pragnie autor przybliżyć podstawę fizyczną oraz prawną współczynnika obciążeń. Możliwe metody jego wyznaczenia oraz metody pomiaru tego współczynnika, które zapewniają powtarzalność, wymaganą dokładność oraz weryfikowalność tego jakże ważnego pomiaru. Opisy, dane oraz metodyki są stosowane podczas badań współczynnika obciążenia w Laboratorium Badań Konstrukcji na stanowiskach do badań podwozi lotniczych, oraz są zaakceptowane przez lotnicze organy regulujące tak krajowe jak i zagraniczne. (**Pomiar Współczynnika Obciążenia w Badaniach Podwozi Lotniczych**)*

Keywords: load factor, landing gear, laboratory tests, aircraft
Słowa kluczowe: współczynnik obciążenia, podwozie lotnicze, badania laboratoryjne, statek powietrzny

Introduction

Landing gear is one of the most important safety system onboard the aircraft [1]. Their existence is as long as aircraft themselves. In time the arrangement and design of landing gears evolved, in order to exist in current form, which despite number of attempts is more or less the same for 100 years and provide the high level of safety both for passengers and cargo onboard the aircraft. Landing gear is the aircraft system which has several functions. Main function is to provide dissipation of landing energy while controlling/maintain safe loads acting on aircraft fuselage in the desired level of safe values. The other landing gear's functions are [2]: enabling ground manoeuvres, supporting aircraft while on the ground, among many others including ensuring control of the aircraft movement direction during take-off and landing as well as includes brakes for on-the-ground velocity control. Due to their role, the requirements for aircraft landing gear are strictly defined in aviation regulations, which requires performing appropriate simulations and tests to prove the correct operation of the landing gear in accordance with the regulations and design assumptions.

Aircraft landing gears are characterized by a number of parameters necessary to be checked during approval (evidence) tests before national (e.g. ULC in Poland, FAA in the USA) and international (e.g. EASA in EU) aviation regulatory authorities [5]. One of the basic parameters to be examined is the load factor to which the aircraft is subjected during landing. Briefly speaking, in landing conditions, the load factor is the multiplication of the gravitational acceleration "g" to which the aircraft is subjected during touchdown and is a dimensionless factor of load acting on the aircraft structure [3] (fuselage, wings, etc. – locations where the landing gear is installed/mounted in the aircraft). The lower the load factor, the lower the force generated during landing and the smaller the impact of acceleration acting inside the aircraft. The load factor is determined in the design phase of the aircraft based on the methods required by the regulations. Load factor's real value is verified during tests both laboratory and flight. The basic assumption is not to exceed the assumed factor's value. In most aircraft, load factor oscillates around 4, which is considered a safe value for passengers and cargo on board. It is worth to mention that lower load factor equals to the lower mass of the aircraft structure due to the lower forces acting on it and in the result less robust design. Moreover, the maximum safe acceleration g-value for average human is no more than 6 [4].

Due to the importance of the load factor in proving the operation of the landing gear, it must be measured accurately and in accordance with aviation regulations. In special and individual cases, it may be the only parameter measured during the tests.

Determination of Load Factor

The load factor for landing gear is determined in relation to the aircraft's centre of gravity (e.g. CS-23.473 [5]). For aircraft landing gear, local load factors are determined, reduced to the centres of gravity of the landing gear –the main and nose/tail landing gears are treated as independent components whose parameters affect the entire aircraft structure.

The reference load factor is usually determined from the formula:

$$n_{zp} = \frac{E_p}{R_F * x_a} + L \qquad (1)$$

where:

n_{zp} – landing gear load factor; E_p – landing energy dissipated per landing gear; R_F – Load/Force on specific landing gear in relation to nominal weight of the aircraft; x_a – other energy dissipation parameters for landing gear(e.g. deflection of shock absorber, deflection of wheel/tyre), L – dimensionless lift coefficient describing lift force participation in whole load acting on the landing gear (according to the regulations L = 0.667 or 1)

The alternate method of load factor calculation (mostly used when test data is available, in later in paper referred as n_{zFz})

$$n_{zp} = \frac{F_{zmax}}{Q_s} + L \qquad (2)$$

where:

Q_s – aircraft weight; F_{zmax} – maximum vertical force/vertical load from the ground acting on the landing gear; L –lift coefficient (see equation 1)

Measurement of the Load Factor (example)

Load factor can be measured in at least two ways:

- Direct: using accelerometers placed on the landing gear in the centre of gravity

- Indirect: using force transducers that measure the vertical force/ reaction on the ground.

