White Paper

Piezoelectric (PE) technology and multicomponent force measurement for landing gear drop testing

Abstract

Aircraft landing gear is one of the most critical subsystems for safety which demands high reliability and performance. Landing gear drop testing is a dynamic test which simulates the aircraft landing impact to qualify the shock absorption system to the operational dynamic loads without failure. During such tests it is common to measure the impact force, acceleration, and displacement for example. Piezoelectric (PE) multi-component force measurement solutions are typically comprised of four, 1 component or 3-component PE force links to comprise a force dynamometer. For drop tests, dynamometers absorb dynamic loads by differential force reactions within the sensor array to accurately measure the dynamic force. PE technology provides advantages of rangability, high overload capacity and high frequency response compared to conventional strain gage technology. PE force dynamometers are inherently stiff with small deflections under high loads providing both long life and operational stability over time compared to strain gage technology. Factory calibration is performed using a multi-component force press with linear actuators, and reference force sensors to measure applied loads and quasi-static charge amplifiers to measure the output for comparison. Insitu checkout is typically performed with static masses and quasistatic measurements. Test stands using PE technology provide added robustness as the measurement range is scalable below the maximum rated range while providing high resolution. As strain gage load platforms are historically used, PE technology solution and application are shown to illustrate the features and benefits that complement the landing gear testing. .

Key Words: landing gear, drop test, piezoelectric dynamometer, design, force plate, multicomponent force measurement, quasi-static and dynamic measurement, finite element analysis, natural frequency, analog bandwidth

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1. Application introduction

The shock absorption test requirements for civil aircraft require landing gear drop testing to validate the limit design landing load factor, and to demonstrate the energy absorption capability for limit and reserve energy levels. This includes validation of the analytical model used to determine the design landing loads to support certification by analysis for landing gear derivatives instead of testing. The analytical model of the landing gear dynamic characteristics is validated by conducting energy absorption tests at the weight (the maximum takeoff weight or maximum landing weight) which provides the maximum impact energy. [2)]

The shock absorption tests use a stationary drop tower as illustrated in Figure 1 and Figure 2, that uses a drop carriage which supports the test fixture and test article and weights to simulate the aircraft weight. Figure 2 shows a typical tower illustration. The carriage moves vertically with minimal friction and reacts to the resulting vertical load, drag and side loads as well as resulting moments. The landing gear is attached to the carriage to accurately simulate the actual geometry and stiffnesses. After release, the carriage may contact the pressurized lift cylinders which simulate aircraft lift prior to contact with the load platform where these cylinders are not used in free drop testing. The load platform has the required frictional coefficient for landing and reacts to the loads created by the tires during the drop test which includes load cells to measure vertical loads, drag, and side loads. Typically, there is one load platform per bogie or sometimes per wheel. The spin-up wheel drag loads are typically simulated by rotation of the wheels in the reverse direction at the required landing speed. The energy absorbed by the landing gear during the drop test is can be determined by numerical integration of the total vertical platform load when in the landing gear is in contact with the load platform. The landing gear must not fail during drop testing.

Fig. 1: iABG drop test platform [1)]

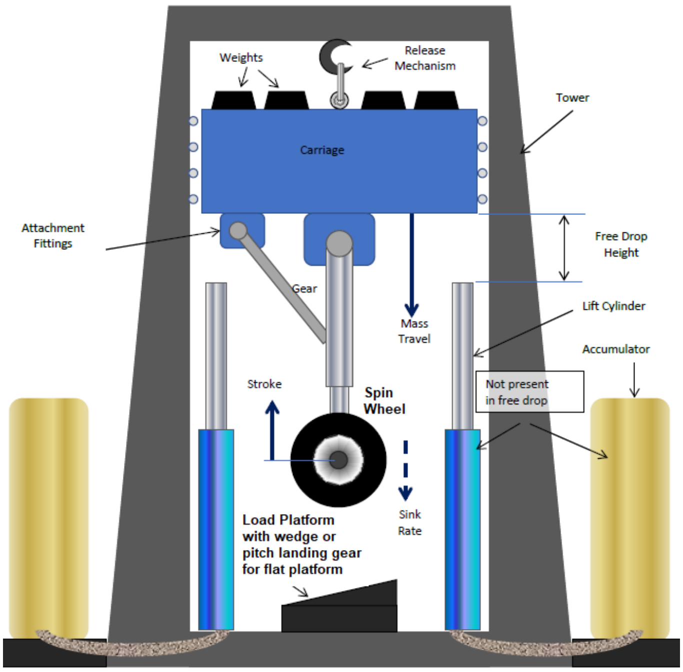


Fig. 2: Adapted schematic drop test tower [2)]

2. Piezoelectric force technology - concept of operation

The PE effect is typically characterized a mechanical force is applied to PE materials producing a proportional electrical charge, PE single crystals such as quartz (SiO2) are often used in PE force sensors. Natural quartz crystals contain too many imperfections to be used in force sensors where use of artificially grown quartz is precision controlled. Artificially grown quartz crystals are grown in autoclaves at a pressure of 1 to 2 kbar (14 to 29 kpsi) and at temperatures between 350 and 400 °C. Large quartz crystal (~1 kg) may take several weeks to grow. Quartz bars are cut to various sizes using ultrasonic techniques and diamond tools. Prior to the cutting, an x-ray goniometer is used to determine the orientation of the major crystal axes to develop cuts. Figure 3 illustrates the quartz material as well as the various cuts of the PE elements such as longitudinal (red) and shear (yellow, blue) which are used in 3-component force sensors.

