KISTLER

measure. analyze. innovate.

Solutions for space testing

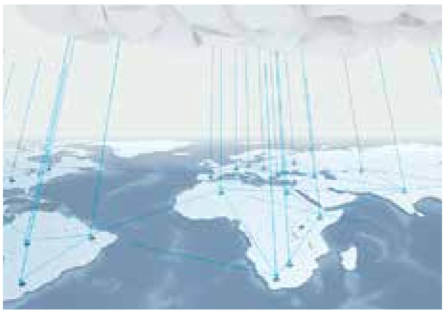
Proven measuring equipment for all application purposes
on the ground, in the air and in space

Absolute Attention for tomorrow's world

Kistler develops measurement solutions consisting of sensors, electronics, systems and services. In the physical border area between emissions reduction, quality control, mobility and vehicle safety, we deliver excellence for a future-oriented world and create ideal conditions for Industry 4.0. We thereby facilitate innovation and growth for – and with – our customers.

Kistler stands for progress in motor monitoring, vehicle safety and vehicle dynamics and provides valuable data for the development of the efficient vehicles of tomorrow.

Kistler measurement technology ensures top performance in sport diagnostics, traffic data acquisition, cutting force analysis and other applications where absolute measurement accuracy is required.



Kistler systems support all steps of networked, digitalized production and ensure maximum process efficiency and profitability in the smart factories of the next generation.

Editorial

Manuel Blattner
Head of SBF Test & Measurement

Space industry is a growing sector of increasing importance that serves mankind all over the world. We rely on space technology every day, using our mobile phones, navigating via GPS to watch the weather forecast. It addresses the most relevant topics, such as climate change, rare resources, health and ageing. Imagine where we would be without satellites?

The space industry is an essential driver of scientific progress and innovation and thus, of economy. It is extremely difficult to develop and manufacture quality space technology. This is exactly where Kistler comes in. As industry insiders, we are dedicated towards developing precisely the kind of sensitivity in sensor technology you need, whatever the test plan may demand. We also offer our professional advice and worldwide services to you.

This is our contribution towards the successful performance of your space mission, knowing it depends on the utmost operational reliability of your equipment.

Contents

Kistler is the space testing partner of choice for safe, smooth and efficient flights

Space testing with Kistler – a good decision

Being enthusiastic about sensors demands absolute conviction that the little things can make a big difference to the world of work of engineers, researchers, measurement technicians, students, manufacturers. Kistler, the pioneer in piezoelectric measurement technology, is proud to have such committed and satisfied clientele. For more than 60 years, we have built that trust and expertise through constant search for perfection and meeting our customers' needs.

Space is an exceptionally demanding industry for new product development and quality control. An uncontrolled rocket start can cause an engine to explode. Equipment often has to be lightweight, robust and long-lasting as it is subject to challenging environments characterized by broad and extreme temperature ranges, pressure fluctuations, shock and vibration levels.

We work in partnership with renowned aerospace centers all around the world. Our aerospace testing expertise allows us to offer you a choice of force, torque, pressure and acceleration sensors based on piezoelectric (PE), integrated electronic piezoelectric (IEPE), strain gage or piezoresistive technologies that are designed for space payload or rocket testing. The sensors highlighted in this brochure provide the widest triaxial force capability, highest sensitivity for measurement of micro-vibration and most stable, very high temperature or most sensitive cryogenic capability in the market.

Our solutions provide the most accurate measuring results thanks to:

- Extremely lightweight accelerometers with low outgassing, wide temperature range and high-temperature-stability capabilities
- Most sensitive cryogenic capacities
- Broad triaxial force capacity featuring a high natural frequency and very low crosstalk
- Innovative cloud-based DAQ solutions
- Professional customized force dynamometer design and manufacturing
- Outstanding service

Kistler can partner with you as a full measuring chain supplier, adding signal conditioning, data acquisition and engineering know-how to its wide portfolio of sensors.

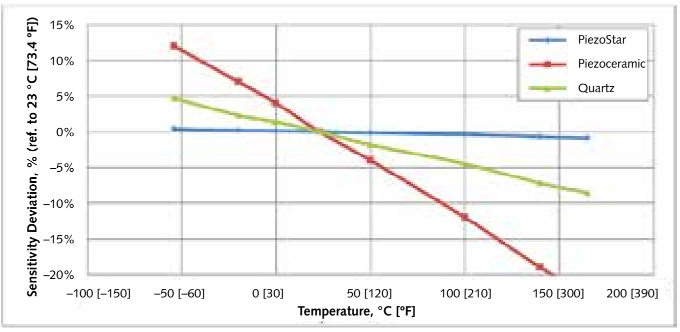
We want to earn the smile that says – measurement technology from Kistler – a good decision.

PiezoStar and high temperature stability

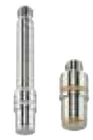
Market trends toward miniaturization and stability at changing or higher operating temperatures have resulted in a need for new types of crystals. The proprietary PiezoStar family of crystals developed by Kistler is the material we use to produce sensors which, with temperature variations, have proven results of very low changes in device sensitivity and are used to measure pressure, force and acceleration even under extreme conditions.

Our new crystal compounds are the result of over 10 years of cooperation and research with universities throughout the world, exhibiting unique performance to improve the data quality for physical measurements. The PiezoStar elements exhibit utmost stiffness leading to a high natural frequency of the sensors that are built upon them. This material is the key element for pressure, force and acceleration sensors featuring higher accuracy and providing better sensitivity even at very high working temperatures.

PiezoStar crystals are just one of many innovations from Kistler



Typical sensitivity deviation with temperature of a PiezoStar voltage mode accelerometer compared to a sensor based on a ceramic- or quartz-sensing element

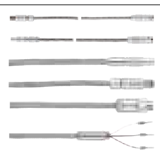
Product highlights	
	Single-axis, teardrop PiezoStar acceleration sensor family Type 8715B • Lightweight and high-temperature stability
	Triaxial mini cube PiezoStar acceleration sensor family Type 8766A • Lightweight and high-temperature stability
	Universal PE and IEPE PiezoStar pressure sensor family Type 601C • High sensitivity and temperature stability
	Triaxial component force link Type 9317 • High sensitivity and high stiffness for high-frequency response
	Force dynamometer Type 9119AA • Ultra-high sensitivity and high stiffness for high-frequency response

Temperatures of 700 °C (1 300 °F) for sustained pressure and acceleration measurements, at even higher temperatures for short-term measurements are possible through our high-temperature sensor solutions

Ultra-high temperature sensor solutions

The proprietary single crystal PiezoStar sensing elements are the foundation of our superior performance, ultra-high temperature pressure and acceleration sensors. They have been thoroughly tested at well over 700 °C (1 300 °F). Unlike ceramic-based sensor elements, they are not pyroelectric and show no popcorn effect.

Due to their outstanding high-temperature capability, the PiezoStar sensor elements can be placed directly in very hot locations. This simplifies the system and delivers more accurate measurements. Ground isolated differential designs, robustness against electromagnetic interference, long lifetime and approvals for operation in hazardous areas are among the features of this measuring system.

Product highlights	
High-temperature pressure and acceleration sensors, differential charge amplifiers and appropriate cables are the main elements to configure the required measuring chain. Our components are available in a vast variety of versions and are designed to guarantee seamless interoperability. Ex-certified components complete the portfolio.	
	700 °C (1 300 °F) high-temperature pressure sensor with hardline cable Types 6021A, 6023A and 6025A
	700 °C (1 300 °F) high-temperature accelerometer with hardline cable Type 8211A
	Low-noise softline cable Type 1652A
	Differential charge amplifier Type 5181A

Cryogenic sensor solutions

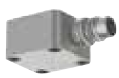
Cryogenic testing on earth to meet and exceed temperatures in space plays a critical role regarding the reliable operation of space-based equipment. Be it force and acceleration sensors applied to investigate background noise during space payload environmental testing or pressure and acceleration sensors applied during rocket testing to optimize cryogenic turbo pumps for liquid fuel handling, all must meet cryogenic requirements.

Acceleration sensors
The cryogenic, voltage mode, IEPE (piezoelectric with integrated electronics) accelerometers from Kistler span an outstanding temperature range starting from below the typical -54 °C (-65 °F) up to -196 °C (-320 °F). The use of specialized, built-in, cryogenic circuitry and PiezoStar sensing technology promote survivability in demanding environments, such as liquid nitrogen or in the presence of helium. Each sensor is hermetically sealed and individually tested to determine the thermal coefficient of sensitivity at -196 °C (-320 °F) ensuring reliable operation and accurate measurements.

Choose from a variety of accelerometers ranging from lightweight units for minimizing mass loading effects to triaxial sensing solutions.

Force sensors
Unlike strain gage technologies, our quartz based force sensor will exhibit very high temperature stability of 1% sensitivity deviation. Cryogenic operation requires some deliberation regarding operational force range. For example, consider derating the maximum by 20% to 30%.

Pressure sensors
Kistler charge output pressure sensors Type 60xC... family can be used with low cryogenic temperatures as well, while offering the same very high temperature stability across the full temperature range.

Product highlights	
	Piezoelectric pressure sensor family Type 601C
	Single-axis piezoelectric force sensor family Type 9011A – 9071A
	Single-axis voltage mode miniature cryogenic accelerometer family Type 8730…
	Triaxial voltage mode accelerometer Type 8793A250M8

The cryogenic environment is very challenging: liquid hydrogen or liquide helium temperatures are often encountered

Lightweight cabling solutions for environmental vibration testing

Every bit of mass that can be reduced means lighter payloads at liftoff and greater efficiency during mission. Also, to save time and prevent contamination risk of the satellite, it is not uncommon to leave cables and sensors inside the satellite once micro-vibration, acoustic, shock and vibration testing using triaxial accelerometers have been accomplished.

