Defining Parameters for Ballistic High Pressure Sensors

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Abstract

Continuous improvements in ballistic pressure sensors over the past 30 years have resulted in sensors which perform extremely well under very difficult conditions. Today's state of the art sensors offer improved accuracy, reliability, longer lifetime and extended measuring ranges with linearity which allows lower pressure measurements.

Most of the ballistic high pressure sensors available today meet the basic requirements with respect to measuring range, natural frequency, operating temperature, shock resistance, etc. However, the ideal ballistic pressure sensor must perform well under actual test conditions and exhibit long term stability regardless of thermal and strain related effects.

The paper explains which parameters and sensor properties are critical in defining the quality of a ballistics pressure sensor. It also discusses some actual field test data of the new NATO approved Kistler 6215 and 6213B. The new Nato approved 6215 sensor is compared to the older 6203 NATO sensor.

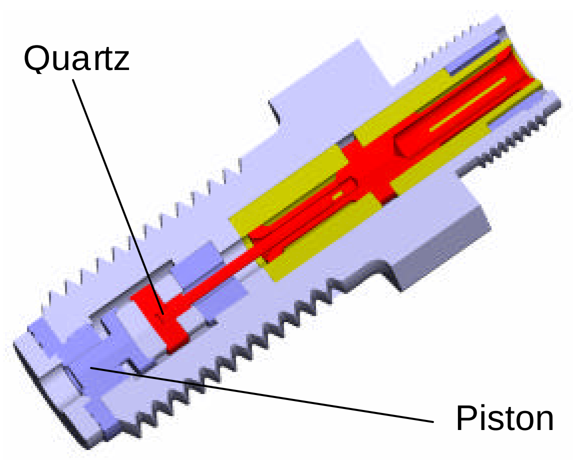
The paper also examines how side effects such as dead volume and imperfections in the mounting port can effect the accuracy of the measuring results.

1.0 Introduction
In 1985, Kistler introduced a new generation of pressure sensors to cover increasing demands from the ballistic community. Although these new sensors are very well established while a large number of the older designs are still being used today.

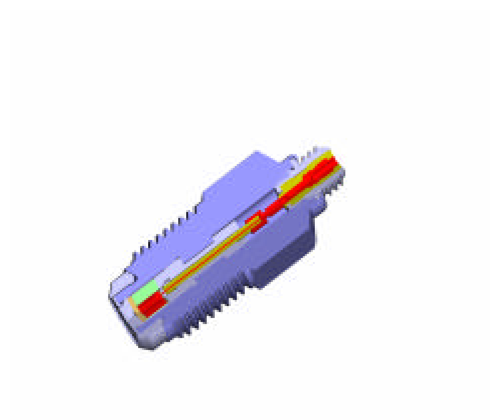
In this paper, we have summarized our experience in ballistic measurements as well as some user feed back from the last 15 years. This summery starts with a brief review of the history and the milestones in the development of ballistic pressure sensors. Also, the performance of a state of the art ballistic sensor is discussed.

2.0 History of piezo sensors for ballistics
As far as is known, the first successful application of a piezo transducer was made at the Deutsche Versuchsanstalt für Luftfahrt, Berlin by Dr. Gohlke in 1935. This type of transducer, called the piston design was in use for about 30 years. At that time through 1965 it was customary that ammunition manufactures would build their own piezo transducer.

Kistler realized that the piezoelectric measuring principle is an ideal technique for the measurement of ballistic pressure, and introduced the first commercially available piston transducer (fig. 1a). This sensor was rather large and required considerable maintenance.



1a



1b

Fig. 1a transducer with piston, 24 mm thread
1b transducer with front diaphragm and recessed seal model 617, 3/8 thread

2.1 Kistler introduced a new generation of piezo transducers in ballistics (fig. 1b model 617) in the early 60's which had considerable size adavanatges. By end of the 60's Kistler introduced the series 6201, 6203 and 6211using welded diaphragms (fig. 2).

