Sensors and systems for the measurement of forces and torques, for the analysis of force-distance and force-time characteristics and for the documentation of quality data in assembly and product testing are only one of the modules of the industry solutions from Kistler Instrumente AG. In addition to assembly and testing technology, we also offer special sensors and monitoring systems for mechanical production, for fuel engines, for automotive engineering, plastic processing and biomechanics.

Numbered among the core competencies at Kistler are development, production and utilization of sensor for the measurement of pressure, force, torque and acceleration. The measurement signals thus acquired can be processed and utilized through Kistler know-how and our electronics systems. The objective is the analysis of physical procedures. These are applied in the control and optimization of processes and in the enhancement of product quality in the manufacturing sector. Each year, Kistler invests 10% of its revenues in research and development, thus providing innovative and economical solutions at the state-of-the-art of knowledge.

The Kistler Group is comprised of 30 Group companies. These are present around the globe in 30 countries at a total of 53 sites. Selected representatives distribute Kistler products and solutions in more than 30 additional countries.
Fundamentals of Cutting Force Measurement.

Challenges in Production
Worldwide, most metallic components are still produced using a variety of machining techniques. However, in recent decades all these production processes have seen major changes, both advancements in technology and ever growing demands for complete process improvement.

Across all industries, conflicting requirements to increase product quality, whilst reducing costs and recognising environmental impact factors are getting ever greater. A detailed understanding of the process is essential in order to meet these new obligations. It is therefore vital to analyse the machining operation so we can better understand and control it.

The forces and torques generated during machining are important indicators which help to determine what is happening to the material, and the tool, when they interact. This information can then be used to improve factors such as surface finish and tool wear.

Acquisition of Highly Dynamic Forces During Machining
The highly dynamic nature of these force and torque signals mean that any measurement or analysis is only possible with sophisticated sensor systems which been developed specifically for a machining environment. Piezoelectric technology provides just such a robust and accurate solution.

Milling of high-grade alloy steel with dynamometer Type 9255C

What is Cutting Force Measurement Used For?

• Analysis of machining process
• Optimization of the machining process
• Comparison and optimization of machining strategies
• Quantification of the energy implemented in plastic-mechanical processes
• Determination of materials characteristics and machinability
• Analysis of tool wear mechanisms
• Dimensioning of machine structures/components
• Optimization of tools
• Verification of simulation results and process models
Possibilities of Cutting Force Measurement

Decades of experience and continuous product development have seen Kistler Dynamometer systems become the benchmark for machining data acquisition and analysis. They provide accurate and reliable measurements with specific units developed for all types of machining operations including turning, milling, drilling and grinding. Our patented sensor technology provides immense signal detail. The exceptionally rigid measuring elements allow signal tooth identification, even for very high speed machining operations, whilst the unique, flexible range selection allows the same system to measure equally accurately newtons and kilonewtons. Our micromachining systems provide reliable measurements down to fractions of newtons. We provide two distinct designs of Dynamometer, one stationary, one rotating. The full, turnkey, system also includes electronics for signal conditioning and software for data analysis.

Accelerations in Machining

In addition to force and torque signals, the acquisition of acceleration measurements can also be important for the analysis of a manufacturing process. A familiar problem, for example, is the chatter that causes the machining process to become unstable due to poor engagement conditions. This leads to the system experiencing excessive vibration and the quality of the surface finish suffers. Accelerometers mounted on the machine make it simple to monitor this vibration induced chatter, or indeed any other vibrations seen by the tool and work piece. Particularly in the area of research, the force and torque signals are frequently combined with those from accelerometers in order to recognize special effects. Kistler designs and manufactures high-quality sensors for the measurement of acceleration and acoustic emission. The robustness of these sensors makes them ideal for metal-cutting and fabrication environments and enables valuable insights into the dynamics of the manufacturing process.
Process Analysis and Optimization.

Important Variable of the Machining Process
The overall optimization of the manufacturing process, and the accompanying reduction in manufacturing costs, are fundamental prerequisites for being able to produce with greater economic efficiency. Process analysis and optimization are becoming ever more important as a result of the increasing requirements. Acquisition of the forces and torques generated during machining have a central role to play here due to the wealth of information they provide. The dynamometers used for the quantification of these two variables are indispensable aids, both for academic research and in manufacturing technology laboratories in industry.