Aviation regulations require the measurement of acceleration [6] as obligatory, which makes the measurement of force an additional data that verifies the measurement of acceleration.

Fig.1. Drop test stand. (source L-Ilot)

Fig.2. Landing gear mounted to the drop test stand. Force measurement plate is visible under the wheel. (dots: see text, source L-Ilot)

Measuring the load factor using acceleration sensors is a complicated task in the conditions of dynamic drop measurements due to its nature. The two most important challenges are interference in the measurement of accelerations and locating the sensor at or as close to the centre of gravity as possible. This proves to be a difficult or impossible task to resolve due to the fact that the landing gear must be tested [7,8] in a flight-analogue configuration (fig. 1.), which usually does not take into account the mounting and positioning of the sensors used in laboratory measurements. In the presented tests (fig. 2.), the accelerometer should be positioned where the yellow dot is but is placed where the red one is due to the tests stand configuration (fig. 3.).

The use of an additional measurement (in this case, force) allows the verification of measurement systems and the selection of appropriate measurement parameters - verification of the sensor position and selection of filtering of the acceleration signal during its processing after testing.

Table 1. Sensors parameters

Nº	Measurement name	Measurement device name	Principle of measurement	Mesurement range
1	Acceleration	MEAS 4810A	Absolute accelerometer (MEMS)	±20 g
2	Vertical Force	Measurement Plate	Strain gauge	max. 100 kN

Please note that for the acceleration measurement absolute/seismic aerometers were used. The reason is that measurement must refer to the earth's acceleration even in stationary or constant velocity conditions. Only absolute/seismic accelerometers can provide this kind of measurement in the contrary to most common vibration non-absolute measurement type accelerometers used e.g. in assessing the unbalances in spinning components as shafts.

Fig.3. Closest possible placement of the accelerometer on the test stand/test interface (in the red circle, source L-Ilot)

Exemplary results

In the figures 4 to 6 there is an example of data acquired in the limit energy/load test performed on the nose landing gear of the 1400 kg small business aircraft I-31P designed by the Lukasiewicz-Institute of Aviation. The results are shown as a representation of the load factor measurement and data analysis process. The presented data is similar for all of the tests performed for the aviation authorities as well as for the landing gear development purposes carried out in the Structures Testing Laboratory of the Lukasiewicz – Institute of Aviation.

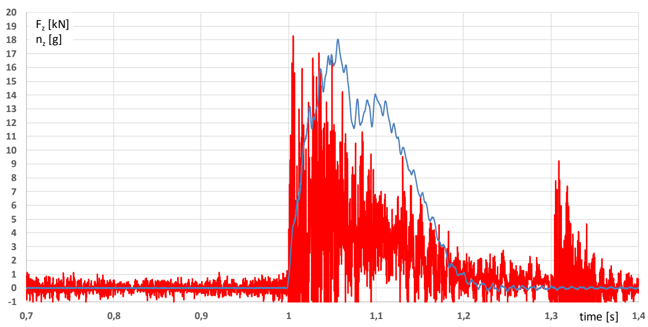

Fig.4. Measured values: vertical force F_z (blue), unfiltered acceleration n_z (red) as raw data for load factor analysis

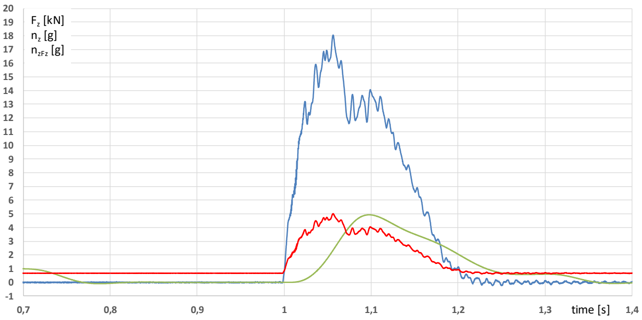

Fig.5. Identity of the waveform: vertical force F_z (blue), filtered acceleration n_z (green), load factor n_{zFz} calculated from the force (red), The graph shows a shift of the filtered signal relative to the force signal by about 200 samples

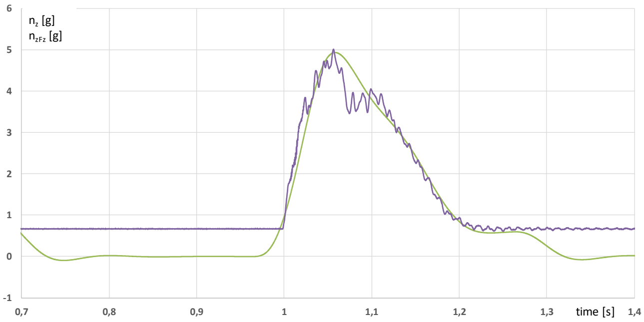

Fig.6. "Equalized" waveforms - filtered acceleration n_z (green), - calculated from the force, load factor n_{zFz} (purple).