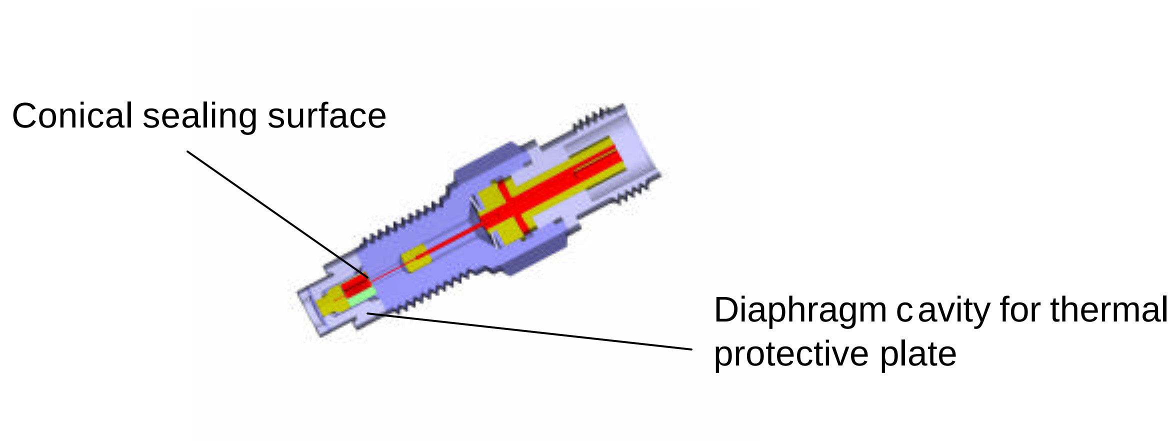


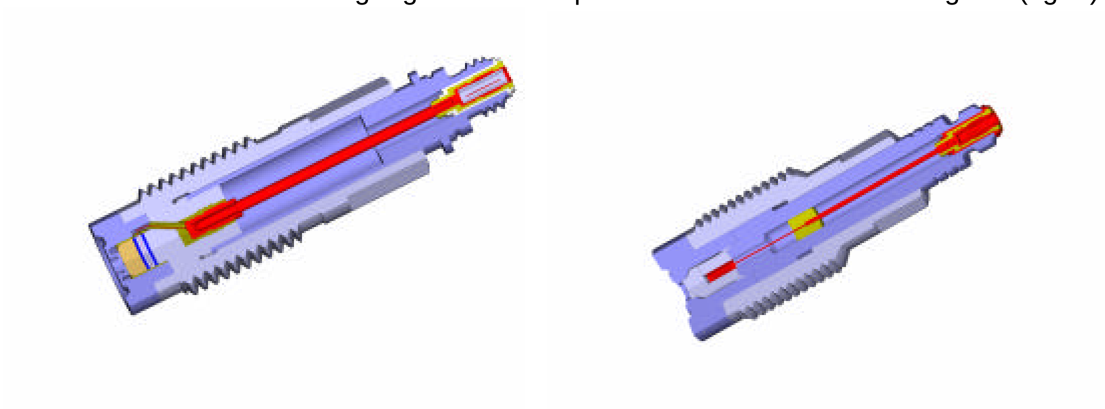
Fig. 2 Model 6203: Transducer with compression diaphragm and conical low torque seal

These sensors introduced some major improvements in the diaphragm design and sealing area. In addition, an easily replaceable thermal protective plate was added to protect the diaphragm.

After exhaustive testing, the 6203 was approved in 1971 by NATO for their ammunition testing.

Over the years, advancements in electronic data acquisition have improved the accuracy of analysis and user became more aware of some of the instability and accuracy issues of the sensor. The durability of the sensors also became an increasing concern. In some cases, the short life of some sensors proved cost prohibitive and users switched back to the old copper crusher sensing method.

Kistler responded to the increasing market needs by introducing a completely new design, which combines front sealing together with a patented anti-strain measuring cell (fig. 3).



6215 **6213B**

Fig. 3 New front sealed sensors 6215 up to 87,000 psi ; 6213B up to 145,000 psi

This combination offers the full advantage of front sealing without the drawback of mounting torque sensitivity. In order to extend the durability, the whole transducer front including the diaphragm are machined from a solid piece of metal, eliminating welds and thereby increasing the life time tenfold. (fig.5)

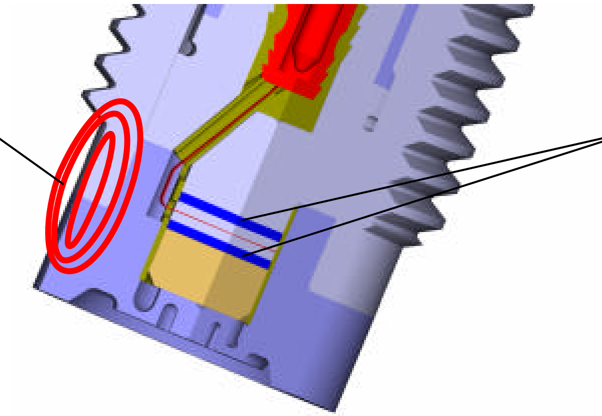


Fig.4. Schematic section through the front part of model 6215

These new transducers were introduced in 1985 but, in spite of their advantages, the switchover to their usage has been rather slow and is still on going. In 1994 NATO re-tested the latest sensor designs and accepted Kistler's 6215 for acceptance testing. The era of 6203 is nearing an end.