Safe Manufacturing Processes Thanks to Process Analysis
The optimization of the manufacturing process with respect to economic efficiency is however just one aspect. Another factor of equal importance is the controllability of the process, in particular with respect to structural elements critical for safety. Examples from the aerospace industry show that a lack of control and understanding in the manufacturing processes can have fatal consequences. This is also made more difficult by the fact that, particularly in the aerospace industry difficult-to-machine materials are utilized more and more. Such materials require specialist knowledge and detailed process analysis to provide an efficient and repeatable manufacturing process.

Dynamometers as the Basis for Process Analysis
It is for these reasons that piezoelectric dynamometers are used for the determination of the machinability of materials, the improvement of tool geometry and coatings, as well as for the qualification of process strategies. Furthermore, they provide invaluable information for the investigation of chip formation and tool wear. Last, but not least, for the verification of process simulations and models. Piezoelectric force sensors offer invaluable insights into the influences of individual process parameters, not only for component manufacturers, but also for ancillary equipment suppliers such as coolant, lubricants, tools and clamping devices. It is only through such detailed analysis that differentiation with respect to competitor products becomes possible and that a decisive sales argument can be made.

Forces Associated with Machining Provide Direct or Indirect Information Regarding:
• Machinability of materials
• Wear mechanisms
• Surface qualities
• Form deviations
• Vibrations/unstable engagement conditions
• Residual stresses
• Thermal energy in the system
Measuring with Dynamometers
As a basic rule, a distinction is to be made between two families of dynamometers. On the one hand, there are the stationary dynamometers, that are mainly set up on the table of the machine tool, while on the other hand there are the rotating dynamometers – also called RCDs – that are retracted into the spindle via the spindle interface and rotate along with it.

Stationary Dynamometers
Stationary dynamometers are very versatile in their utilization. With them, the workpiece is often fastened on the dynamometer with which the reaction forces in manufacturing processes such as milling or drilling are measured. Stationary dynamometers are also used for turning applications. These are fitted directly to the turret head with corresponding machine adapters. The tool is placed on the dynamometer with a suitable tool holder. Depending on the structure of the stationary dynamometer, the forces are measured by one or more multi-component force sensors and are available at the connector of the dynamometer in the form of charge signals.

Rotating Dynamometers
Rotating dynamometers (RCD) are mounted directly on the machine spindle via the spindle interface. The tool is mounted at the RCD with the aid of a tool holder. The RCD is used mainly in milling and drilling processes. In contrast to stationary dynamometers, only one multi-component sensor is installed in each rotating dynamometer. In addition to the sensor, the rotor also contains the charge amplifiers, i.e. the electronics that converts the charge into voltage, and the telemetry electronics. The measurement data is forwarded to the stationary part of the measuring chain via near-field telemetry, where it is subsequently made available as analog voltage signals.

Piezoelectric Technology in Dynamometers
The consistent utilization of piezoelectric technology in the dynamometers results in several decisive advantages. To be mentioned here, for example, is the large measurement range that extends over several decades. In combination with the high linearity that piezoelectric sensors bring with them, it is possible to measure small forces, even with large dynamometers. A further decisive advantage is the rigid construction of the measuring devices and the great rigidity of the piezoelectric crystals themselves. This enables high natural frequencies of the dynamometer to be achieved. These in turn also make it possible for processes with high tooth passing frequencies, i.e. excitation frequencies, to be able to be acquired and measured properly. Kistler dynamometers are designed for application in raw environments and are therefore very robust and durable in their construction.

Advantages of Kistler Dynamometers

- High rigidity and consequently high natural frequency
- Wide measuring range
- Robustness
- Cooling lubricant-proof (IP67)
- Compact design
- Exceptionally durable
- Simple operation
Stationary 3-component dynamometers contain four 3-component force sensors that are installed in the structure of the dynamometer under high pretension. The outputs of the four sensors are interconnected in such a way that, in addition to the conventional 3-component force measurement, the force/torque measurement ($F_x, F_y, F_z, M_x, M_y, M_z$), is also made possible. The torques are calculated from force components. The structure of the sensors and the dynamometer excludes ground loop problems to a large extent.