Important properties of quartz include:
- Quartz crystals act as very stiff, ideal springs
- Very high rigidity (1…62 kN/µm), high linearity and negligible hysteresis
- High mechanical stiffness - high natural frequency - wide frequency range
- Wide operating frequency range – quasi-static to greater than 50 kHz
- Ultrahigh insulation resistance (>1014 Ohms) = low freq. measurements (<1 Hz)
- Very wide dynamic range – typically 1,000,000:1 (in charge mode)
- Temperature resistance up to 350°C (662°F)

Quartz sensitivity stability is demonstrated by nature in that over 1-million-year-old natural quartz has the same pC/N sensitivity with virtually no sensitivity shift over its lifetime.

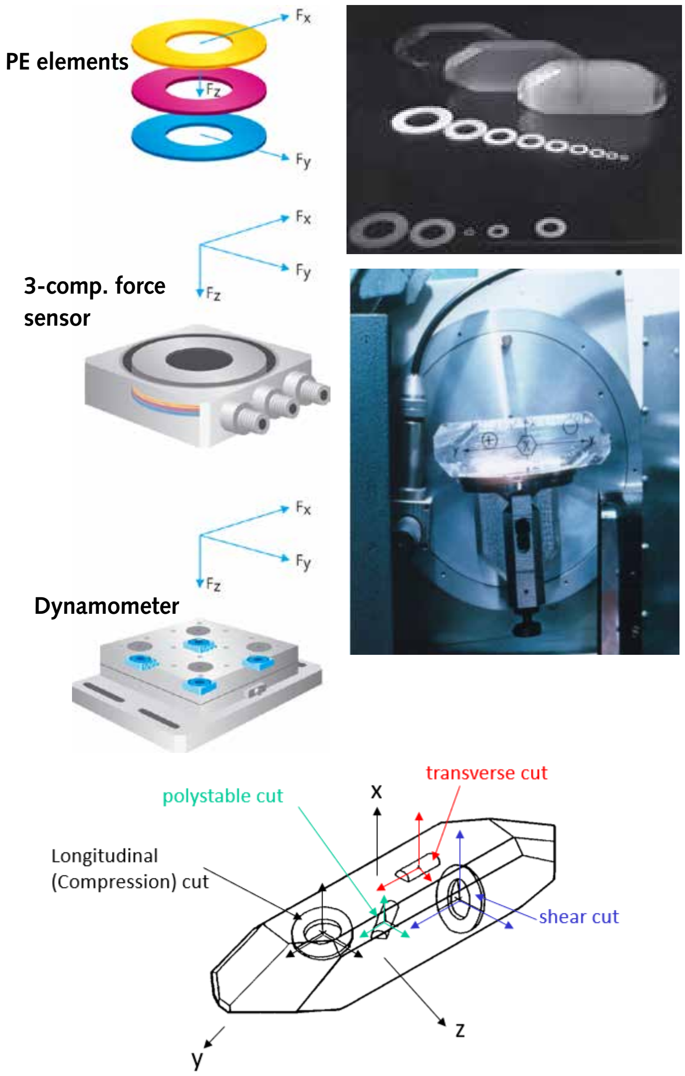
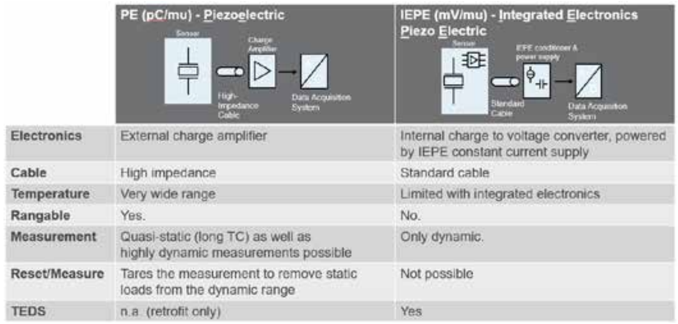


Fig. 3: Illustration of quartz crystal and use in 3-component force sensors and force dynamometers

2.1 Piezoelectric terminology

PE sensors do not have internal electronics and require and external charge amplifier to convert the electrical charge signal to a proportional voltage. An Integrated Electronic Piezoelectric (IEPE) sensor has internal electronics powered by a constant current supply providing a voltage output. A comparison of PE and IEPE properties is shown below in Figure 4.