Miniature accelerometers and connectors from Kistler provide low mass and a small mounting footprint. Positive keying and blind mating support flexible sensor mounting and good electrical connections.

A critical aspect that one seeks to avoid is the mass load effect through sensor and cable onto a lightweight structure under test, since it can eventually affect the resonance modes of the subject under evaluation. Therefore, Kistler has developed its own 4-pin miniature connector technology for triaxial accelerometers. It reduces mass on the connector side but also on the cable side. In the case of using 20 accelerometers with 5 m (16 feet) length cables, for example, one could gain a total mass of 961 grams (34 ounces), which is highly significant.

Product highlights Mini 4-pin connector sensors and cables	
	Mini 4-pin connector sensors and cables
	Triaxial voltage mode miniature accelerometer family Type 8763B…
	Mini 4-pin connector cable family Type 1784…

Environmental and ground modal testing of space structure (Source: ESA)

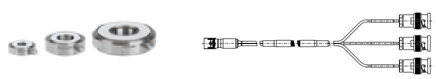
Low outgassing sensor and cable solutions

Material outgassing in sensors and cables is a challenge to any electronic equipment used in high-vacuum space environments. It can seriously affect a wide range of applications, such as satellites or other equipment.

Released gas can condense on surfaces, as, for example, on camera lenses, thereby rendering them inoperative for the intended application. Kistler offers a range of low outgassing accelerometers based on titanium housing, as well as force load cells – all of them are fully hermetically sealed. Similarly, we can also provide low outgassing cable solutions.

All non-metallic materials outside a hermetic package intended for use in a vacuum environment comply with NASA standards featuring a TML[1] (total mass loss) less than or equal to 1% and a CVCM[1] (collected volatile condensable mass material) of less than or equal to 0.1%.

Low outgassing triaxial accelerometer Type 8763B and its low outgassing cable Type 1784

Product highlights Low outgassing sensors and cable solutions	
	Triaxial piezoelectric load cell family Type 9017C-9077C and its compatible low outgassing cable Type 1698AS
	Triaxial voltage mode miniature accelerometer family Type 8763B and its compatible low outgassing cable family Type 1784B
	Piezoelectric & IEPE pressure sensor family Type 601C and its compatible low outgassing cable Type 1631CR

[1] TML and CVCM are verified either using NASA documentation or test results from an outside laboratory

Our engineering team will work closely with you to carefully analyze your specific setup and offer a sensing solution

Customer-specific force dynamometer solutions

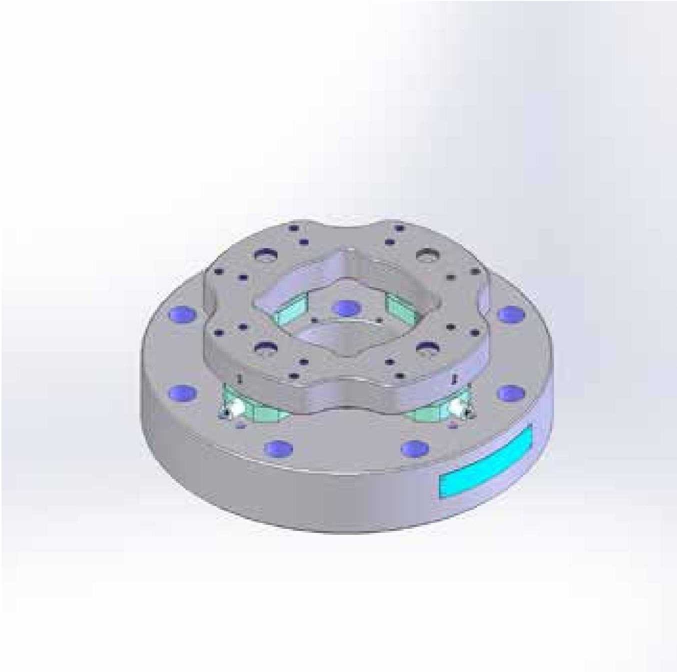
Due to the great variety of the size and accuracy requirements of test objects, standard dynamometers very often will not fit. It is our passion to provide you exactly the measuring tool that will meet your requirements best. Therefore, our engineering team will work closely with you to carefully analyze your specific setup and offer a sensing solution.

We know to ask the right questions based on the expertise we have gained in designing and manufacturing custom specific dynamometers for space applications over the course of many years. This is why we strive to perform the correct actions from the very beginning.

Professional design and manufacturing services by Kistler – your benefit:

- Careful analysis of your requirements
- Control drawing, including dynamometer design and most important specifications
- Approval by customer
- Detailed design, manufacturing of all parts and assembly of the dynamometer
- In-house calibration on our unique 3-component reference force press
- Delivery of the final dynamometer, including the calibration certificate and bode diagram of natural frequency

In-house calibration on Kistler's unique 3-component reference force press



6-component dynamometer (Source: Bosch Bühl). The dynamometer is built of four Type 9047C force sensors. The top and base plate were specifically designed for the customer's requirement. A special calibration with a specific adapter adopts the situation as in the real application.

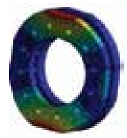
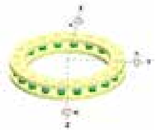
Thanks to our absolute commitment to quality we can say: The dynamometer will meet your specifications and work right from the beginning, throughout the test plan.

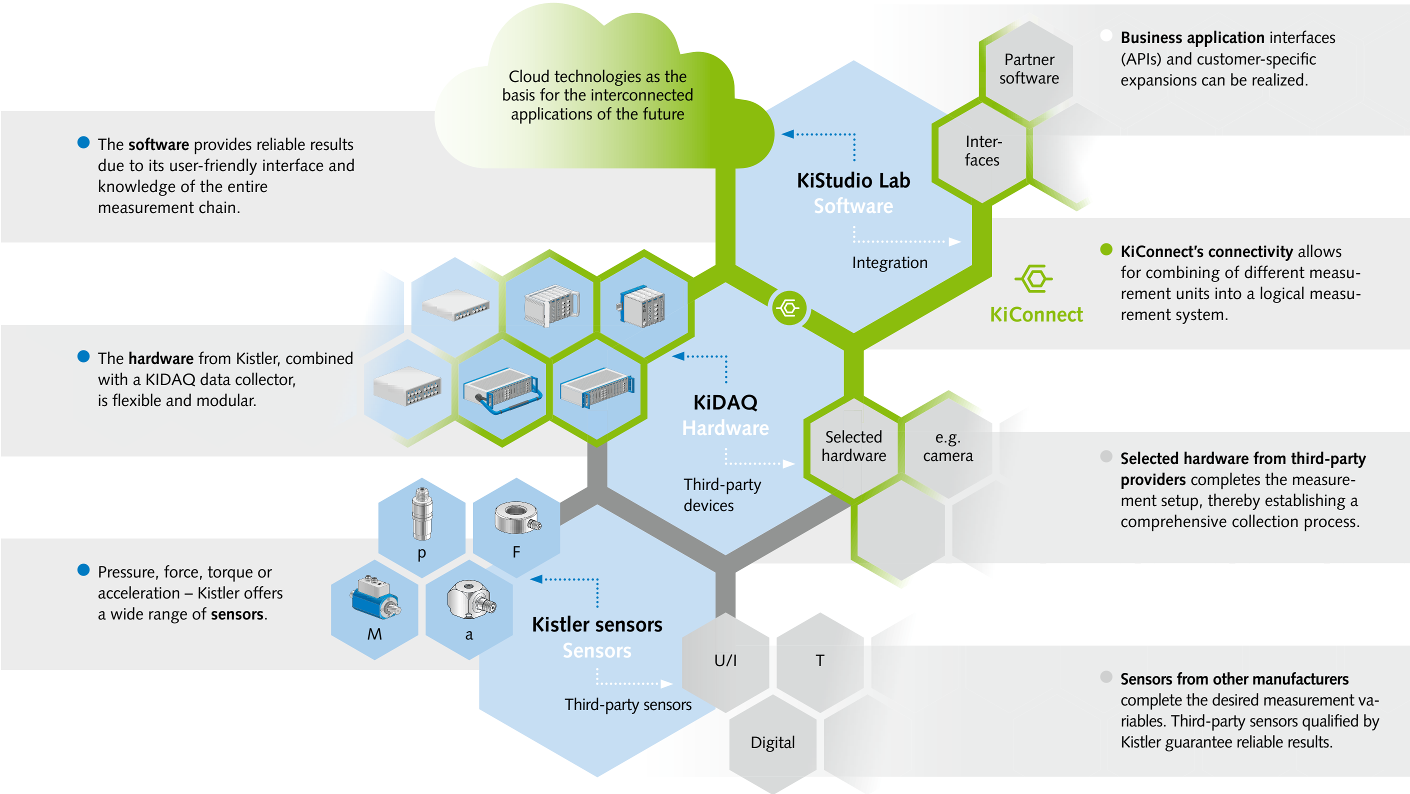
- **Multi-component**
  Our 3-component force sensors are at the core of all customer-specific dynamometers.

- **Single-source**
  For sensors to be used under extreme operating conditions, Kistler grows its own crystals. Precision measuring equipment from Kistler is subject to 100% quality control; all manufacturing steps are accomplished in-house.

- **Highly specialized**
  Our customized specific high-performance dynamometers will meet your specifications, unlike self-built dynamometers.

- **Professional**
  Many years of experience and expertise in designing and manufacturing dynamometers for the space industry make us your ideal partner. We speak your language and know exactly what it is all about.