Stationary 4-component dynamometers contain only one multi-component sensor. This is also installed in the structure under high pretension. The measurement of the three force components ($F_x, F_y, F_z$) is accomplished through stacking of measurement elements with respective sensitive directions. The direct measurement of the torque $M_z$ is enabled by a multitude of shear-sensitive crystals that are aligned tangentially around the vertical axis of the sensor.

Depending on their design, rotating dynamometers are equipped with a 2-component or a 4-component sensor. These are tensioned under high pretension between the spindle adapter and the tool holder of the RCD. The structure of the 4-component sensor used is similar to that of the sensor that is installed in stationary 4-component dynamometers, although this sensor is completely rotation-symmetrical in order to prevent unbalance.

Advantages of Rotating Dynamometers

- Direct measurement of the torque $M_z$
- Measurement very close to the tool
- No influencing of the dynamics by changes in the mass of the workpiece
Influence of Pretension
The structure of dynamometers is always similar as a rule. A piezoelectric force sensor is mounted under high pretension between two massive plates, the base and the cover plate. A so-called pretension screw that is guided through the center of the sensor, connects the base and cover plate and ensures that the force sensor placed between them is pretensioned. This pretensioning is exceptionally important for two reasons. On the one hand, the structure requires the pretension in order to be able to record shear forces and measure them accordingly. On the other hand, the pretension ensures linear behavior of the dynamometer. Particularly with small forces, the behavior of the structure would be markedly non-linear without the pretensioning.

Possibilities of the Pretension
Two possibilities exist for the pretensioning of the sensor with the stationary dynamometer. Vertical pretensioning is very well-known. It has been in use for many years. At the same time, horizontal pretensioning has come into increasing use in recent years. The two pretensioning methods will be discussed in the following.

Advantages of Dynamometers with Vertical Pretension
- Larger measurement range
- Hardly any limitations with respect to size

Advantages of Dynamometers with Horizontal Pretension
- Significant minimization of thermal influences on signals
- Compact construction
- Higher natural frequencies

Vertical Pretensioning
Vertical pretensioning represents the classic method of a structure. The multi-component force sensor is placed between a base and a cover plate and is pretensioned with a pretension screw. The pretensioning proceeds in vertical direction - one also speaks in such cases of a standard pretensioning.

Horizontal Pretensioning
The horizontal pretensioning patented by Kistler is much less widely used. The classic structure with base and cover plate is thereby no longer used; instead, two multi-component force sensors are pretensioned between the two side plates and the cover plate with a pretension screw. The pretensioning direction is horizontal. Negative influences by temperature changes on the measurement signal can be significantly reduced by the appropriate selection of the coordinate system of the two jointly pretensioned sensors and by the corresponding switching of the signals. In addition, the smaller overall height and higher natural frequencies are also numbered among the advantages of this pretensioning method.
Special Considerations of Piezoelectric Materials

All of the dynamometers manufactured by the Kistler Company for use in machining are based on the piezoelectric measurement principle. Piezoelectric materials are installed in the sensors as sensitive elements. These generate a charge proportional to the effective load. As a basic rule, piezoelectric materials are sensitive in just one direction and are cut out of the crystal or quartz bars in accordance with the desired measurement direction.

Utilization of Various Effects

In the case of 3-component force sensors, both the longitudinal effect and the shear effect is used for the measurement of the forces. If a longitudinal crystal disk is exposed to vertical loads, then minuscule shifts in the center of gravity of the charge arise in the disk. In contrast to crystals with longitudinal cross-sections, crystals with cross-sections in the direction of the shearing react sensitively to shear loads. With the shear effect as well, an offset of the centers of gravity of the charge also take place in the crystal, leading in turn to a charge difference between the surfaces. These measurable charge differences are conveyed through highly insulated cables to the charge amplifier, where they are converted into voltage signals.

Meaning of Cleanliness

The charge differences described are exceptionally small. In order to be able to achieve meaningful measurements of them at all, and also in order to be able to achieve the high insulation resistances, very high requirements are made of the production and cleaning processes of all sensor and cable structural elements with respect to cleanliness. It is only thus that negative influences on the measurement signals can be avoided.