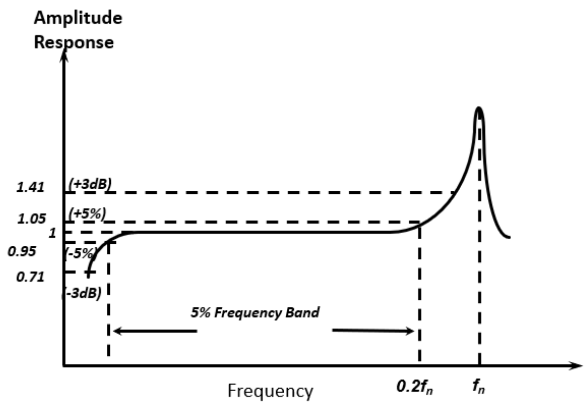


	PE (pC/mu) - Piezoelectric	IEPE (mV/mu) - Integrated Electronics Piezo Electric
Electronics	External charge amplifier	Internal charge to voltage converter, powered by IEPE constant current supply
Cable	High impedance	Standard cable
Temperature	Very wide range	Limited with integrated electronics
Rangable	Yes.	No.
Measurement	Quasi-static (long TC) as well as highly dynamic measurements possible	Only dynamic.
Reset/Measure	Tares the measurement to remove static loads from the dynamic range	Not possible
TEDS	n.a. (retrofit only)	Yes

Fig. 4: Comparison of PE and IEPE piezoelectric sensors types

2.2 Piezoelectric sensor frequency response

PE sensors can be represented as a lightly damped second order system at medium to high frequencies and a single order high pass characteristic at low frequencies as illustrated in Figure 5. PE quartz technology permits quasi-static operation where for long duration impacts the time constant of the charge amplifier is increased to accommodate the measurement event duration where typically the minimum time constant >100x duration of the impact. The 5%, 10% and 3 dB amplitude response is related to the sensor natural frequency by the relationships shown in Figure 5.



Approximation for PE Sensors

$f_{5\%} \sim f_n/5$; $f_{10\%} \sim f_n/3$; $f_{3dB} = f_{+41\%} \sim f_n/2$

Fig. 5: Typical frequency response of a PE sensor

2.3 Quasi-static and dynamic measurement

An external charge amplifier creates a quasistatic and dynamic measuring chain which provides the ability to use a long, medium or short time constant for measurement. The measuring chain also can set to measure/reset which also sets the electrical zero starting point when no applied force is present at the force sensor. For static events or long duration transient events a long time-constant selection can be used to optimize measurements for lower frequency (~0 Hz). For long time constant, the charge amplifier exhibits a small linear drift with time (ex. <0.008 N/sec) but for aircraft landing gear drop testing, the drift is negligible due to the short time duration of the measurement. If the time constant is not high enough for transient impacts (>100x impact duration), there could be an exponential decay of the measured event due to a high pass filter effect. Such quasistatic and dynamic measurement can be used for various signal types as shown in Figure 6 where the proper selection of time constant supports the measurement.

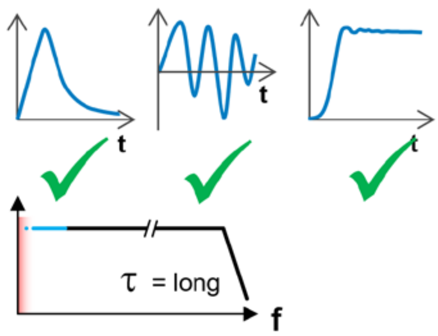


Fig. 6: Signal illustrations supported by PE quasi-static and dynamic measurement

2.4. Piezoelectric measuring chain rangability

The PE measuring is rangable using an external charge amplifier where noise (resolution) scales as a function of selected measuring range. Figure 7 below illustrates an example of the noise (resolution) as a function of selected range. Broadband rms noise is over 10 kHz where for landing gear drop testing the required bandwidths as much lower resulting in a lower rms noise. The rms noise is the integration of the noise power spectral density over the operational frequency range. The Reset/Measure function of the amplifier also permits taring the measuring chain from a static mass acting on it as.

Full Scale Range (FSR = 10V)	Output Scale Factor (N/V)	Broadband Noise rms	Broadband Noise rms
1 N	0.1 N/V	0.0045 Vrms	0.00045 Nrms
25 N	2.5 N/V	0.0012 Vrms	0.003 Nrms
1000 N	100 N/V	0.0006 Vrms	0.06 Nrms
10000 N	1000 N/V	0.0006 Vrms	0.6 Nrms

Fig. 7: PE measuring chain rangability example

3. Strain gage technology- concept of operation

Strain gauge-based sensors include load, pressure, and rotary torque sensors for example. Strain gauge consists of a pattern of resistive foil which is mounted on a backing material. When foil is subjected to stress, the resistance of the foil changes in a defined way using a Wheatstone Bridge which is proportional to the applied force. If these stresses are kept within the elastic limit without permanent deformation, the measuring element is used for a force sensor.

Bonded gauges are strain gauges that are glued to a mechanical structure that is under stress. As stress is applied to the bonded strain gauge, a resistive change takes place and unbalances the Wheatstone Bridge where the resistance changes proportional to the applied force. This measurement method is based on structural flexure of the sensor to change the bridge resistance.