3. Defining parameters for ballistic high pressure sensors
Measuring ballistic pressure is very demanding task for a sensor because at high pressures of several thousand psi, deformations occur in the mounting area. The high pressure also causes extremely high surface loads of up to 145,000*lb/in*^{2} which may alter or damage components of the sensor after a short period of use resulting in unstable performance. High temperature transients over 2000°K adds to the stress.

It is essential for the user to select a sensor which provides accurate and repeatable data. The table below (fig. 5) shows a comparison of the of the key parameters. These factors depend on:

Linearity/ Hysteresis: For accurate measurements, good linearity and hysteresis are basic requirements. These parameters also determine the measuring range of a sensor.

Strain sensitivity: The lower the strain sensitivity, the more accurate the results. Strain sensitivity of a sensor can be checked readily by measuring the output signal while torquing the sensor.

Stability: Stability of the sensitivity over the entire service life. Important parameters for the stability are the linearity and the hysteresis. A sensor with a good linearity of < 1% will stay very stable over the whole life time. A sensor with bad linearity will change duringoperation; even aging the sensor with a certain number of pressure cycles will not help to improve the stability.

Thermal shock: The high temperature shock on the diaphragm during propellant burning causes thermal stresses which generates a force inverse to the pressure acting on the diaphragm. This error results in a lower peak pressure indication, and a zero undershoot of the pressure trace.

Life time: For an accurate sensor, the most critical parts are the diaphragm and the sealing area, therefore special attention is given to the design of these areas to assure durability.

The table below shows a comparison of the of the key parameters:

	6203 / 6211	**Others**	**6215**	**6213B**
Linearity/Hysteresis 100% range 10% range	 ? ? 1% FSO ? ? 3 ... 5 %	 ? ? 2% FSO	 ? ? 1% FSO ? ? 1% FSO	 ? ? 0,5% FSO ? ? 0,5% FSO
Strain sensitivity*	5%		0,7%	1%
Stability	5%		1%	1%
Thermal shock **	? 145 psi		? 145 psi	? 145 psi
Number of Rounds typical	1000		> 10'000	> 10'000

Fig. 5 Critical Specifications of Various Ballistic Pressure Sensors

* Measured by mounting the sensor into an adapter with a blind hole. A force equal to the maximum pressure is applied to the adapter. The stated value in percent indicates the change of sensitivity.

** Typical thermal shock in psi with 7,6mm cal. The 6215 and 6213B are equipped with thermal protective shields. In spite of the machined diaphragm, the thermal shock behaviour of the 6215 is about the same as that of the 6203, which uses a very thin sheet metal diaphragm. This has been achieved by using an additional thermal protective shield to absorb the heat energy. These shields not only reduce the thermal shock but also protect the sensor from damage.

The 6215 and 6213B have much better values for all key parameters. Most significant are the extended life time and the reduced strain sensitivity, but also the stability is improved compared to the older design. Finite Element (FE) calculations show the sealing section of the 6215 (fig. 6 right) and the front part and sealing section of the 6203 (fig. 6 left) which helps explain why the 6215 is superior to the 6203. The FE calculation simulates a pressure of 73,000psi plus an additional surface load due to the sealing area, simulating the tightening torque.