The results acceptance limit for both development and certification is 5%. This value is not defined strictly by the regulations but largely accepted the aviation authorities. It can be rarely loosen in individual cases.

The obtained results from this example are satisfactionary - the maximum load factor values for both measurement methods are: n_{zp} = 4.93 n_{zFz} = 5.01, which gives a difference of approximately 1.6%.

In rest of the limit energy tests the range of difference was between 0.2% and 2.1% below agreed 5%.

The dispersion of measurement results is due to the uniqueness of each single test. Both test object and test method are the generally same but because of the wear and overall complexity of the landing gear the results are not 100% the same in every tests case.

Discussion

As a rule, the load factor curve and its value should correspond regardless of the measurement performed (acceleration of force). Using this analogue is customary to perform first “calibration” drop test usually from the low height (speed) in order to assess the response of the measurement system. The results of the both acceleration and force measurement are compared. Acceleration signal is filtered accordingly to the result on force signal. The curves are equalized and drop test is repeated. If the results of equalization are satisfactory (meaning the maximum values and the curve are similar, usually in the range of 5% in maximum value) the full drop test campaign is performed. The results are compared every test in order to be able to catch any differences that may result in e.g. acceleration sensor shift or force plate malfunction.

The data obtained by the force measurement plate can be replaced or completed [9] by the use of load/force measurement devices in the mounting nodes of landing gear. It is necessary to mention that the load/force sensor data must be equalized to the loads from the ground as required by the regulations. The vertical load/force comparison is simplest as it is basically the sum of measurements out of all of the vertical forces acting on landing gear mount is the same as vertical force acting on the plate. For other forces/loads acting on the landing gear (vertical, lateral etc.) the simple measurement of the values is geometry dependent e.g. lateral loads measured on the ground level compared to the loads from mounting nodes would be subjected to the momentums coming from height of the landing gear but not being present in the direct ground measurement. In this case equalization of the results could be tricky since the real geometric data is hard to obtain with high precision. The calculated load can be subjected to the propagating errors coming out of the all consisting measurements. Mounting node force sensors can be in the form of strain gauge equipped pins, bolts or connectors/rods between landing gear and test interface.

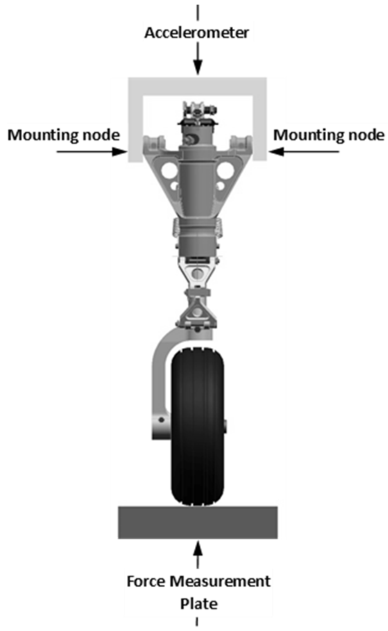

Fig.7. Measurement devices placement example (source L-Ilot)

From the point of view of data processing and the subsequent use of the load factor, the data shift during filtering of the acceleration signal is of little importance. First, because in tests for compliance with aviation regulations, only the maximum value in the landing process and its exact position in time are to be known, and secondly, the filtered signal can be "shifted" by the amount of time (number of samples) resulting from the filter used. Another assumption is that filtered signal maximum value must occur in the first (shown in the figures 3 to 5) stage of the touch down process. The touch down is composed out of several stages (usually 4 to 7) where only first stage is regarded important from landing gear landing efficiency and safety point of view. The whole touch down process can last up to 2 seconds but the most important stage lasts only more or less 0.3 seconds. This stage is the time when the landing gear absorbs all of the landing energy by deflecting maximally and generating highest value of the force (reaction from the earth) acting on the aircraft structure. Since vertical force is analogue to the acceleration – the highest value of the acceleration should be located in the area of maximum force, as well as highest value of the load factor in the result.