Advantages of the Piezoelectric Technology in Dynamometers for Machining

- High surface pressure of around 150 N/mm²
- High linearity
- Very high rigidity
- Negligible hysteresis
- Large frequency range
- Practically unlimited number of load cycles
Measuring Chains.

Measuring
The core of a measurement system for cutting force measurement is the actual measuring device itself: a dynamometer. The forces and, depending on the type, the torques as well are measured.

Here, too, the central concern when measuring the cutting forces is the reliability of the system. In order for this to be able to be guaranteed, Kistler placed great emphasis, even in the planning stages for the measuring devices, on the coordination between components. Particular attention is directed thereby to the stability and key figures of the individual components and to their insulation against coolants and other sources of soiling. Dynamometers and cables are equipped with ground isolation, thus guaranteeing malfunction-free operation.

Connecting
A reliable connection between dynamometer and charge amplifier is of maximum importance for the quality of the measurement signals. The ground-insulated cables for the cutting force measurement are protected with a sealed metal hose, thereby making them suitable for the raw operating conditions in a machine tool. The cables are fitted with stable connectors at both ends, thus ensuring that the protection class IP67 is achieved at the connection to the stationary dynamometer. The cable concept offered by Kistler is uniform, thus simplifying its application.
Amplifying
So-called charge amplifiers are necessary in order to utilize effectively the charge difference that arises when piezoelectric sensors are loaded. These electronics are essentially comprised of an inverting charge amplifier with high inner amplification and convert the charge signals into proportionate voltage signals. Dynamometers that measure more than one component require the corresponding number of charge amplifiers. The multi-channel charge amplifiers developed by Kistler are optimized for measurement tasks such as cutting force measurement and are very modular in their design to some extent. This makes it possible to combine force and acceleration signals very readily in the same device. Depending on the Type, the adjustment of the parameters can be undertaken directly using menus on the charge amplifier or conveniently at the computer.

Acquiring/Analyzing
Kistler offers optimized software for data acquisition and analysis with cutting force measurement. With the Kistler DynoWare, it is possible to set all of the parameters of the respective charge amplifiers that are important for data acquisition. The acquired data is presented in a graphics form and facilitate, together with various functions, the signal processing and analysis of the measurement signals. With DynoWare, it is easy to document and export the data.
Cutting Force Measurement – Turning.

**Fundamentals of Turning**
Turning is a process with a geometrically defined cutting edge and circular cutting movement for which as a rule the workpiece performs the rotary movement and the tool performs the feed movement.

**Turning as Model Case of Machining**
Turning, particularly longitudinal turning, is a model case of machining with a geometrically defined cutting edge that is used, because of its constant engagement conditions, to determine and characterize specific forces \((k_c, k_p, k_f)\) of certain materials subject to different ancillary conditions. Cutting force measurement is frequently resorted to investigate plastic-mechanical processes in the actual cutting process, to analyze chip formation and its influence on the process or to highlight wear processes with force progressions.

**Stationary Dynamometers with Turning**
Stationary dynamometers are used to measure the forces during turning. These dynamometers are modular in structure and are usually mounted on the turret of the machine tool with the aid of a suitable adapter. The tool is fastened to the dynamometer with a tool holder, whereby the dynamometer is embedded between the tool and...
the turret. With this structure, the forces at work can be acquired accurately and highly dynamically so that even the smallest changes in the process chain can be quantified at once.

The cutting force created by the turning process is broken down immediately into the three components cutting force \( F_c \), feed force \( F_f \) and passive force \( F_p \) with the aid of multi-component dynamometers.

**Modularity of Stationary Dynamometers**

Depending on the size of the machine tool, the tools and the loads, users have several dynamometers to choose from for measuring cutting force while turning. They are modular in construction and can be equipped in just a few steps with various machine adapters and tool holders. As a result of their structure, negative thermal effects are largely minimized, thus resulting in a considerable enhancement of signal quality and the information it provides.

**Forces during longitudinal turning**

**Typical measurement signals while turning**

**Directly Measurable Force Components While Turning**

- Main cutting force \( F_c \)
- Feed force \( F_f \)
- Passive force \( F_p \)
Cutting Force Measurement – Milling.