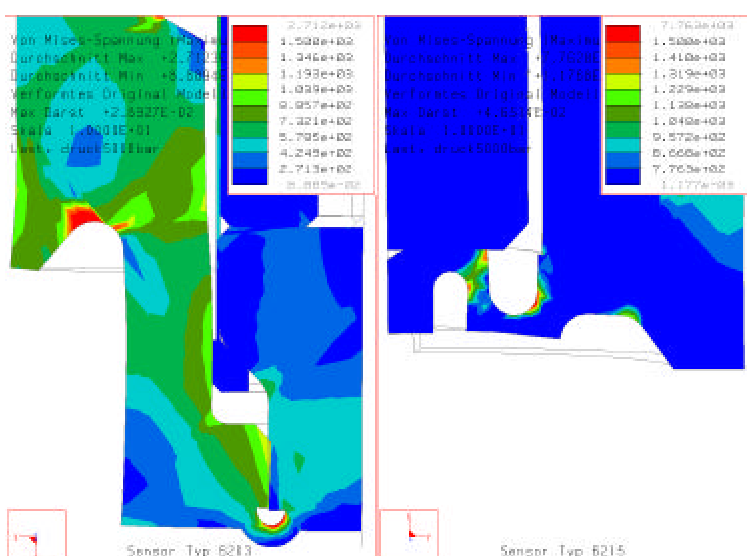


Fig. 6 (left) : The FE calculation of 6203 shows a very high loads over 200,000*lb/in*^{2} at the sealing grooves and some deformations caused by the non-uniform load distribution across the entire front portion.

Fig. 6 (right): The FE calculation of 6215 shows a relatively low and a nearly equal load distribution to all sections of the diaphragm. Due to this low and equal load distribution the sensor remains very stable over the entire life time.

4. Field testing of Kistler 6203 and 6215 at Oerlikon-Contraves Pyrotec AG

A few years ago a Swiss customer made extensive investigations to find the most suitable ballistic sensor. The investigation was finalized by field testing both types.

4.1 Redundant test using two 6203 located 90° to each other

Test Procedure:

Five pairs of 6203 sensors were randomly selected and tested in a 30 mm barrel with 5 rounds of the reference ammunition GRB-OB 1-80. The deviation of each of the two main pressures is shown in fig. 7.

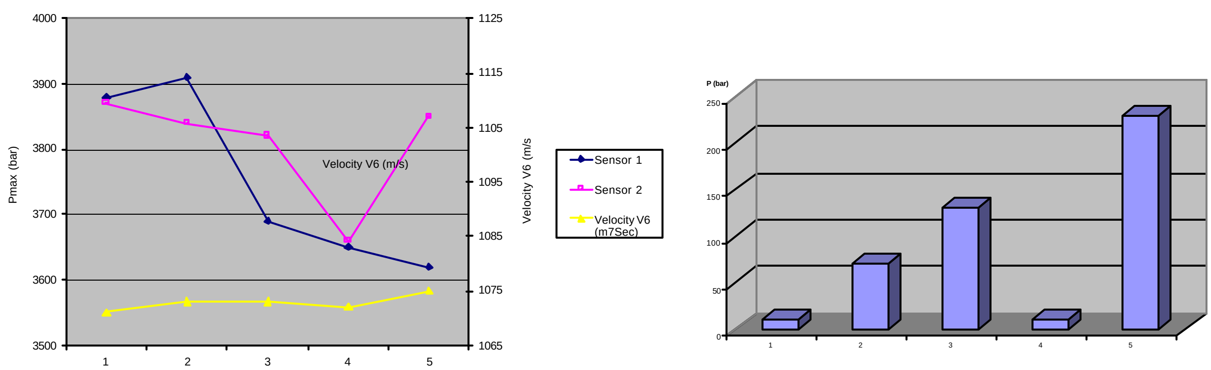


Fig. 7 Left: sequence of pressure versus velocity; right: difference between two sensors from each pair

Sensor pair 1 and 4 shows nearly perfect tracking, while the other pairs show large deviations. However, in either case, the pressure does not track muzzle velocity. Also, using the same round, the pressure difference of one pair measured over 2,900 *psi*.

4.1 Redundant test using two 6215 located 90° to each other

Test Procedure:

Eight 6215 pairs were randomly selected and tested according to the following plan in a 35 mm test barrel:

Pair 1 was subjected to 5 rounds. The difference of P1 – P2 (average) was then plotted. Transducer pair 1 were removed and installed in reverse order (hole change) and again tested with 5 rounds. The variation of P1-P2 (average) was plotted, etc. Afterwards, the test was repeated with the other pairs. (fig.8)