Product highlights	
	Specific dynamometer for thrust measurement
	Exported micro-vibration measurement platform for cryocooler-specific dynamometer
	Customer-specific force measurement device for force limited vibration applications



KiDAQ measurement architecture at a glance

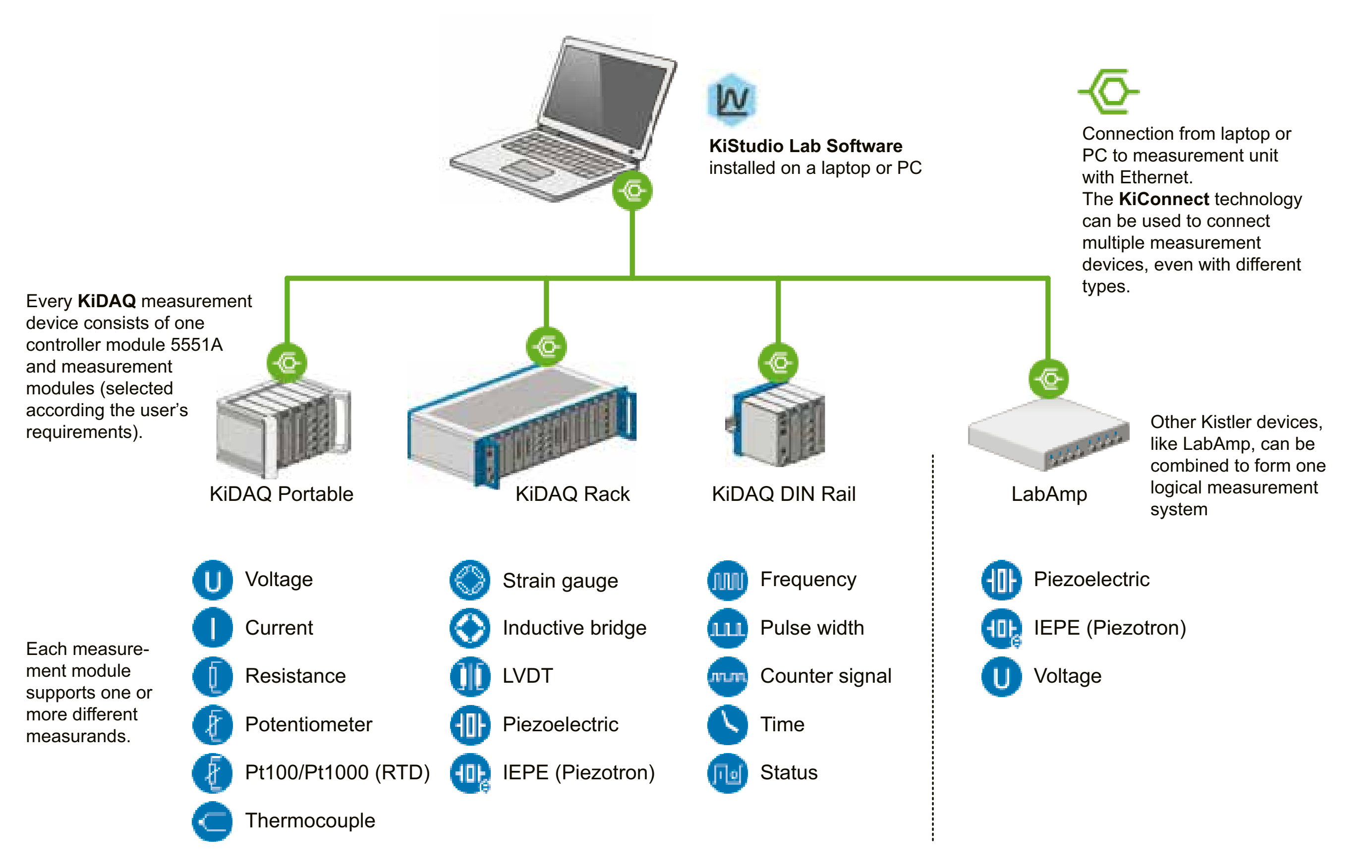
Innovative cloud-based DAQ modular solutions with transparent measuring chain reliability

In space research and development, every measurement task usually starts with a complex and lengthy test setup. This is due to the fact that measurement technicians or measurement engineers first have to connect the measurement elements of different origin before they can assemble the system. With KiDAQ, the measurement technology experts from Kistler present an innovative and integrated data acquisition system that offers all the components you need for a given measurement task from a single source.

The intelligent KiConnect technology is the connecting element inside the KiDAQ data acquisition system. It allows users to flexibly and easily connect Kistler products and selected devices from other suppliers in order to assemble a logical measurement setup and to enable time-synchronized measurements using the Precision Time Protocol (PTP).

As the leading manufacturer of piezoelectric measurement technology with decades of experience, Kistler offers extensive measurement technology and application know-how. This knowledge enables measurement technology experts to provide reliable information about the measurement uncertainty of the entire measuring chain. Once users know the measurement uncertainty percentages and magnitudes of each individual component, they can reduce the percentages by changing operating conditions or optimizing device selection and thereby benefit from a maximum level of transparency and know-how. Kistler has filed a patent for the procedure for determining the measurement uncertainty of a measuring system.

Product highlights



An highly modular hardware portfolio inter-connecting thanks to KiConnect technology

Satellite vibration qualification tests are among the most carefully run tests in the world

Space payload: environmental vibration testing

Due to the high costs, satellite vibration qualification tests are among the most carefully run tests in the world. The payload is subject to extensive testing, both during product development in order to optimize the structure and also during manufacturing in order to ensure survivability during launch, deployment and long-term operation.

To simulate the environmental conditions a space payload may endure during rocket launch, electrodynamic shakers are used to perform realistic dynamic load testing.

The payload is excited through a wide panel of profiles starting from micro-vibrations up to shock through Random and Sine vibrations. Engineers thoroughly analyze the dynamic processes that are measured through the acceleration sensors' output in order to compare it with their calculation models.

Satellite environmental vibration testing – Sine and Random vibration – (Source: NASA)

Important technologies for the application

- **Low mass and lightweight triaxial accelerometers**
  Spacecraft structures are often made of thin, lightweight materials and require low mass accelerometers. In some cases, sensors and cables are launched within the satellite which makes mass loading even more critical.

- **Low outgassing**
  Exposure to the high vacuum level of a space environment induces material outgassing releasing entrapped gas. This can condense on surfaces, such as camera lenses, thereby rendering them inoperative for the intended application. Sometimes, the hermetically sealed sensors and low outgassing cabling solutions from Kistler are allowed to be used in thermal vacuum chambers or even to be left on the satellite for launch.

- **Low noise**
  Space payload must endure a wide panel of environmental testing from micro-vibration requiring very low sensor threshold up to higher g levels encountered during random vibration testing. Kistler low noise solutions allow for the very same sensor to be used to cover the entire panel.

Product highlights	
	50g triaxial miniature voltage mode accelerometer Type 8763B050AB
	Low outgassing mini 4-pin to standard ¼-28 cable Type 1784M016SP
	Low outgassing mini 4-pin to pigtail cable Type 1784M015SP
	Low outgassing mini 4-pin to 3xBNC cable Type 1784BLK04SP

3-component force links mounted on the base plate, which is connected to the shaker. A force ring is then mounted to the load cell, which is sandwiched between the top and bottom ring. The space payload is mounted on the top ring for the FLV-test. (Source: ESA)

Space payload: force limited vibration testing

Space payload test vibration specifications are representative of the enveloped actual flight environment. By measuring and limiting the reaction forces between the payload and the slip table, the acceleration at the payload resonances will be notched; preventing over-testing, which could damage expensive space payloads.

In actual flight, input acceleration is notched at the payload resonant frequencies, as the mechanical impedance of the structural mount and payload is similar.

In shaker testing, space payload interface forces are higher at the payload resonances because the shaker has very high mechanical impedance and is controlled by the enveloped interface acceleration.

Interface force measurement is performed by a force dynamometer to resolve the forces (and moments) during vibration testing. Kistler 3-component force sensors are sandwiched between two metal rings. The ring assembly is attached to the slip table and to the payload under test to measure the reaction forces.

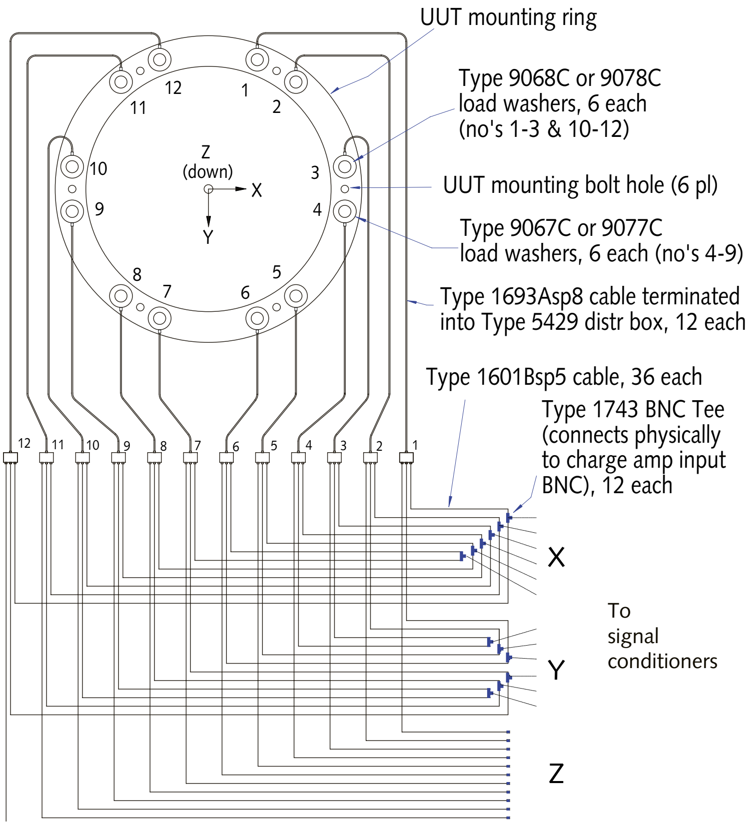


Diagram of force ring for a force limited vibration test

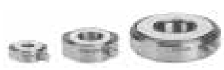
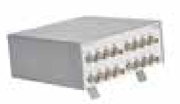
Important technologies for the application