Fundamentals of Milling
Like turning, milling is a process with a geometrically defined cutting edge. The rotating and usually multi-cutting edge tool performs the cutting movement while the feed movement, depending on the type of construction of the machine tool, is carried out by either the spindle head or the machine table. The cut is interrupted, i.e. the cutting edge of the tool is not engaged during the entire rotation. Because of the changing chip thickness and the varying number of cutting edges currently engaged, the forces are also changing constantly. This means that the dynamometer is subjected to extremely strong dynamic loads. Particularly with milling, the high natural frequencies of the piezoelectric dynamometers are a decisive advantage for obtaining high-quality signals despite high tooth passing frequencies.

Stationary or rotating dynamometers can be used for cutting force measurement when milling, depending on needs and requirements.

Stationary Dynamometers with Milling
If a stationary dynamometer is used, then this will be mounted on the table of the machine tool while the workpiece is installed on the dynamometer. In order to reduce the mass on the dynamometer and thus to reduce the negative influence on the dynamics of the dynamometer, the workpiece is screwed directly to
the dynamometer, thus making it possible to dispense with the heavy and often non-rigid clamping devices. The active force can be calculated in simple steps from the feed force and the normal feed force.

**Rotating Dynamometers with Milling**

A rotating dynamometer (RCD) is inserted directly into the machine spindle while the tool is connected with the RCD via the respective tool holder. The RCD rotates as well during operation due to the connection with the machine spindle. An RCD has two advantages over stationary dynamometers: On the one hand, the dynamics of the measurement instrument is not influenced by changing masses, as the tool mass remains constant. On the other hand, it is possible with the aid of the built-in multi-component sensor to measure the torque $M_z$ directly during the entire measurement, thus making it possible to have, for example, precise statements regarding the wear on the tools.

The utilization of rotating dynamometers also permits the calculation of the active force $F_a$ in simple steps from the forces $F_x$ and $F_y$. The cutting force in effect $F_c$, in addition to the normal cutting force $F_{cn}$, can be calculated with the aid of the torque $M_z$ and the active force.

**Forces Measurable with Stationary Dynamometer During Milling**

- Feed force $F_f$ (force in the feed direction of the tool)
- Feed normal force $F_{fn}$ (force perpendicular to $F_f$)
- Passive force $F_p$

**Forces Measurable with Rotating Dynamometer During Milling**

- Spindle moment $M_z$
- Passive force $F_p$
- Forces $F_x + F_y$ in the active cutting plane
Drilling is also a process with a geometrically defined cutting edge. Processes similar to drilling, e.g. counterboring, reaming or tapping, are also based on the same process kinematics. Most of the tools used for these processes have more than one cutting edge. The rotating tool to be found in most cases performs the cutting movement, while the feed, depending on the type of construction of the machine tool, is carried out by either the spindle head or the machine table. Because of the non-interrupted cut, excessively long chips often result that must also be conveyed out during drilling. The thermal load of the workpiece and the drilling tool is high, which is why particular attention is paid to this process, particularly in cases of structural elements critical to safety. The cooling of the drilling process is of great importance in this connection.

Possibilities of Force Measurement
Either stationary or rotating dynamometers can be used for the measurement of the processing forces during drilling. A rotating dynamometer (RCD) is inserted directly into the machine spindle while the tool is connected with the RCD through the respective tool holder. The RCD rotates as well during operation due to the connection with the machine spindle. The cutting force $F_c$ and passive force $F_p$ that affect the drilling process can be measured directly.

Advantages of Using a Rotating Dynamometer
- Direct and precise measurement of the drilling process $M_z$
- Possibility of using the internal cooling of the tool
- No influencing of the dynamics of the measuring device by the workpiece mass
tool can be calculated with the aid of the drilling torque \( M_z \) and the deflective forces \( F_x, F_y \), whereas the feed force \( F_f \) can be determined directly.

**Rotating Dynamometers with Drilling**

In comparison with the stationary dynamometer, the use of rotating dynamometers for drilling exhibits decisive advantages, which is why the use of RCDs for measuring forces during drilling is recommended.

The first advantage in particular, namely that the measurement of the drilling torque takes place directly, enables for example a distortion-free acquisition of effects of tool wear during the process.