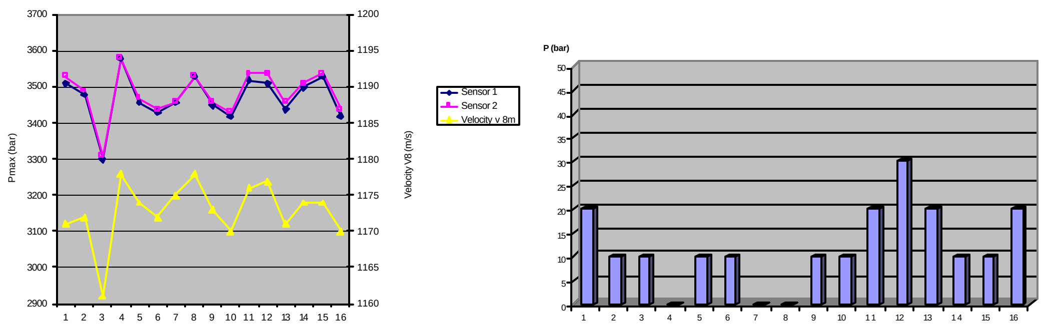


Fig. 8 Left: sequence of pressure versus velocity Right: difference between two sensors of each pair

The graph shows that the 6215 transducer pairs never exceeded a 400*psi* deviation. All 6215's performed similarly when compared to each other. The velocity correlation looked clean as well.

5.0 Error sources in ballistic measurement

5.1 Mounting errors

Measuring technology has been greatly improved as a result of front sealing sensors with the anti-strain design. Nevertheless, for optimum performance, an accurately machined mounting port with proper sealing surface is still essential for these sensors.

The mounting port must be carefully machined according to the installation manual and using the special tools offered by Kistler.

The most common mounting error is a concave sealing surface caused by using improper tools for machining this surface. (Fig. 9)

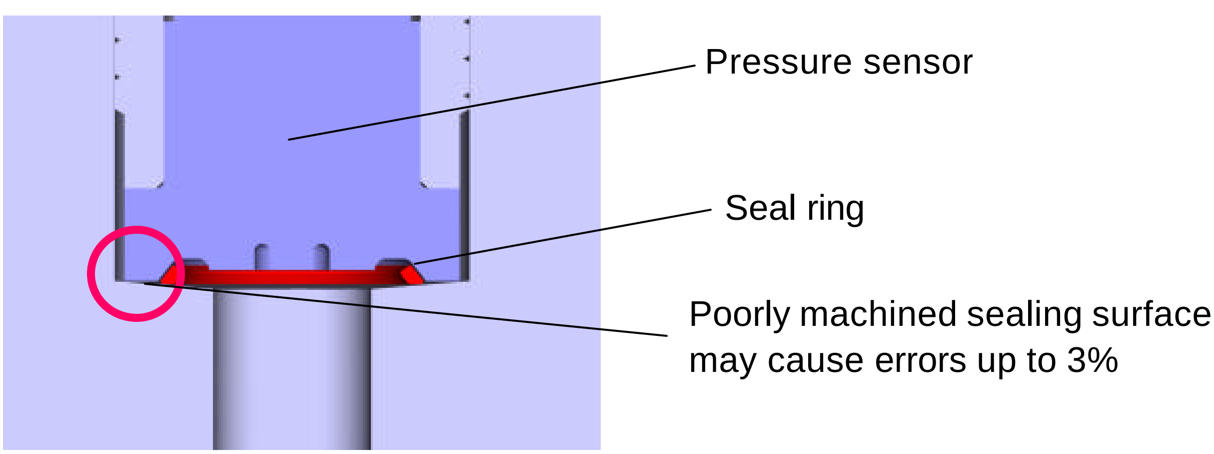


Fig. 9 concave sealing surfaces

An incorrectly machined port causes the load to be unequally distributed which can cause a measuring error of up to 3% (for 0.001*in* deviation). In extreme cases, the sensor may be damaged.

5.2 Use of grease

Silicon grease applied to the front of the sensor reduces thermal shock error. This method is still very widely used today and presents no problems for pressure measurements up to about 50,000*psi*. Above 50,000*psi* grease starts to cause measuring errors of several percent. The error increases at higher pressures (Fig. 10). The high pressure causes a hardening of the grease, restricting the pressure propagation.