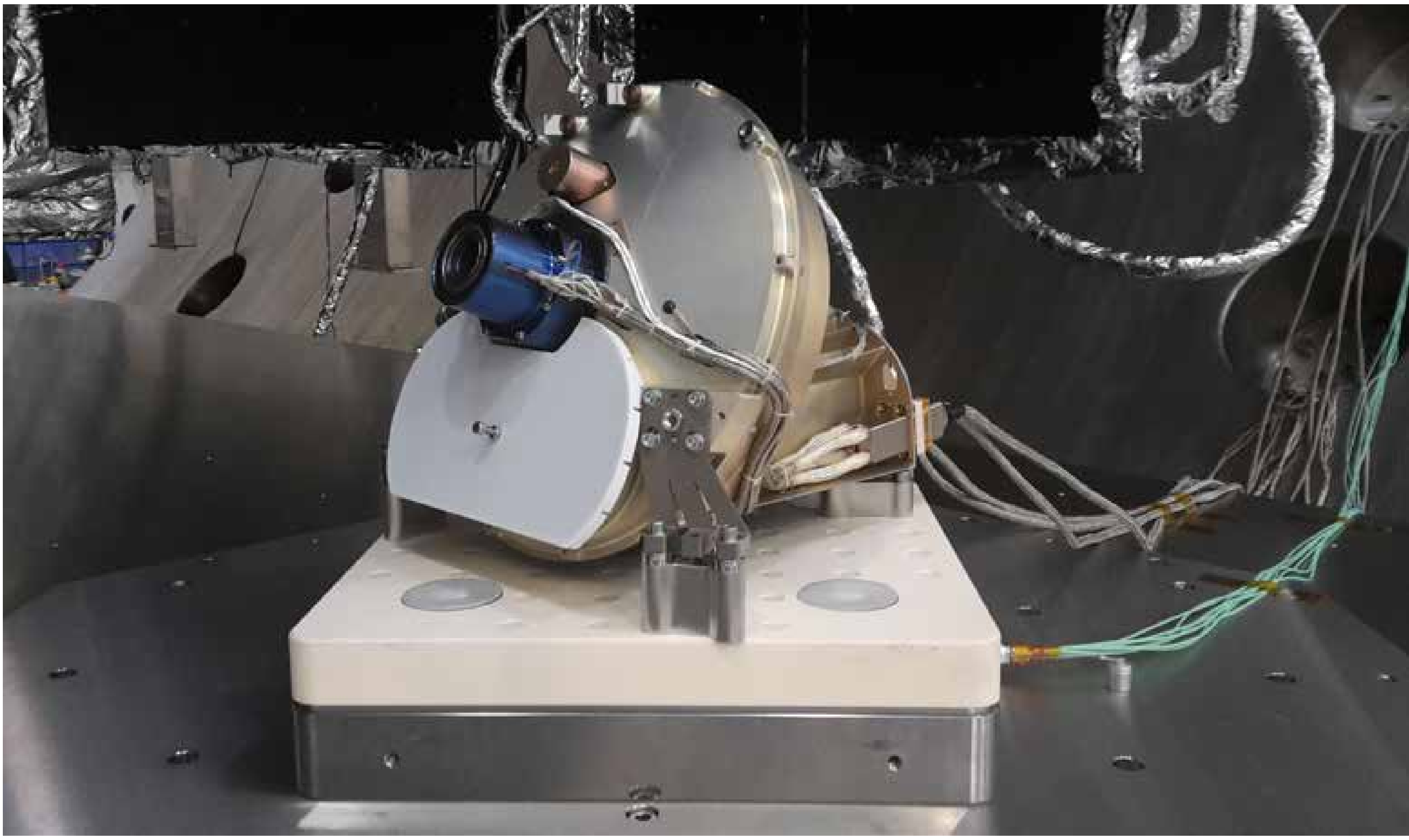
- **Low outgassing**
  Exposure to the high vacuum level of a space environment induces material outgassing, thereby releasing entrapped gas. This can condense on surfaces, such as camera lenses, thereby rendering them inoperative for the intended application. Force sensors may also be used in vacuum chambers. Kistler offers hermetically sealed sensors and low outgassing cables suitable for those cases.

- **Optimal mounting**
  If not limited by space and frequency response requirements, it is recommended to apply sensors from the preloaded force link family. Those are already calibrated and can directly interface the force ring. If space is limited and the stiffness of the system needs to be optimized for a wider frequency response, the application of load cell sensors is the preferred choice. Preloading is accomplished within the customer force ring and demands for an on-site calibration.

- **Low crosstalk**
  The resulting forces and moments are calculated through the three signals provided by each sensor around the force ring. The lower the crosstalk, the higher the force measurement and moment calculation accuracy.

- **Easy summing**
  Charge output sensors do not only allow an easy preloading. It is also possible to pre-sum signal packages by connecting the respective cables prior to the conditioning stage. The modern charge amplifiers allow a convenient and flexible summation, too. This allows the user to optimize the number of required DAQ channels without using inconvenient voltage summing methods.

Product highlights	
	3-component load cell family Type 9017C–9077C
	3-component force link family Type 9317C–9377C
	Dynamic 4-channel charge amplifier and data acquisition Type 5165A
	Quasi-static 8-channel charge amplifier and data acquisition Type 5167A



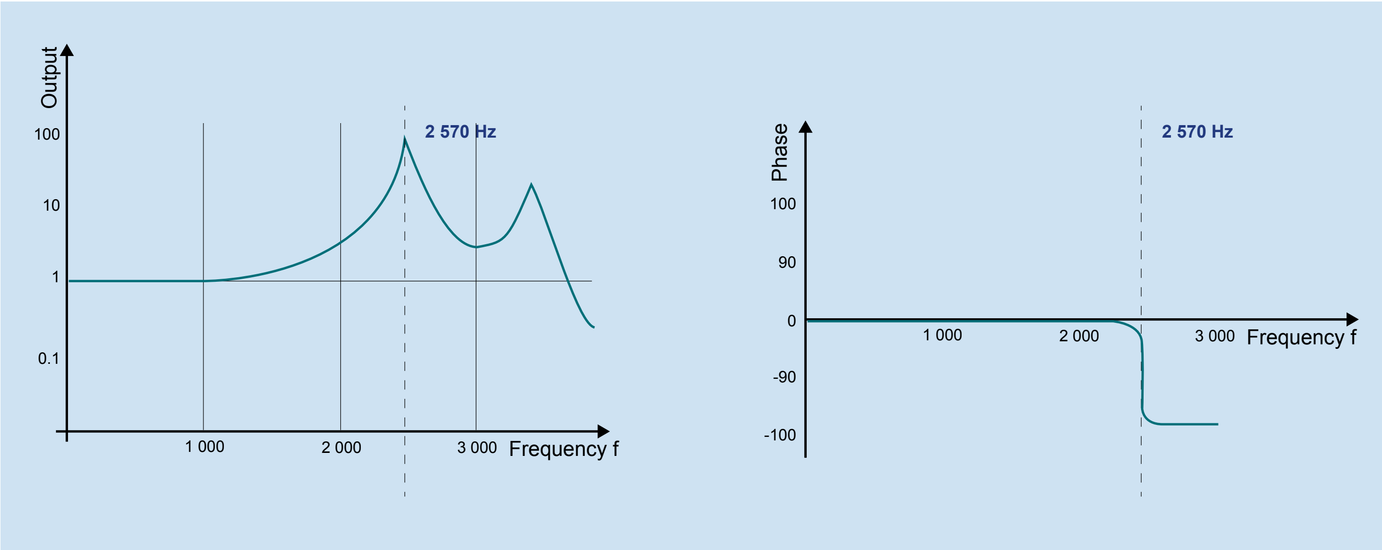
UVN CAA mounted onto the micro-vibration dynamometer Type 9236A2 (Source: CSL)

Micro-vibration and jitter testing

Satellite jitter, or blurring of the images originating from micro-vibrations, is a severe deviation source that affects the geometric accuracy of high-resolution imagery. Studies in recent years have seen major advances in terrestrial observation – accompanied by a dramatic increase in the need to measure the earth's surface and atmosphere with ever-greater precision.

The quality of these pictures would have been unimaginable only a few years ago. Critical steps in achieving this progress include the reduction of micro-vibrations on board satellites. Every satellite requires numerous drives, position controls, reaction wheels, actuators and cryocoolers, and so on. These devices consist of mechanical components that cause vibrations when they operate. Micro-vibrations consist of extremely small accelerations of very low intensity. Measuring them is a challenging task. Measuring high frequency jitter can be solved by applying piezoelectric force sensors, charge amplifiers and low noise accelerometers and dynamometers.

Recent innovative designs using ceramic top plate dynamometers allow for higher sensitivities, higher frequency range and possible water-cooling optimized for reaction wheel jitter and cryocooler micro-vibration applications.