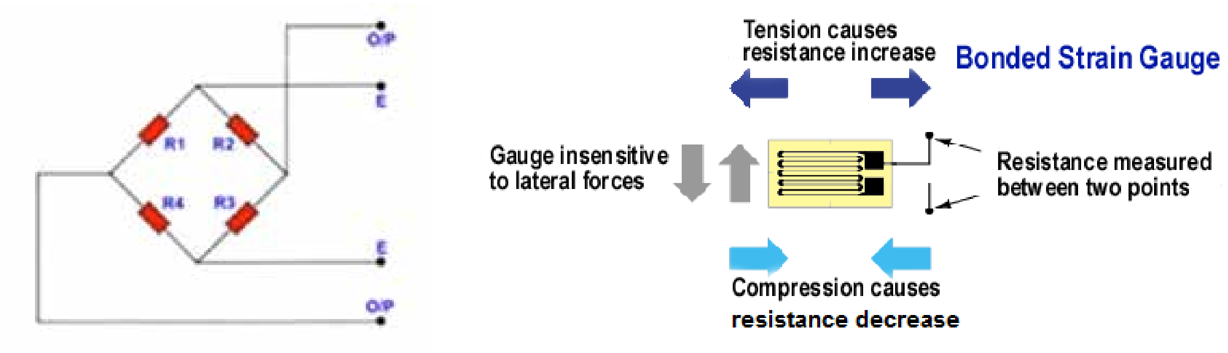


Fig. 8: Foil strain gage and wheatstone bridge

4. Piezoelectric and strain gage comparison

Figure 9 shows a general comparison between PE and strain gage force measurement technologies. Strain gage is an optimum measurement for static forces where PE is optimum for dynamic forces. The fundamental stiffness of the PE technology provides high natural frequencies and faster response times. This is especially important with mass acting on the sensor where the test article mass at impact would also act to reduce natural frequency. For example, landing gear drop test impact durations in vertical can be relatively long (ex. 100-200 msec) but shear components are relatively short (ex. 20-50 msec) where the required analog bandwidth is on the order <50 Hz. The PE sensors allow users to build 6 degrees of freedom test stands that are rigid and offer a fast response time as well as being a simple bolt together design without the complicated use of flexures or linkages.

The adaptivity of the test stand is often a consideration for test laboratories providing services over the several landing gear assemblies. In this regard, PE force sensors are rangable with an external charge amplifier where the measurement resolution is related to the "selected range" of interest. The measurement noise is scaled as a function of noise voltage as previously illustrated. Conversely, strain gage can offer external amplification gains which reduces the measuring range due to electrical saturation, but the resolution is still related to the "full scale range" of the force plate.

Main characteristics of force sensors0.	Piezoelectric (PE) 		Strain Gauge (SG) 	
Static measurements	✓	Quasi-static force measurement/Drift	✓	Ideally for static force measurements
High dynamic measurements	✓	Very stiff, ideal for dynamic meas.	✓	Limited due to stiffness.
Wide measuring range	✓	Range 1:1,000,000 Rangable with C/A	✓	Range 1:10,000 Not Rangable
Measure small forces at high initial load	✓	C/A "Tares" initial load to optimize on low level	✓	initial load + small Forces- Lower Resolution
Small sensor dimensions	✓	Sensitivity, threshold and resolution indep.of the sensor range/size	✓	Different sensors sizes have different performance
Cycle lifetime	✓	Solid state, no glued bonding used	✓	Fatigue/Creep effects possible
Overload	✓	Typically 20%-50% overload possible	✓	higher range for overload – lower Resolution
Temperature effects	✓	Preloading makes temp compensation difficult	✓	Very good temp compensation possible
Operation at high temperatures	✓	-196°C to +200°C	✓	-269°C to +250 °C Chrome Nickel/Polymide
Harsh cable environment	✓	High insulation cabling needed.. Durable	✓	No need for high insulation cables
Accuracy	✓	Typically 0.1%...1% FSO	✓	Typically 0.01%...1% FSO

Fig. 9: Comparison table of PE and Strain gage technology

5. Piezoelectric force dynamometer design measurement

Off-center forces applied to an individual force sensor creates moment loads that, at best, degrade accuracy and, at worst, can break the sensor. A PE force dynamometer is comprised of an array of force sensors mounted between thick metal plates. Force dynamometers absorb non-axial loads and distribute moment loads by differential force reactions within the force sensor array and can be of various shapes and sizes square, triangular, rectangular, circular. A PE force dynamometer measures the magnitude and direction of Fx, Fy, Fz acting on the dynamometer – but not their spatial location on the top plate.

Typically, four force sensors are used between two parallel plates to calculate the 6 components forces and moments. A typical dynamometer geometry is shown in Figure. As shown a, b is the vertical and horizontal separation relative to the force sensor center to dynamometer center line respectively.

$$F_x = F_{x1+2} + F_{x3+4} \quad (1)$$
$$F_y = F_{y1+4} + F_{y2+3} \quad (2)$$
$$F_z = F_{z1} + F_{z2} + F_{z3} + F_{z4} \quad (3)$$
$$M_x = b * (F_{z1} + F_{z2} - F_{z3} - F_{z4}) \quad (4)$$
$$M_y = a * (-F_{z1} + F_{z2} + F_{z3} - F_{z4}) \quad (5)$$
$$M_z = b * (F_{x1+2} + F_{x3+4}) + a * (F_{y1+4} - F_{y2+3}) \quad (6)$$