**Stationary Dynamometers with Drilling**

Stationary dynamometers can also be used for the acquisition of forces during drilling. It is possible with them to acquire the forces in three directions. The torque will not be measured directly, but will instead be calculated from the various measurement signals of the force sensors.

**Typical measurement signals while drilling (acquired with rotating dynamometer)**

![Diagram of forces during drilling](forces_during_drilling.png)

**Directly Measurable Components with Drilling Processes with Rotating Dynamometers**

- Drilling moment \( M_z \)
- Deflective force \( F_x \)
- Deflective force \( F_y \)
- Feed force \( F_f \)

**Directly Measurable Components with Drilling Processes with Stationary Dynamometers**

- Feed force \( F_f \)
- Deflective force \( F_x \)
- Deflective force \( F_y \)
Piezoelectric Technology – Charge Amplifier.

Charge Amplifiers
Charge amplifiers convert the charge yielded by a piezoelectric sensor into a proportional voltage. A charge amplifier consists essentially of one inverting voltage amplifier with high internal amplification and capacitive feedback. If one ignores the two resistances $R_t$ and $R_i$, the following output voltage results:

$$U_o = \frac{-Q}{C_r} \cdot \frac{1}{1 + \frac{1}{AC_r} \left(\frac{1}{C_t + C_r + C_c}\right)}$$

If there is sufficiently high internal amplification $A$, the quotient $1/AC_r$ is near zero. The cable and sensor capacity thus lose their influence and the output voltage depends solely on the charge at the input of the charge amplifier and on the range capacitor:

$$U_o = \frac{-Q}{C_r}$$

Schematic diagram of a piezoelectric measuring chain
The amplifier acts as an integrator and continuously compensates the electrical charge emitted by the sensor with an equal and opposite charge at the range capacitor. The voltage that arises via the range capacitor is proportional to the voltage emitted by the sensor and thus also proportional to the effective measurement variable.

The charge amplifier thus converts an electrical charge \( Q \) at the input into a voltage \( U_o \) proportional to it at the output that can be readily processed further.

**Time Constant and Drift**

Two properties of the charge amplifier important for practical use are the time constant and the drift. The time constant \( \tau \) indicates the time after which the voltage at a capacitor has dropped during discharge to \( 1/e \) (37%) of the starting value. The time constant of a charge amplifier is determined by the capacity \( C_r \) of the range capacitor and the time constant resistance \( R_t \):

\[
\tau = R_t \cdot C_r
\]

Drift is used to refer to an unwanted change in the output signal over a prolonged period that is not a function of the measurement category. Even the best electronic structural elements exhibit leakage currents which are mainly responsible for the drift. An insulation resistance \( R_i \) at the input that is too low can cause an additional drift. However, as long as the insulation resistance in the feedback loop is sufficiently high (>\( 10^{13} \Omega \)) and no additional time constant resistance is switched in parallel, the charge amplifier will drift only very slowly into either the positive or the negative limitation. This drift determines the possible duration of quasi-static measurements and is not dependent on the selected measuring range.

**Frequency Range and Time Range**

In addition to the time frequency, the time constant also influences the frequency range. It determines the lower limit frequency. The longer the time constant is, the lower the lower limit frequency will be and the longer the usable measurement time will become. For quasi-static measurements like cutting force measurement, the largest possible time constant is always used for working with for this reason.
Piezoelectric Technology – Calibration.

Calibration
Sensors and measuring devices must be calibrated regularly because their properties and thus the measurement uncertainties can change over time due to usage, aging and environmental influences. The measuring equipment used for calibration are subject to national recall and are also subject to an internationally uniform quality assurance. Calibration certificates document the values measured at the time of the calibration and the calibration conditions.

Safety and Reliable Measurements
Quality assurance systems and product liability statutes require the systematic monitoring of all testing equipment that is used for the measurement of quality-relevant features. It is only this way that the measurement and testing results achieved can provide a reliable and trustworthy basis for quality control.

All sensors and electronic measuring equipment have a certain measurement uncertainty. Because of the fact that measurement deviations may change over time, testing equipment must be calibrated periodically.