Amplitude, phase response and natural frequency in Fz direction for ceramic top plate dynamometer Type 9236A2

Important technologies for the application

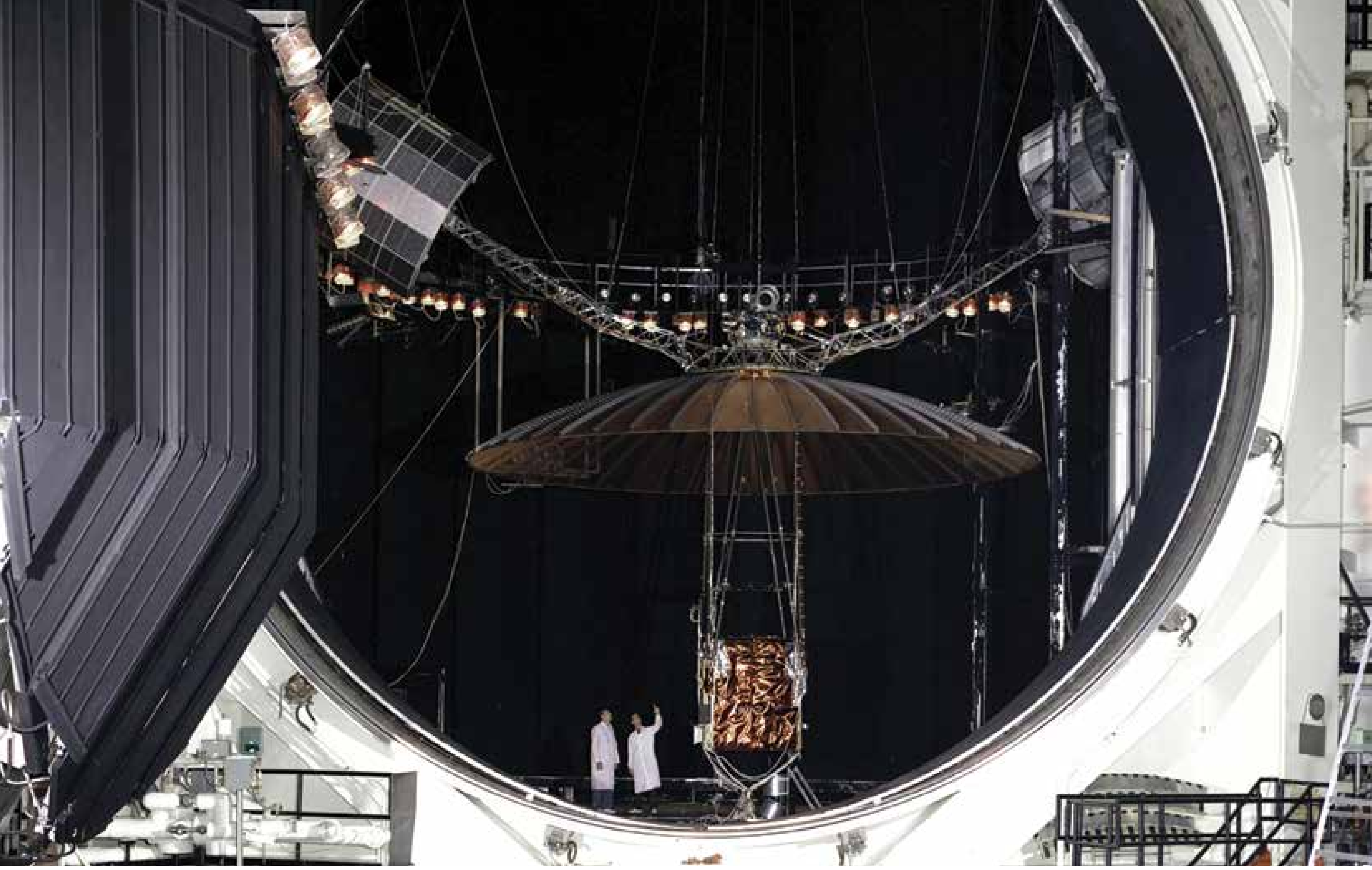
- **High resolution dynamometers**
  Piezoelectric force sensors and dynamometers combined with high sensitivity charge amplifiers are ideally suited as they offer very high resolutions of up to 100 000. This makes it possible to measure dynamic force changes down to 0.01 N (0.002 lbf) and moments down to 0.08 10^{-3} Nm (0.7 mlbf-in), even if the object to be measured weighs more than 10 kg (22 lb).

- **High frequency response dynamometers**
  Optimized micro-vibration dynamometers featuring high rigidity allow for very high natural frequencies of more than 1 500 Hz, which enable measurements of up to 500 Hz.

- **Low crosstalk dynamometers**
  The resulting forces and moments are calculated through the 3 signals provided by each of the 4 triaxial force sensors constituting the dynamometers. The lower the crosstalk, the higher the force measurement and moment calculation accuracy.

- **Lightweight and low-noise accelerometer solutions**
  Lightweight acceleration sensors generating lowest possible noise are generally preferred in cases where the micro-vibration levels are still high enough. These properties are the key to prevent mass loading effects while still detecting micro-vibration levels.

Product highlights	
	Ceramic micro-vibration force plate family type 9236A (force/moment)
	6-component force link Type 9306A (force/moment)
	Ultra-high sensitivity 8-channel charge amplifier Type 5080A
	Ultra-low-noise & lightweight voltage mode triaxial accelerometer Type 8688A5

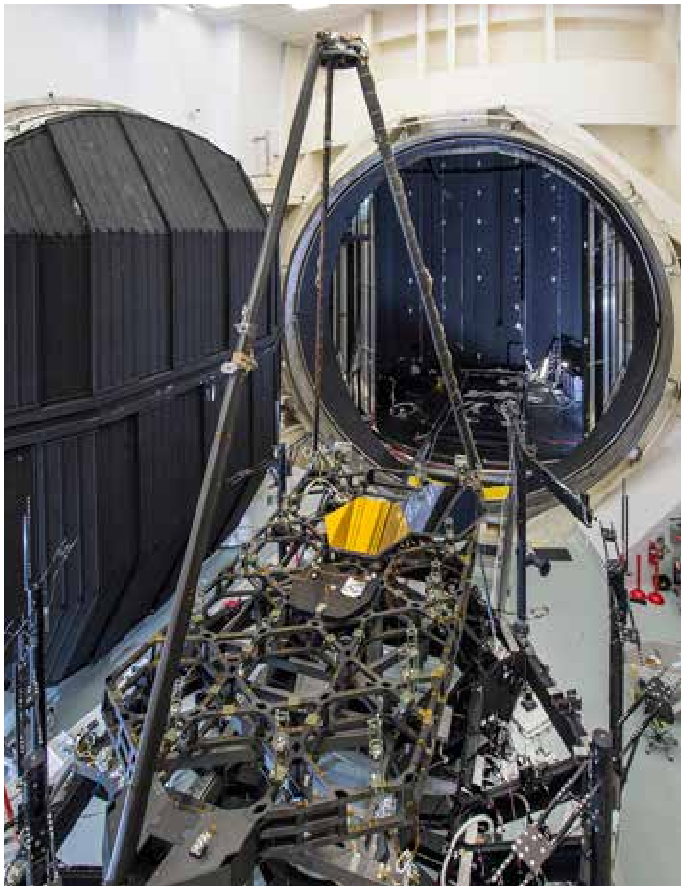

Satellite environmental testing in thermal vacuum chamber

Mechanical characterizations in thermal vacuum chambers

Telescope performance requires stability in the nanometer range. Therefore, the stability of the fully instrumented backplanes is critical. They need to be tested in thermal vacuum chambers suitable for testing down to cryogenic conditions. These are designed to provide a unique thermal stability at temperatures colder than -250 °C (-420 °F). Testing in the vacuum chamber requires accelerometers and force sensors with ultra-low temperature capabilities.

Backplanes can carry the primary mirror plus other telescope optics and the entire module of scientific instruments. Testing allows modification of the system through which the backplanes, then ultimately the telescope, will be isolated in the chamber. Some of the testing environments provide a new, layered, helium and nitrogen cooling system allowing the backplanes to achieve the low temperatures that simulate the operating temperatures in space. They allow for cryogenic optical alignment and testing of multiple primary mirror segments in a process known as "phasing". In such testing, accelerometers and force sensors with ultra-low temperature capabilities are required.

NASA's James Webb Space Telescope Structure getting ready to undergo thermal vacuum testing (Source: NASA/Chris Gunn)



The full-scale James Webb Space Telescope pathfinder (test version of the back-plane) shown going into NASA Johnson's huge Chamber A for cryogenic testing (Source: NASA/Chris Gunn)

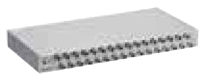
Important technologies for the application

- **High resolution**
  Accelerometers from Kistler detect background vibrations on the order of micro-vibrations.

- **High temperature stability**
  Our PiezoStar-based IEPE (voltage mode) accelerometers are the ideal sensors for precision vibration testing since they exhibit very low device sensitivity with temperature variations.

- **Cryogenic capability**
  Charge output sensors or cryogenic, voltage mode, IEPE accelerometers from Kistler provide an outstanding temperature range from below the typical -54 °C (-65 °F) down to -196 °C (-320 °F) to securely survive thermal vacuum chambers' liquid helium temperatures.

- **Low outgassing**
  Exposure to the high vacuum level of a space environment induces material outgassing which releases entrapped gas. This can condense on surfaces, such as camera lenses, thereby rendering them inoperative for the intended application. Hermetically sealed sensors and low-outgassing cables from Kistler are designed to ideally fulfill all needs.