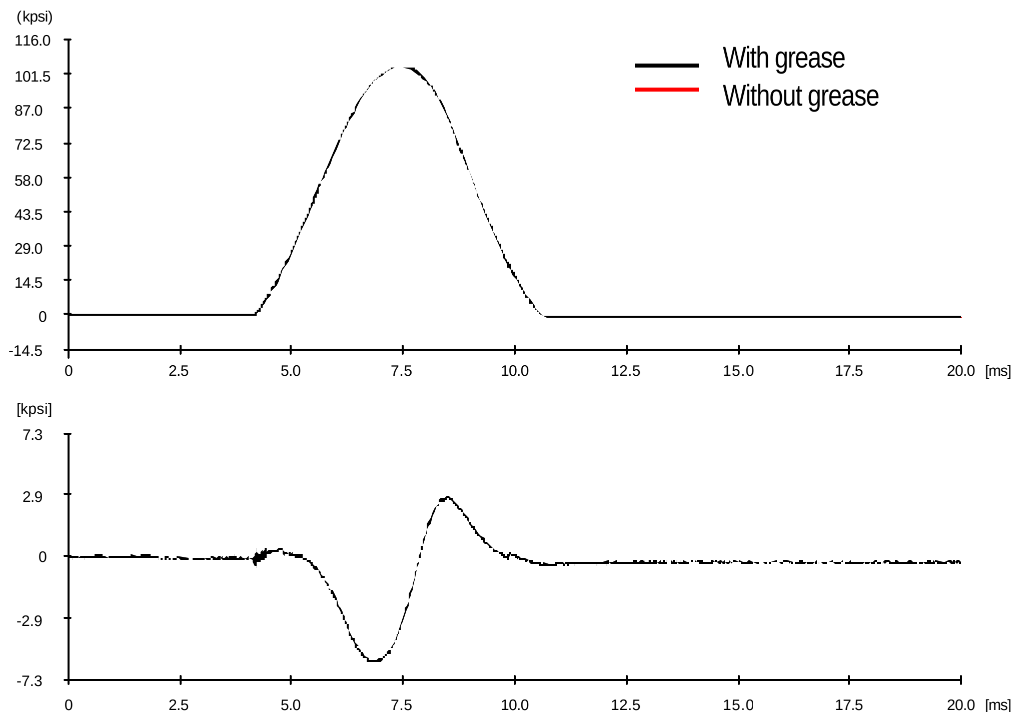
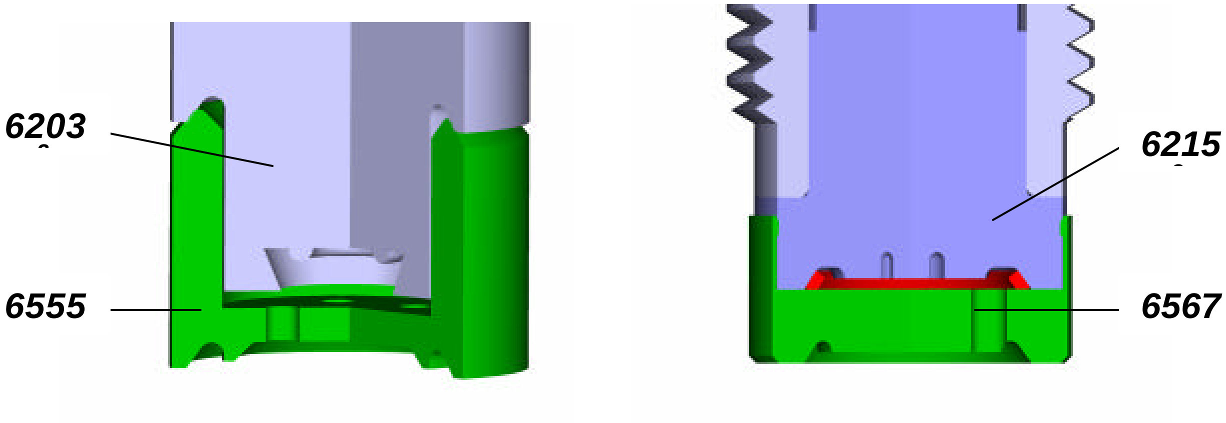


Fig. 10 Comparison: The upper trace shows the pressure reading with the 6213B & thermal protection shield 6563A versus the 6213B protected with silicon grease. The lower plot shows the pressure differential between both sensors.

6. 0 Converting from type 6203 to type 6215

6.1 Reworking the mounting port

The combination of the 6215 and diaphragm protector 6567 represents a considerable improvement compared with the measuring arrangement of the 6203 with damping seal 6555A (NATO Manual AC 7225). In most cases it is possible to continue using the existing barrels by increasing the thread depth. The thread must be tapped and additional 0.20*in* deep for direct mounting of the sensor type 6215 into the existing 6203 port. When the 6125 sensor is mounted with a diaphragm protector 6567, the thread only needs to be tapped an additional 0.12*in* deep (Fig.11).