Basic principle: Calibration is the use of a defined method under specified conditions to determine the relationship between a known input variable and a measured output variable.
For this purpose, determination is made of the deviation of the measured value from a value that has by agreement been recognized as being correct (reference value or so-called calibration norm). The result of the calibration then permits either the allocation of the values of the measurement category to the displayed measurement values or the determination of corrections for the display. The information required for this purpose is documented in a calibration certificate.

**Calibration Procedure**

**Continuous calibration** is usually used for the calibration of piezoelectric sensors, i.e. also for the stationary and rotating cutting force dynamometers.

During continuous calibration, the load is increased continuously to the desired value during a defined time period and then reduced back down to zero within the same amount of time. For the never-exact linear characteristic curve that results, a so-called ‘best line’ that runs through the zero point is determined that has a slope that corresponds to the sensitivity of the sensor. The linearity results from the deviation between the characteristic curve and the best line. The hysteresis corresponds to the maximum distance between the ascending and descending progression of the characteristic curve.

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**Calibration at a Glance**

Kistler offers complete service for all aspects of calibration:

- testing equipment calibration
- accredited calibration laboratory (SCS 049, DKD-37701)
- comprehensive function testing and
- versatile verification documents

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The continuous procedure is the most suitable for the calibration of piezoelectric force sensors.
Piezoelectric Technology – Special Considerations For Calibration.

Influences on the Measurement Results
Numerous mechanical, electrical and climactic parameters influence the calibration result and thus the accuracy of a measuring chain. In order to achieve a calibration that is as accurate as possible, assembly errors are to be avoided and the position and angle of the initiation of both force and torque are to be noted. Furthermore, the non-linearity of various electrical variables along the measuring chain is to be taken into account. Last but not least, temperature and humidity also play an essential role.

The simultaneous calibration of three force components is numbered among the most sophisticated requirements for the calibration of multi-component dynamometers. The force load is initiated sequentially on the 3-component calibration system at Kistler, while the calibration object remains in the installation position.

Drift
The drift of a charge amplifier is a global description for the drifting of a signal zero point, caused mainly by charge losses on the feedback loop capacitor and leakage currents at the amplifier input. A fault current flows through the insulation resistance by which the feedback capacitor is exponentially discharged with the time constant – the product of the insulation resistance and the capacitor capacity. If sufficiently high insulation resistances are present, then the time constants are very high, which means in turn that the discharge is relevant only for very long measurement times. As a result of comprehensive investigations, the drift characteristics of charge amplifiers are very well known, which means that their maximum value can be applied for the evaluation of the influence of drift on the calibration result.
Linearity
The overall behavior of electrical devices is generally not linear, given that it is rare to have all installation components exhibit linear behavior. This applies as well for charge calibrators and charge amplifiers, the very low non-linear characteristics of which influence the calibration result. Force and torque sensors also exhibit a non-linear characteristic. The linearity that is determined as the result of the calibration is documented in the calibration certificate and is incorporated as a contribution into the measurement uncertainty observation of the calibration. The linearity of the reference sensor is already included in the measurement uncertainty and requires no further consideration.

Humidity
Relative humidity affects the behavior of electronic structural elements, as it also does that of the capacitors used in charge amplifiers and charge calibrators. The thermal properties of electrical measuring devices are acquired and documented at the time of type testing. This knowledge makes it possible to determine the influence of humidity fluctuations on the calibration result.

Best-Measurement Capability
A reference sensor with a so-called ‘Best Measurement Capability’ is used for calibration in accordance with the comparison procedure; the reference sensor possesses a documented measurement uncertainty resulting from its calibration against a higher-quality standard. The charge amplifier is also to be calibrated with the aid of a precision charge calibrator before the calibration object is calibrated. This ensures that the voltage displayed on the charge amplifier is coordinated with the charge that was created by the force sensor. In the absolute standard process, a calibration system is used for which the physical input variables are prescribed. The calibration system also has a Best Measurement Capability.

Temperature Influence
Mechanical components are subject to thermal expansion and the resistance of electronic structural elements is temperature-dependent. Temperature fluctuations during the calibration process consequently have a direct effect on the calibration result. The temperature dependency of the sensitivity of piezoelectric sensors is determined in the context of type testing. Reliable data is also available for charge amplifiers with respect to their thermal behavior.