Product highlights	
	Ultra-high sensitivity PiezoStar cryogenic accelerometer Type 8712B5D0CB
	Low outgassing cable Type 1761B
	+36V compliance voltage IEPE coupler optimized for cryogenic temperature Type 5148M09

Generally, test units undergo combinations of extreme thermal and vibration stress tests

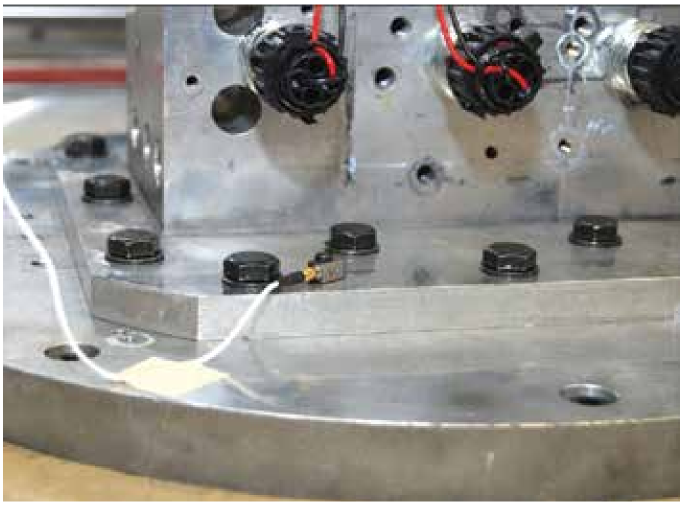
Highly accelerated life testing (HALT) and highly accelerated stress screening (HASS)

Environmental testing is applied to validate the design criteria during product development in industries, such as aerospace products and others, to ensure reliability goals are met. Environmental Stress Screening (ESS) is a mode of environmental testing to ensure a product's life cycle and that it complies with quality, safety and other standards. This test is typically applied primarily to electronic components in order to force latent weaknesses and defects to manifest themselves through failure during the screening procedure.

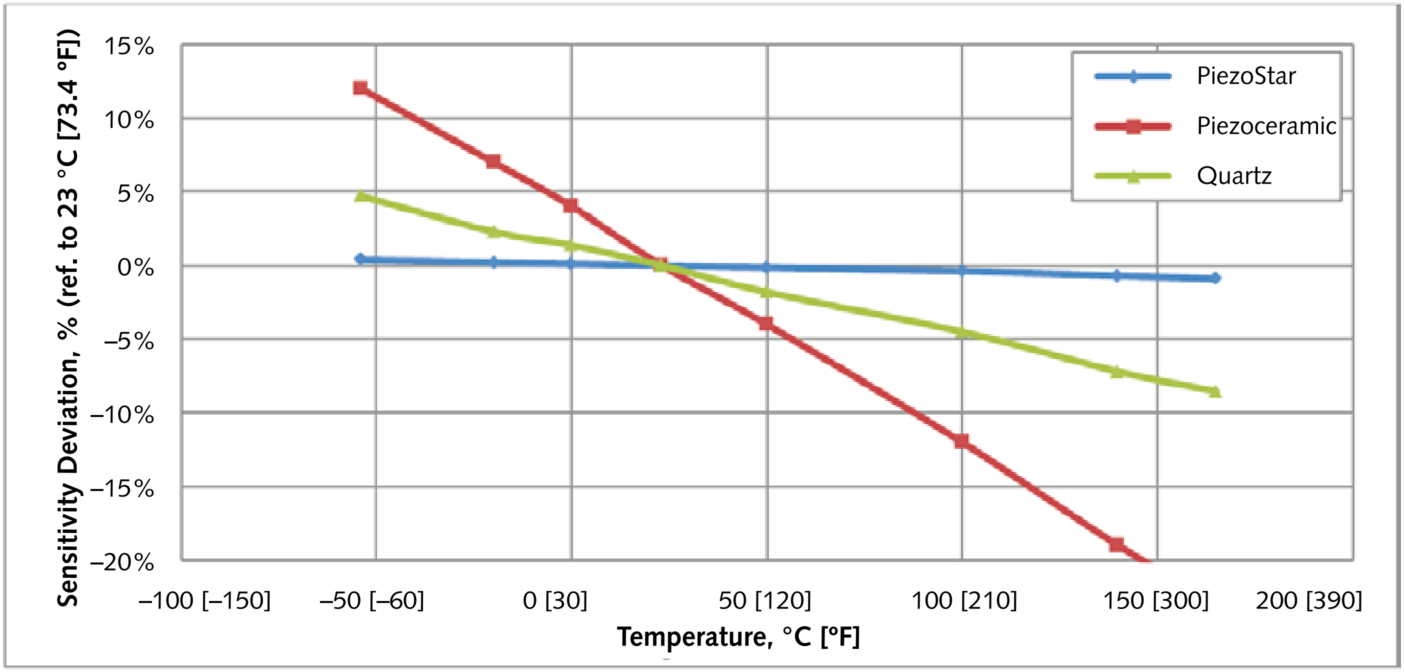
Generally, test units undergo combinations of extreme thermal and vibration stress tests. These again are distinguished into highly accelerated life testing (HALT) and highly accelerated stress screening (HASS).

Highly accelerated life testing (HALT) is a design verification process performed before a product is manufactured in order to detect design and assembly flaws. Subsequent improvements in design or assembly techniques can then be undertaken to ensure that the quality of the product is further improved.

Highly accelerated stress screening (HASS) is an evaluation process applied on production assemblies to all final products to help identify weak components and manufacturing defects that cause a higher probability of early failure. HASS involves exposure to environmental influences including vibration, temperature, humidity, and pressure.



Type 8715B250…teardrop PiezoStar accelerometer mounted to an electrodynamic shaker in a thermal chamber for highly accelerated life testing (HALT)



Typical sensitivity deviation with temperature of a PiezoStar voltage mode accelerometer compared to a sensor based on a ceramic or quartz sensing element

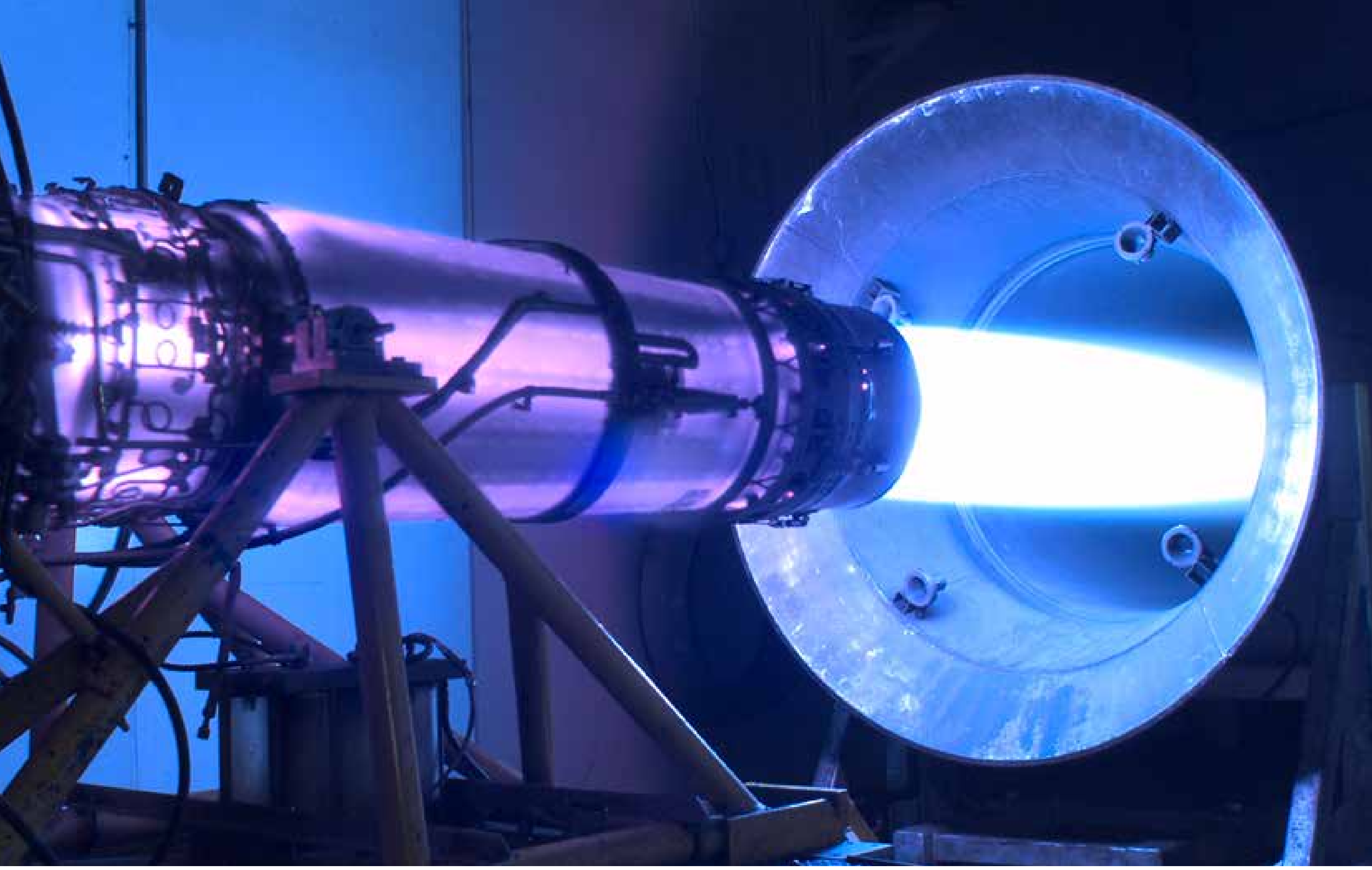
Important technologies for the application

- **High temperature stability**
  The PiezoStar-based IEPE (voltage mode) accelerometers from Kistler are the ideal sensors for precision vibration testing since, with temperature variations, they exhibit very low device sensitivity. There is no need to numerically compensate distorted input and output signals for temperature after the testing. This has been a problem with commonly used materials, notably piezoceramics, such as PZT (lead zirconate titanate).