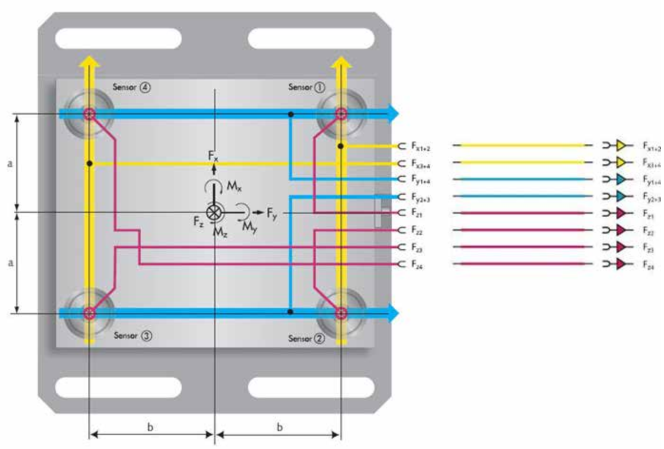


Fig. 10: Dynamometer geometry with 4x 3-component force sensors resulting in 6-component equations for Fx, Fy, Fz, Mz, My, Mz

A PE dynamometer can be represented as a simple spring mass model consisting of
- Base plate
- Top plate with mass m
- Spring with stiffness kf
- Damper with damping coefficient

PE sensors and dynamometers usually have a very low damping 0 < D < 0.01. The natural frequency is an important factor for landing gear especially in shear direction. The quartz plate sensing elements for the 3-component sensor have a large cross section resulting in a very high stiffness supporting high frequency measurement. Even with an additional mass, the natural frequency of a PE dynamometer remains high due to the equivalent stiffness. The dynamometer has the same behavior to a lightly damped 2nd order system as shown in Figure 11 and Figure 12. Added mass acts to reduce the natural frequency as illustrated.

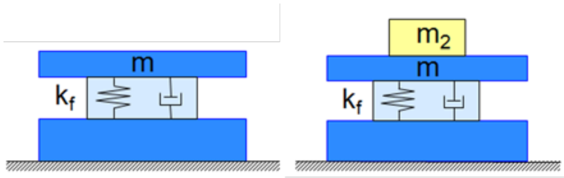


Fig. 11: Spring mass model of PE dynamometer

$$f_r = \frac{1}{2\pi} \cdot \sqrt{\frac{k_f}{m}} \quad (7)$$

$$f_{r,red} = \frac{1}{2\pi} \cdot \sqrt{\frac{k_f}{m + m_2}} \quad (8)$$

m: mass of top plate
m_2: added mass
k_f: stiffness of spring
$f_{r,red}$: reduced resonance frequency

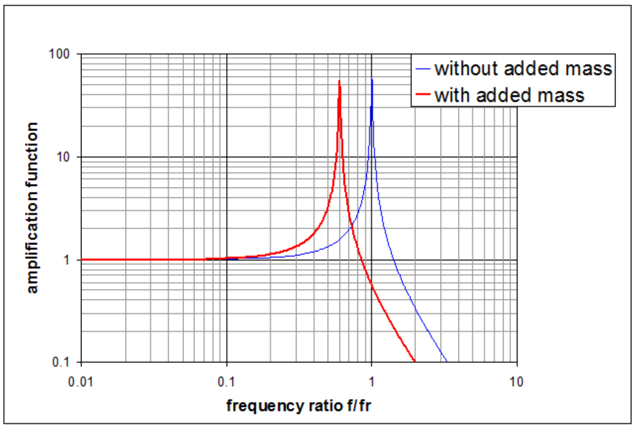


Fig. 12: Natural frequency of spring mass system

5.1. Analog bandwidth considerations of the measurement

For PE force measurement the charge amplifier determines lowest and highest frequencies that can be measured. The test article and application define the required frequencies of interest and associated resolution. However, the test stand, fixtures and mass acting upon the PE force dynamometer determine the highest possible measurement frequency. As the amplitude response tolerances can be expressed as a function of natural frequency the 5%, 10%, 3 dB bandwidths can be selected to make the measurement (Figure 5).

For short duration transient measurement of the drop test, the required analog bandwidth of the impact signal is inversely proportional to the impact duration. In addition, the natural frequency of the force dynamometer must be greater than the analog bandwidth required (fn >4 x signal bandwidth) to filter the sensor resonance if excited by the test with a high order low pass filter. If a sensor resonance is too close or within the required signal bandwidth, it cannot be filtered without distorting the signal of interest. Figure 13 illustrates the separation between signal bandwidth and sensor natural frequency.

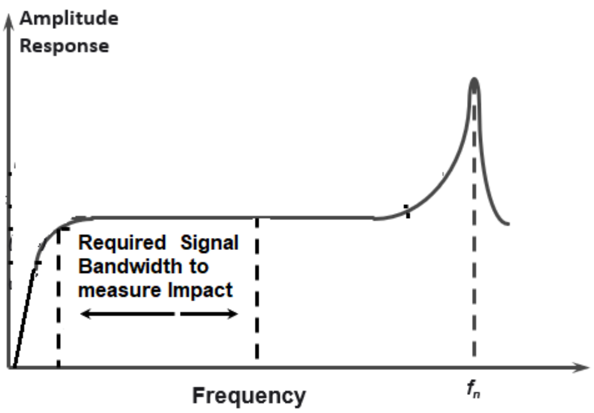


Fig. 13: Illustration of required signal bandwidth and force sensor natural frequency

The essential analog bandwidth is the portion of signal frequency extent that contains most of the signal energy to represent the signal of interest. For example, the frequency extent at which the signal bandwidth contains 50%, 90% or 99% of energy. Typically, the essential bandwidth is between 90% to 99% of the energy but is a decision to be made. The energy is the integral of the energy spectral density. Continuous time events, such as vibration from a gear train, will have an analog Bandwidth easily defined by the Fourier transform of the signal. However, a short duration transient events have frequency bandwidth that is inversely proportional to the duration T which is illustrated in Figure 14 for a rectangular and half sine shaped pulse. Figure 15 and 16 show the frequency domain relationships.