As mentioned before the placement of the acceleration sensor is highly dependent on the tests stand configuration and can be quite distant from the desired location which is the landing gear centre of gravity. The result of the measurement has to be adjusted to the centre existent centre of gravity due to the necessity of calculation and experimental data evaluation. One of the methods is described above as calibrating/equalizing the acceleration measurement by using the force signal. This method is simple and efficient but relies on the force measurement and its precision (in this case it is advisable to measure the force with no more than 1% of uncertainty and with high both precision and accuracy). The equalizing method also require the force measurement at all what is not so obvious in some tests although good laboratory has this capability due to the most customers requirement on measuring forces/loads intendedly from the acceleration as a definitive proof of forces acting on aircraft structure.

Second method of acceleration measurement adjusting is analytical method based on the geometrical data provided by the landing gear designer. This method allows to adjust the result by recalculating it due to the differences in actual position of the senor and the theoretical position of the centre of the gravity. This method heavily relies on the good measurements of the relative position of the senor and in most of the cases is very limited in data quality due to the usual “crowdedness” and problems to fit-in the measurement equipment (see: Fig. 1 and 2). In conclusion geometrical method is possible but should be used al last resort due to its limitations.

Summary

The attached sample measurement data shows that the measurement and data processing methodology used proves a good correlation of the measurement of an aircraft operational parameter that is so important - from the point of view of certification and subsequent safe use. The presented methodology is successfully used in development and certification tests at the Structures Testing Laboratory of the Łukasiewicz Research Network - Institute of Aviation, and with its help a number of Polish and foreign aircraft have been implemented for production and subsequent - safe - use.

It is necessary to remember that load factor measurement is hard to be done properly and requires not only the right equipment but it requires lots of expertise and experience of the researchers.

The aim of this paper is to show the load factor measurement techniques accepted by the aviation authorities in Poland, EU, and the USA. The use of both techniques alongside is meant to create redundancy in case of failure or other errors in measurement chain that can affect tests meant to provide crucial information for safety of the aircraft. There are several attempts to improve this process but are now in educational stages and not widely accepted by the authorities. Please refer the REFERENCES [eg. 10, 11, 12, 13, 14, 15] for these approaches not described in this paper due to the formal reasons of both accreditation of the author’s laboratory and authorities acceptance.

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REFERENCES

[1] Currey N.S., Aircraft Landing Gear Design Principles and Practices, *Washington AIAA* (1988)
[2] Schmidt, R. K., Design of Aircraft Landing Gear, Volume 1 & 2, SAE International (2020)
[3] Kowalski W., Kowalski W., Laffite A., Mikulowski G., Remmers L., State of the art in landing gear shock absorbers, *Transactions of the Institute of Aviation*, 181 (2005)
[4] Pierce C., https://www.sciencefocus.com/science/whats-the-maximum-speed-a -human-can-withstand, (2024)
[5] Normal, Utility, Aerobatic and Commuter Aeroplanes CS-23, European Aviation Safety Agency (EASA)
[6] Landing Gear Shock Absorption Testing of Civil Aircraft, *SAE International ARP5644* (2019)
[7] Skorupka Z., Paprzycki I., Laboratoryjne badania podwozi lotniczych, *Transport przemysłowy i maszyny robocze*, Wrocław (2014)
[8] Connecting-the-Dots for Landing Gear Innovation, *Ryerson Aerospace Engineering Centre, Toronto, ON,* (2019)
[9] Skorupka, Z., Laboratory Investigations on Landing Gear Ground Reactions (Load) Measurement, *Journal of KONES* (2017), Vol. 24/ No. 2, 225-2303
[10] Morison D., Neff G., Zahrae M., Aircraft Landing Gear Simulation and Analysis, *Annual Conference, Milwaukee, Wisconsin* (1997), 2.59.1 - 2.59.8
[11] Delprete C., Dagna, A.; Brusa, E., Model-Based Design of Aircraft Landing Gear System, *Appl. Sci.* (2023), No. 13, 11465
[12] Hall A. W., Statistical Study of Normal Load Factor Just Prior to Ground Contact For Five Light Airplanes, *NASA Technical Note D-5767* (1970),
[13] Paletta N., Dmytriv A., Belardo M., Landing Gear Concept and Dynamic Landing Loads of the Unmanned Space re-entry Vehicle USV3, *1st International Conference on Structural Integrity, Procedia Engineering 114* (2015), 38 - 45
[14] Liu W.; Wang Y.; Ji Y., Landing Impact Load Analysis and Validation of a Civil Aircraft Nose Landing Gear, *Aerospace* (2023)
[15] Józwik J., Pytka J., Tofil A., Dynamic Analysis of Aircraft Landing Gear Wheel, *5th IEEE International Workshop on Metrology for AeroSpace* (2018), pp. 462-467