- **Lightweight**
  Our PiezoStar based sensors are small and lightweight in order to avoid any mass loading effects that would lead to a change in behavior of the unit under test. These are two to four times smaller than any other crystal based sensors typically used under changing temperature conditions.

- **Easy mounting**
  Sensor solutions from Kistler may use a center hole design that allows for screw mounting when usage of standard removable adhesive is no longer possible. In addition, they offer an easy cable and measurement axis orientation. Generally, these sensors are ground isolated to avoid any ground loop issues.

Product highlights	
	Single-axis teardrop center hole PiezoStar accelerometer family Type 8715B
	Triaxial center hole PiezoStar accelerometer family Type 8765A
	Triaxial mini cube accelerometer family Type 8766A500



Characterizing the thrust of the engine itself allows for clear understanding of how much thrust can be produced with a given nozzle design

Rocket engine testing: thrust characterization

The fuel efficiency in both solid propellant for solid rocket engines, or fuel mixture in the case of liquid rocket engines, is of high concern for rocket engine designers. Characterizing the thrust of the engine itself allows for clear understanding of how much thrust can be produced with a given nozzle design. It allows engineers to compute the specific impulse of the combustion material and to study the different phases during the functioning of a rocket engine.

During start phase, ignition must be as fast as possible to produce a “clean burn” and avoid using too much fuel in this start phase.

During burn-in phase, one should not see vibrations nor pulsations in the thrust signature or in the dynamic pressure signature that will be mentioned in the following pages. Pulsations can increase the heat transfer drastically, resulting in nozzle burn-off. During this particular phase, it will also be very important to study the stability of the engine and particularly look into the shear forces that are generated with the aim to reduce them.

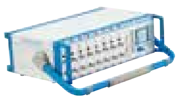
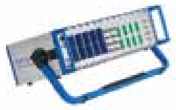
During switch-off phase, thrust must stop immediately. It is crucial that there will be no residual fuel that would generate toxins inside the rocket engine.

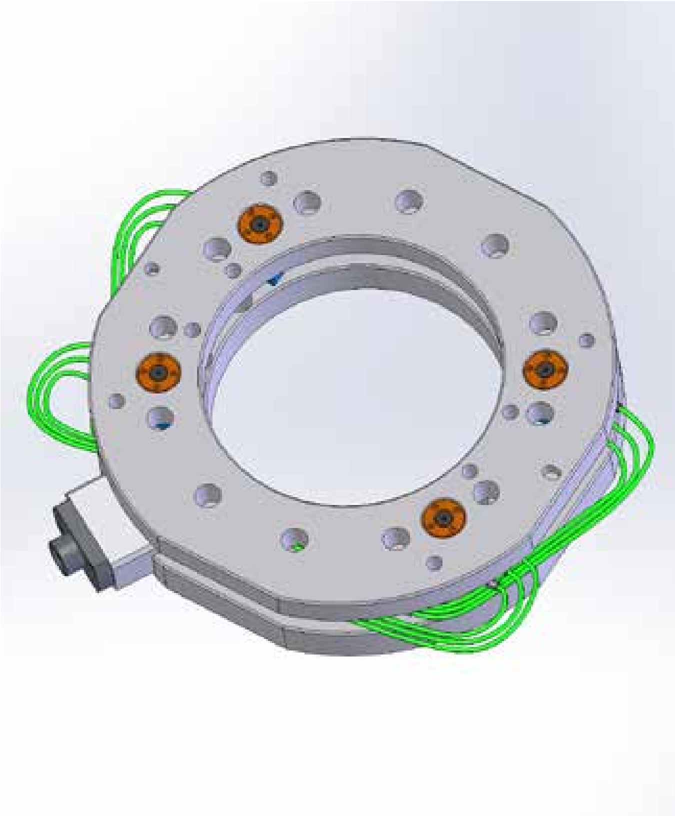
Important technologies for the application

- **High natural frequency**
  Depending on type of rocket engine, high frequency dynamic measurements are of interest during thrust characterization. Force solutions must exhibit at least 1 500 to 3 000 Hz natural frequency.

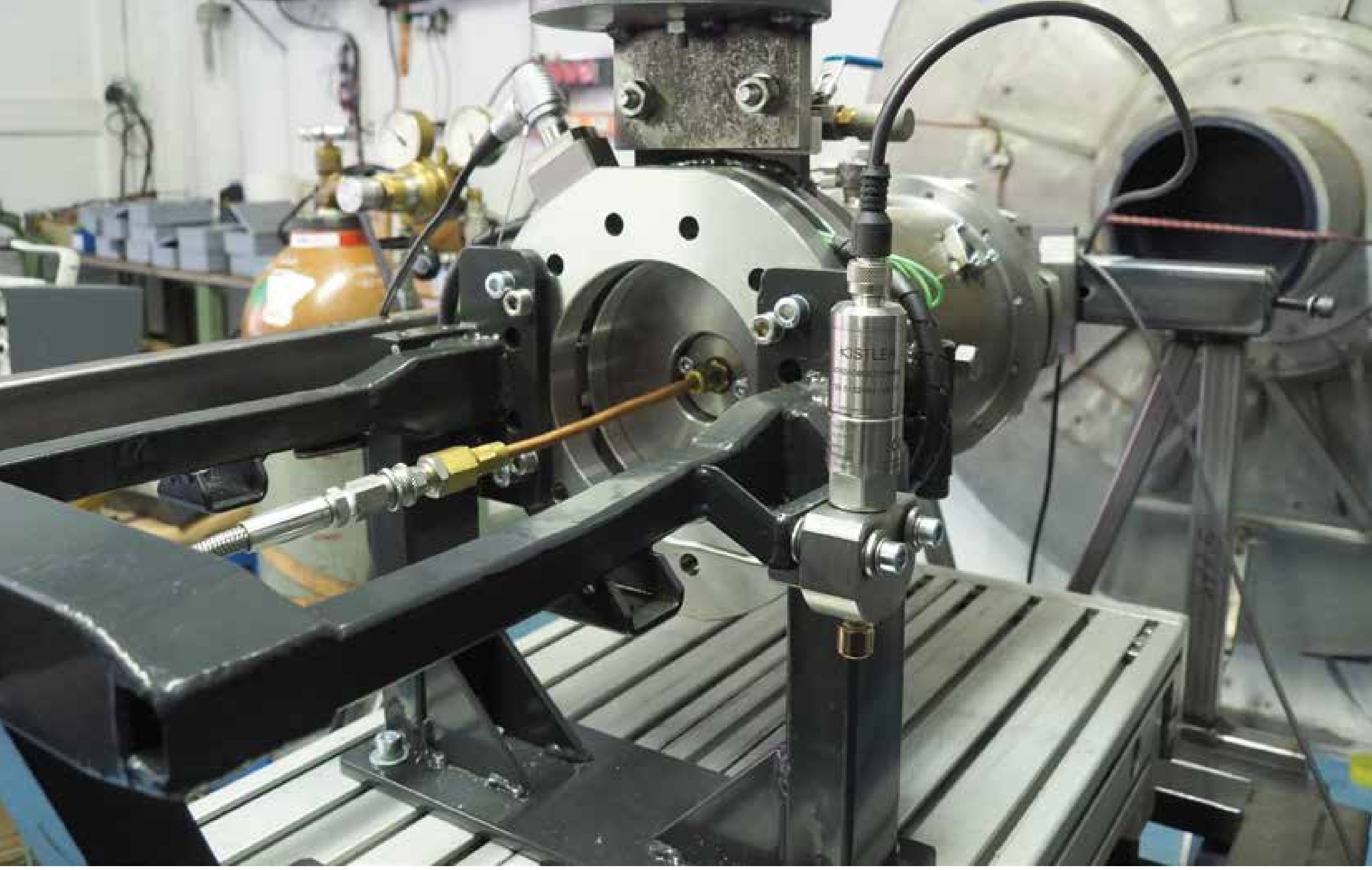
- **Rangeability**
  Piezoelectric force measurement technology allows both quasi-static and dynamic measurement with high resolution. The piezoelectric measuring chain allows to focus on the lower dynamic signals. It is through this capability that the high fidelity measurement can be achieved of the low level signals originating from thrust instabilities.

- **Adaptability**
  Single and multi-component force sensors from Kistler can be configured into dynamometers to satisfy specific application requirements and allow for the flexibility to adapt other dynamometer designs as requirements evolve.