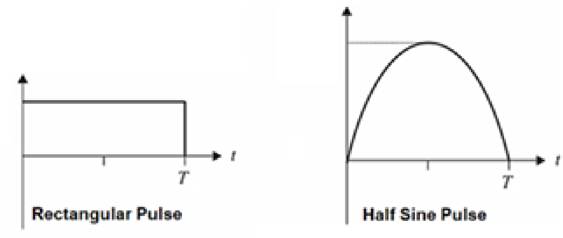


Fig. 14: Illustration of short duration pulse shapes

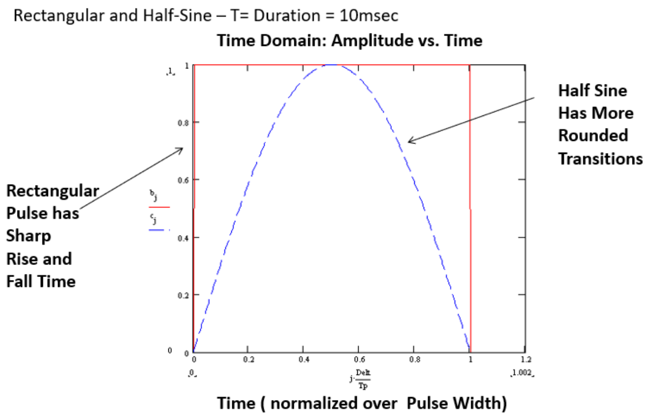


Fig. 15: Time domain and frequency domain representations of the pulse shapes

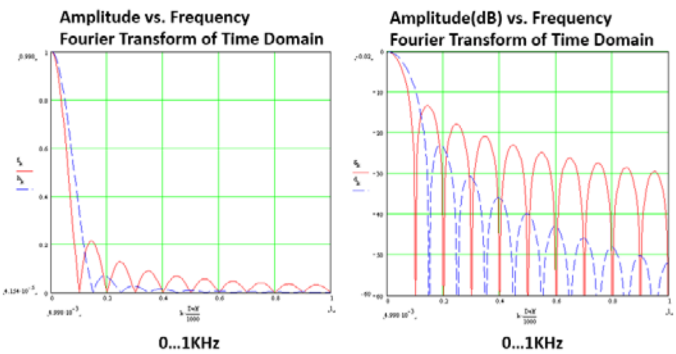


Fig. 16: Time domain and frequency domain representations of the pulse shapes

The rectangular shape transient event requires the highest bandwidth where shaped impact events like the half sine require less bandwidth. In aircraft drop testing the impact would be best represented by a shaped profile with lower bandwidth requirements.

The following can be said about the frequency content.

- Rectangular pulse (red); 90% = 0.85/T; 99% ~10.3/T
  - If 99% criteria are selected as the essential bandwidth then bandwidth = 10.3/T
  - Sharp pulse edges relate to higher frequency content
- Half sine pulse (blue); 90% = 0.78/T; 99% = 1.18/T
  - If 99% criterial is selected as the essential bandwidth the bandwidth = 1.18/T
  - Rounded or shaped pulses have lower frequency content

5.2. Design drivers for landing gear drop test

Landing gear drop tests are used for testing the energy absorption performance. A landing gear drop test dynamometer consists of either four or six 3- component force sensors. Six sensors support higher load handling and the higher equivalent stiffness supports higher frequency response. The output of each of the sensors are summed in Fx, Fy and Fz for the resulting impact forces where moments are not typically measured for the application. The PE force dynamometer will have a very large measurement range and is rangable allowing for measurements for very small and very large landing gear assemblies. As a result, one PE dynamometer size will fit all measurement requirements. Additionally, PE force sensors can accept a high overload without damage where the landing gear dynamometer is almost indestructible. High natural frequency, especially in shear direction is required where the dynamometer must also provide a stiff interface with easy mounting possibilities. Lastly the PE dynamometer will use an integrated charge amplifier for rangability, high dynamic range and high signal fidelity as well as reduce effects of long cables.