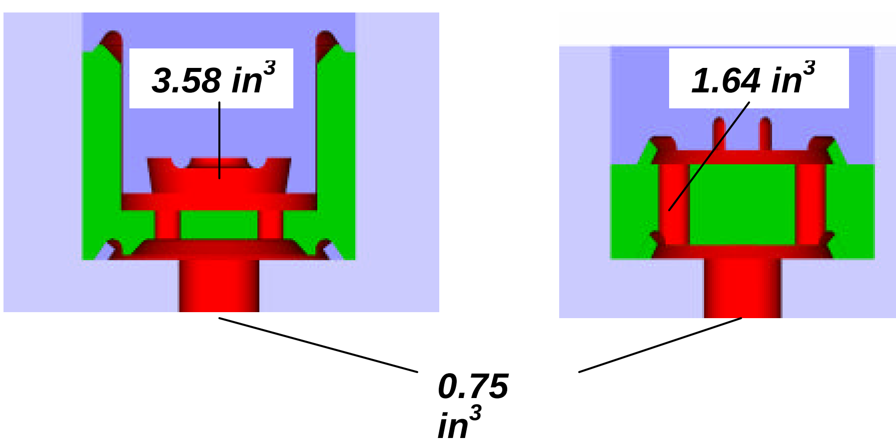
a b

Fig. 11a Configuration 6203 / 6555A
11b Configuration 6215 / 6567 mounted in the reworked mounting bore

Important: Measurements using the combination of the 6215 with the 6567 diaphragm protection indicate approximately 3% higher peak pressures compared to the 6203 with the 6555A measuring arrangement. The smaller dead volume in front of the diaphragm causes the increase in pressure.

The dead volume of different arrangements is shown in the table below.

Dead volume	**6215 + 6567**	**6203 + 6555A**	**6215 + 6565 + 1181A**
Diaphragm + accessories	1.64 in^3	3.58 in^3	1.87 in^3
Bore ? 0.098 mm x 0.079mm	0.75 in^3	0.75 in^3	0.75 in^3
Total	**2.39 in^3**	**4.33 in^3**	**2.62 in^3**



12a 12b

Fig. 12a: Dead volume of arrangement 6203+ 6555A
Fig. 12b: Dead volume of arrangement 6215+6567

6.2 Using a Reduction Sleeve Z14998

In many cases, it is possible to fit the sensor 6215 in existing holes of 6203 by using a reduction sleeve Z 14998 .

Important: after installing a reduction sleeve, sufficient threads must remain for secure mounting! If not, this solution must be rejected (Fig.13).

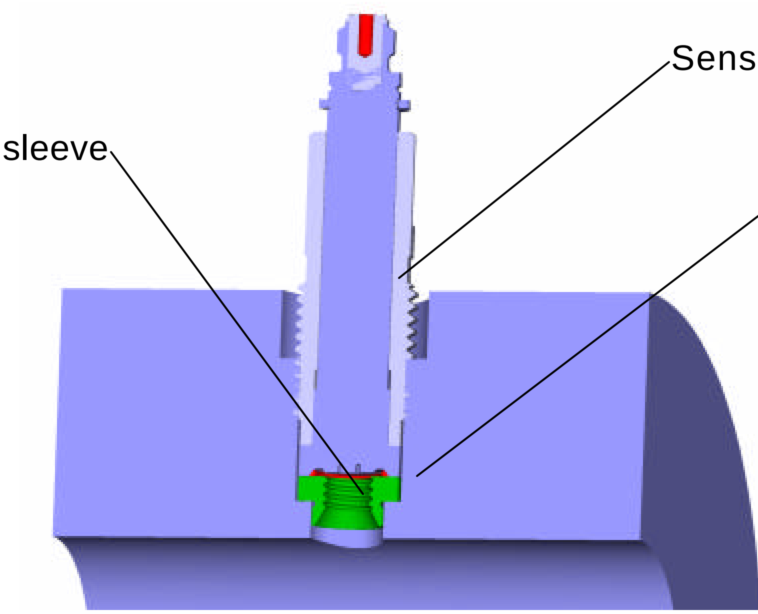


Fig. 13 Type 6215 fitted with reduction sleeve type Z14998

7.0 Sensor calibration

All sensors are calibrate d at Kistler and supplied with a certificate. Ballistic sensors should be regularly checked and calibrated. The calibration interval depends on the application as well as the pressure range.

Since the 6213B and 6215 have a much improved stability compared to the old design, the calibration intervals can be extended. The table (fig. 14) shows the recommended calibration intervals.