Product highlights	
	Custom specific 6-component piezoelectric dynamometer (force/moment)
	Quasi-static 8-channel charge amplifier and data acquisition Type 5167A
	Type 5080A high-resolution laboratory charge amplifier for low-level thrust
	Universal and modular conditioning & DAQ system KiDAQ Type 5500 series



Special force dynamometer specifically designed for rocket thrust measurement on the Swiss Propulsion Laboratory test bench



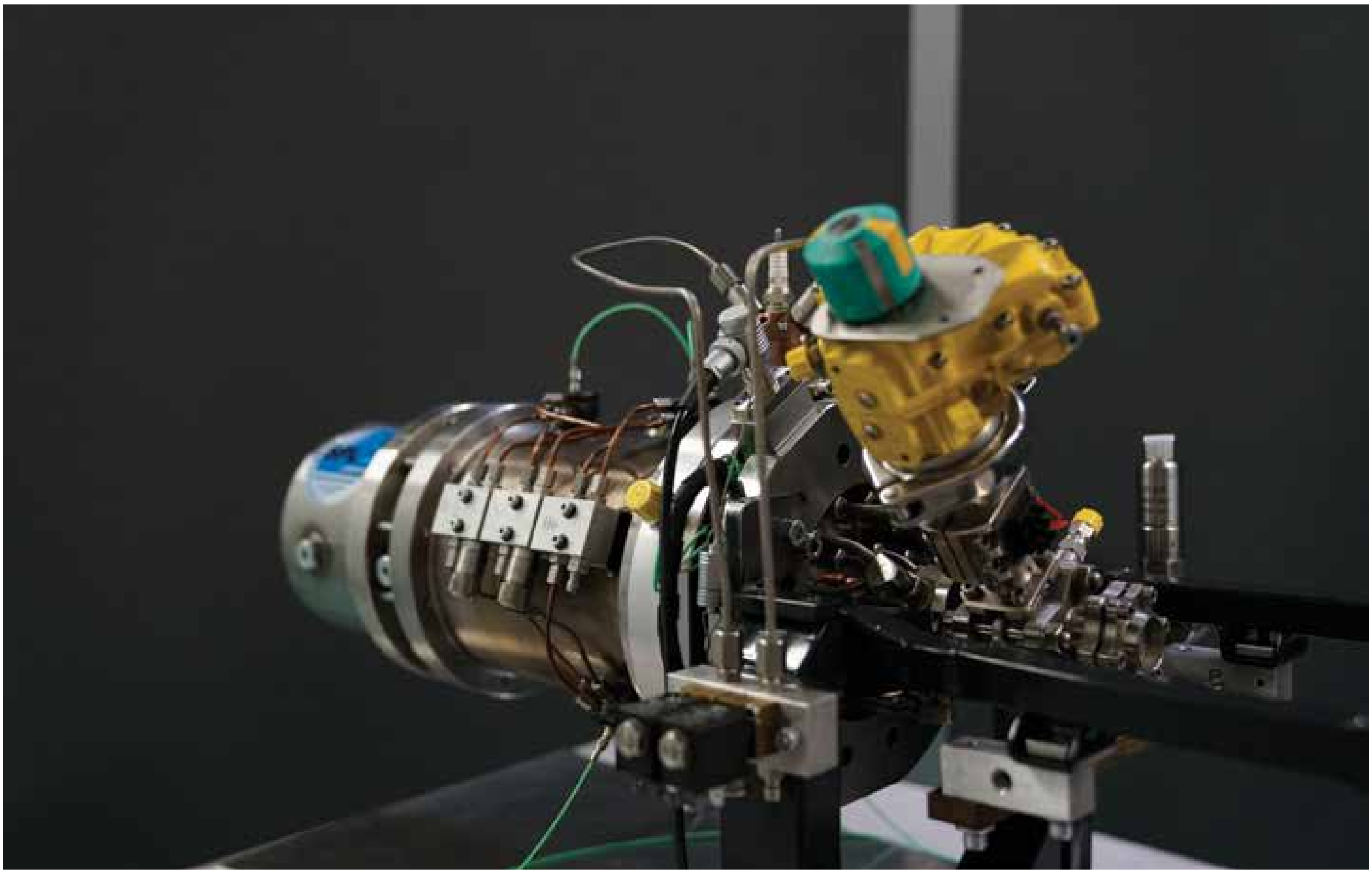
PRT pressure sensor Type 406xA series used for monitoring and control of propellant pressures (Source: SPL)

Rocket engine testing: static pressure monitoring and characterization

Static pressure monitoring is among the most important measurements conducted on a rocket engine test bench. This includes monitoring and controlling of propellant flow, as well as measuring the static pressure in the combustion chamber.

The monitoring and control of propellant flow for liquid propellant rocket engines requires static pressure sensors. Piezoresistive pressure sensors provide both a static and a limited dynamic measurement capability. Such pressure sensors utilize a cavity-etched, micro-machined, silicon-sensing element and are suitable for applications with media that are compatible with silicone oil filled capsules.

For measuring the static pressure in the combustion chamber, practical options include limited temperature piezoresistive pressure sensors featuring both static and limited dynamic measurement capabilities. Such piezoresistive pressure sensors are used with a long standoff distance from the combustion chamber to reduce the temperature at the sensor. In general, every meter of piping reduces the temperature by 125 °C (260 °F).



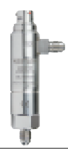
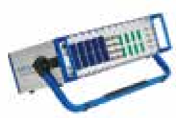
Fully instrumented rocket engine test bench with force dynamometer for thrust measurement, high temperature pressure and acceleration for combustion instabilities, as well as static pressure of control of propellant

Important technologies for the application

- **Frequency response**
  Long-term static pressure measurement requires piezoresistive technology which has inherent operation from 0 Hz up to 2 kHz unlike piezoelectric sensors, which allows only for quasistatic operation.

- **Intrinsic safety**
  Depending on the use and installation of the pressure sensor, inherent protection against igniting explosive environments may be required.

- **Long-term stability**
  Piezoresistive pressure sensors utilize an oil-filled and cavity etched, micro-machined, silicon-sensing element which provides inherent 0.1%/year long-term stability.

Product highlights	
	Absolute piezoresistive pressure transmitter Type 4260A
	Differential piezoresistive pressure transmitters Type 4264A
	Relative piezoresistive pressure transmitter Type 4262A
	Universal and modular conditioning & DAQ system KiDAQ Type 5500 series

Rocket engine ignition

Rocket engine testing: dynamic pressure and vibration characterization

In depth understanding of injection of fuel components and their mix, ignition time and combustion is absolutely essential in order to verify the reliable performance of a rocket engine and to drive the development of propulsion technologies. Piezoelectric pressure and acceleration sensors from Kistler span the extreme range of ultra-high temperature stability and dynamics required to tackle the challenges encountered in extreme thrust chamber environments.

Combustion instabilities
New or modified rocket engines require testing to demonstrate that combustion instabilities will not occur. Combustion instability is caused by pressure pulsations and acoustic resonances in the combustion chamber. It can reduce engine performance, induce structural vibration and lead to catastrophic failure by breakdown of the thermal insulation boundary layer of the nozzle or other engine components. The most widely used method to detect combustion instabilities is by means of piezoelectric pressure sensors located as close as possible to the thrust chamber to prevent pipe oscillation.

Liquid propellant fuel supply characterizations
When using liquid propellants, their distribution mechanism needs to be characterized and optimized. The opening and closing of the valves, for example, can induce a hammering effect which can be measured by means of pressure sensors. Cryopumps require testing as well. Here, dedicated cryogenic accelerometers and pressure sensors are to be applied.

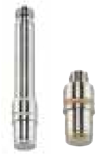
Ignition
Ignition systems can be designed in many ways and include different methods, such as pyrotechnic, electrical (spark or wire) and chemical ignition. The ignition of a rocket engine requires highest precision. A delay of ignition of a few tenth of milliseconds can cause overpressure of the chamber due to excess propellant. An uncoordinated start can even cause an engine to explode. Therefore, measuring the dynamic ignition pressure is essential for a safe rocket launch.

Important technologies for the application

- **Ultra-high-temperature capabilities**
  Ultra-high-temperature acceleration sensors from Kistler can be mounted close to the combustion chamber and are the preferred choice for optimized combustion instability measurement. In such applications, temperatures can reach up to 550 °C (930 °F). Standard piezoelectric sensor families with watercooling or helium bleed solutions can be applied as well, but the waterflow will generate noise.

- **Cryogenic capabilities**
  The cryogenic piezoelectric accelerometers and pressure sensors from Kistler span an outstanding temperature range down to -196 °C (-320 °F). During liquid propellant fuel supply characterizations, liquid methane temperatures can reach down to -173 °C (-280 °F) and liquid oxygen can reach temperatures down to -183 °C (-300 °F).

- **High-pressure capabilities for ignition**
  While measuring during the ignition phase, highly dynamic high pressure sensors will detect high pressure peaks, very high and fast rising thermal shock events with very harsh sensor diaphragm exposure.

Product highlights	
	700 °C (1 300 °F) high-temperature pressure sensor with hardline cable Types 6021A, 6023A and 6025A
	700 °C (1 300 °F) high-temperature accelerometer with hardline cable Type 8211A
	Piezoelectric pressure sensor family Type 60xC… with cryogenic capabilities
	Single-axis voltage mode miniature cryogenic accelerometer family Type 8730
	Triaxial voltage mode cryogenic accelerometer family Type 8793A250M8

Combustion instability investigations use high-temperature Type 6021A pressure and Type 8209A acceleration sensors

Kistler Services: increasing success you can measure

Good service is the cornerstone in daily interactions with customers. For Kistler, however, the term "good" is simply not good enough. We therefore provide you with an extensive service program that is tailored exactly to your specific needs.

Kistler Services do not end with the purchase of sensors and electronic measuring equipment. We are happy to provide you with advice regarding your measuring problem and help you select the right components. Our experienced service technicians provide on-site support to ensure that your new Kistler system is optimally integrated, connected and configured into your system. After a short introduction, you can immediately begin your measurement task.

Calibration with continuous documentation
Our calibration service provides you the security of knowing that your Kistler sensors and systems will remain fully functional over the entire operating time – the basis for precise and reliable measurement results. Each calibration is documented, without exception. On request, our measurement technology experts can also perform the calibration directly at your location. Thanks to calibration laboratories in China, USA, Japan and Germany, we can perform recalibrations quickly and efficiently on-site.

Custom solutions
As a system provider, Kistler supplies you with complete solutions that optimally meet your measurement needs. Our specialists are happy to design a new, tailor-made solution together with you – for even better performance in your field of application.

Kistler Services
- Guidance on how to define your measurement task and to select the components
- Start-up
- Device calibration
- Repair
- Training
- Customized solutions

At our customers' service across the globe

Thanks to Kistler's global sales and service network, we are always close to our customers. Approximately 2 000 employees at 61 locations are dedicated to the development of new measurement solutions and offer customized on-site support of individual applications.

Find out more about our applications:
www.kistler.com/applications

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