5.3. Mechanical design and calibration

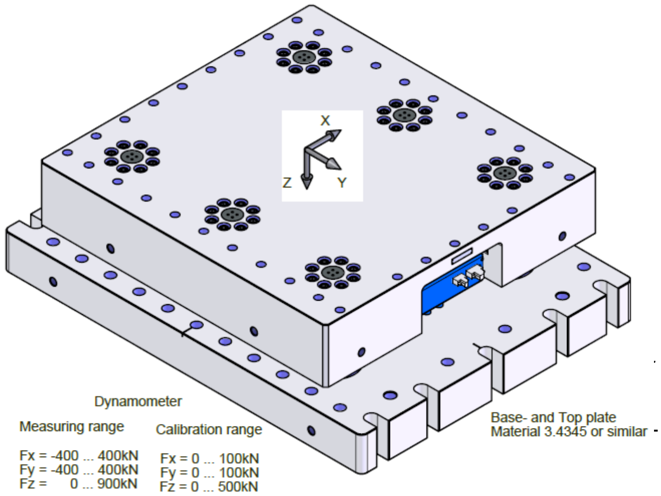


Fig. 17: Landing gear drop test pe dynamometer Type Z21594

The dynamometer consists of six force sensors type 9397C1 as shown in Figure 17 with a built- in charge amplifier. The Base plate with many holes and slots for easy mounting per the end customer requirements. The maximum load Fx, Fy = 400 kN, Fz = 900 kN where the dynamometer is highly linearity with high stiffness and natural frequency. Figure 18 shows the landing gear drop test dynamometer to be tested with an impact hammer to determine the high natural frequencies which are shown in Figure 19.

Fig. 18: 3-component force link 9397C (-200KN to 450KN Range) Fx, Fy up to ±100 kN, Fz: -200 … 450 kN

Fig. 19: Landing gear drop test Z21594 dynamometer for impulse hammer testing

Natural frequency test – conditions in mounted state:

f_n on channel

X [Hz]	Y [Hz]	Z [Hz]
437	500	565

Figure 20 shows the calibration test stand where calibration is performed using a multi-component press for high loads as illustrated below. In each axis there is a strain gage sensor to control the applied force and a PE force sensor to quasi-statically calibrate the PE dynamometer in Fx, Fy, Fz. Figure 21 shows the calibration results indicating very low cross talk and highly linear operation of the multicomponent PE force platform.

Fig. 20: 3-component force link 9397C (-200KN to 450KN range) Fx, Fy up to ±100 kN, Fz: -200 … 450 kN

Force	Calibrated range (kN)	Sensitivity (mV/kN)	Linearity ≤%FSO	Cross talk (%)	Cross talk (%)
Fx	0 ... 100	25.03	0.08	Fx→Fy 0.0	Fx→Fz 0.2
Fx	0 ... 10	250.1	0.1	Fx→Fy 0.0	Fx→Fz 0.4
Fy	0 ... 100	25.06	0.07	Fy→Fx 0.4	Fy→Fz 0.3
Fy	0 ... 10	250.8	0.09	Fy→Fx 0.5	Fy→Fz 0.1
Fz	0 ... 500	11.16	0.14	Fz→Fx 0.2	Fz→Fy 0.0
Fz	0 ... 50	111.2	0.08	Fz→Fx 0.1	Fz→Fy 0.0

Fig. 21: Landing gear drop test Z21594 dynamometer calibration results

6. Piezoelectric dynamometer comparison with strain gage

Strain gage dynamometers have historically been used for aircraft landing gear drop testing. With this said, as the paper shows the performance of PE force dynamometers are also very suitable for the landing gear drop testing applications.

PE dynamometer technology is known for endurance and longevity where is not uncommon for over 25+ years of use. Complementing longevity is that PE technology does not use adhesives but welded steel construction with quartz sensing element sandwiched in the steel assemblies. In addition, PE measuring technology is based on a quartz crystal, which does not change properties over time. Conversely, strain gauge uses flexure as the principal of operation where the strain gages are bonded with adhesives inside the force sensor. Adhesives can degrade with long term use and environmental conditions creating nonzero offsets and creep for example.

As PE technology is rangable where resolution scales as a function of selected range not the full-scale range of the dynamometer, one high capacity dynamometer with large top plate can be used to easily accommodate various landing gear assemblies requiring different load ranges. The rangability also allows for optimizing the available dynamic range for the selected measurement range providing a high fidelity measured signal. PE technology has inherent 20% overload capability which provides added safety margin to the test. Conversely, exceeding strain gage sensor load limits can often damage the sensing element by exceeding the elastic limit.

PE technology requires the precision machining and alignment of the quartz sensing elements which provides inherently low inherent crosstalk (<1%) where high preloading provides inherently highly linear operation (<0.2% FSO). Although PE technology has higher natural frequency, the impact durations are relatively long where the required signal bandwidths are low <50 Hz for example.

7. Landing gear drop test example

The aircraft landing gear drop test is a dynamic test that simulates the impact of an aircraft landing. The newly designed landing gear generally needs to be verified by the drop test to verify that the landing gear shock absorber system meets the energy absorbing requirements. Other considerations include if technical parameters such as service/buffer stroke, overload of the landing gear, tire pressure meet the design requirements, and whether the structure meets the expected strength and rigidity. The directional stability of the drop test impact is also important as the shear forces at landing can influence that the aircraft remains straight on the runway after touchdown. For example, the shear forces can be of shorter duration (higher bandwidth) compared to the vertical force at landing for example.

Figure 22 shows a landing gear drop test stand with the Z21594 dynamometer where Figure 23 shows the Z21594 dynamometer and landing gear wheel coordinate systems respectively.