Model	**Removing/cleaning after < 50 rounds**	**Removing/cleaning after > 50 rounds**
6213B	1000 rounds	2000 rounds
6215	1000 rounds (< 72,500 psi) 200 rounds (> 72,500 psi)	2000 rounds (< 72,500 psi) 500 rounds (> 72,500 psi)
6203 ... 6211	100 rounds	200 rounds

Fig. 14 Recommended calibration intervals for old and new designs.

7.2 Calibration method

Dead weight tester

The most accurate way is still a dead weight tester (?? 0,1%), but static calibration stresses the sensor far more than dynamic testing, especially for the older designs, resulting in a shortened life time.

Reference method with Kistler Calibration System

In order to perform a quick and accurate check of high pressure sensors, Kistler offers a system which is based on a reference sensor, a pressure generator and an electronic 2-channel comparator.

Depending if dynamic testing or a full calibration is required either a spindle pump or drop weight can be used (fig. 14).

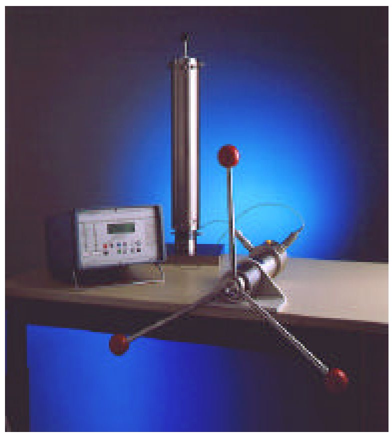


Fig. 14 Spindle pump 6905A, dynamic pressure generator 6909 and two channel electronic 6907B

With this system the linearity and the sensitivity of a sensor can be compared to a piezoelectric reference sensor. For the calibration, the sensors are exposed to a steadily increasing pressure which is produced by a spindle pump. While the pressure is increased, the electronic comparator compares the two signals and calculates the sensitivity and linearity of the sensor under test as in Fig. 15a.

A dynamic pressure generator can be used to measure the dynamic behaviour of the sensor. (Fig. 15b)

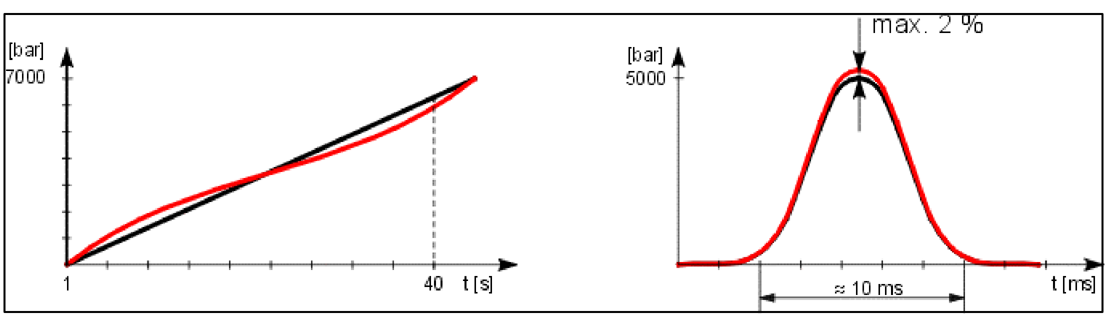


Fig. 15a calibration by comparison

Fig. 15b Comparison of dynamic behavior

In order to assure reliable test data and long sensor life time, we recommend following this checklist:

- ✍✍It is usually sufficient to test the sensor dynamically at the intervals listed above. Calibrate sensors at longer intervals to reduce excessive stressing.
- ✍✍If this dynamic tests reveals a deviation of > 2% of peak value, the sensor should be subjected to a full calibration to determine the linearity and the sensitivity.
- ✍✍If the sensitivity has changed, the sensor may still to be used providing the linearity is still within the factory tolerance.
- ✍✍In case the linearity exceeds the tolerance, the sensor should not be used for accurate test work because is no longer reliable. It may be used for le ss accurate work however.

8.0 Conclusions

This paper has explored how commercial sensor designs have evolved during the past four decades. It has been discussed and shown how key performance parameters of linearity/hysteresis, strain sensitivity, stability and thermal shock are effected by sensor designs. The state of the art sensor, Kistler's anti-strain 6215, has been shown to be superior to the older welded diaphragm designs. It has also been shown how mechanical diaphragm protection is better than grease at high pressures. Machining of the mounting port remains the final key parameter for proper sensor function. Kistler has prepared a complete set of installation tools to assist the installer with mounting port fabrication.