Fig. 22: Drop test stand and landing gear under test using Z21594 dynamometer

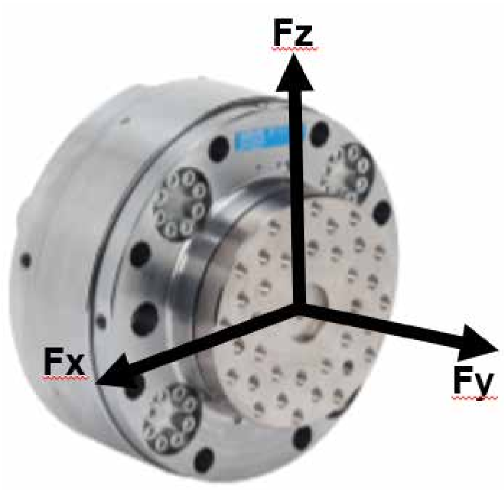


Fig. 23: Landing gear wheel coordinate system

The drop test is performed on the landing gear system which includes struts, rocker arms, buffers, wheel tires, retractable actuator cylinders and other components. The test stand includes

- Mechanical system: Upright column, hanging structure, counterweight, lifting cylinder
- Hydraulic system: Oil pump motor system, tank, filter, cooling, ventilation, and PLC control
- Wheel turning system: pump, oil cooling, remote control
- Test system: Sensors, signal converters, software

Test setup includes the following where the test scenarios are summarized in Figure 24

- Hanging structure: Maximum 4 m drop height, 25 Ton counterweight, 15 Ton heading load with safety code 2.0
- Landing pitch attitude: 0° or 10°

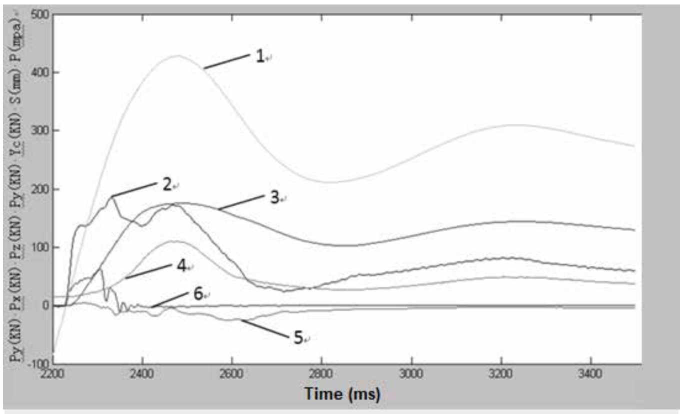
Test No.	Sink speed (m/sec)	Sink speed (ft/sec)	Equivalent Mass (kg)	Landing pitch angle (°)	Approach (m/sec)	Shock absorber stroke pressure (kPa)	Tire pressure (kPa)
1	2.5	8.2	10 000	0/10	78.84	2 500	950
2	3.05	10.0	10 000	0/10	78.84	2 500	950
3	3.15	10.3	10 000	0/10	78.84	2 500	950
4	3.45	11.3	10 000	0/10	78.84	2 500	950
5	3.66	12.0	10 000	0/10	78.84	2 500	950

Fig. 24: Drop test conditions to be evaluated. Sink is the vertical downward component of the landing speed at touchdown.

8. Force plate drop test example

Figure 25 shows the measured test results for case 2 with sink speed of 3.05 m/s (10 ft/sec) using the Z21594 3-component force dynamometer. The width of the two wheels is 810 mm where the movement of the wheels in y-direction (fore/aft) is 180 mm. The wheel is spinning before dropping to simulate the landing speed of the aircraft (in this case 78.84 m/sec, is approx. 280 km/h).
The PE force dynamometer has the landing gear drop test centered over the dynamometer surface. The PE force dynamometers helps to optimize the efficiency of the shock absorber, the maximum loads on the mechanical structure of the landing gear and helps to optimize the directional stability of the landing gear.

Therefore the drop plate dimension of 1000 mm x 950 mm is suitable for the application where the force plate is stiff and easy to use with natural frequency of 360 Hz under load where the system set for the measuring range of , Fz ~450 kN and Fx ~150 kN. Comparing the different parameters and measuring curves, the best result the is for Test Case 2 which resulted in the landing gear having the lowest load and highest efficiency factor with the best energy absorption of the drop impact. Also, the plot shows that Fx increases significantly when the rotating wheel contacts the force plate then the spinning wheel stops immediately, creating the sharp peak in Fx force. The shear force handing and frequency response of shear axis complements the measurement.



Key:
1= Displacement center of gravity of the hanging structure (mm)
2= Vertical force Fz (kN) – Wheel coordinate system
3= Shock absorber displacement (mm)
4= Shock absorber air pressure (MPa)
5= Side force Fy (kN) – Wheel coordinate system
6= Course force Fx (kN, fore-aft in wheel coordinate system)

Fig. 25: Drop test results plot, test number 2

9. Conclusions

Aircraft landing gear is one of the most critical subsystems for safety which demands high reliability and performance. Landing gear drop testing is a dynamic test which simulates the aircraft landing impact to qualify the shock absorption system to the operational dynamic loads without failure. PE force dynamometers are shown to be both suitable to the application and having application advantages such as ease of use, endurance/ longevity and as a one size fits all solution.

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