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A new type of transducer for accurate and dynamic pressure measurement up to 15000 bar using foil type strain gauges

André Schäfer, Wolfgang Viel, Christoph Rapp-Hickler, Karl Mikulecki

Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany

Abstract – Applications in the ultra-high pressure range are on the move forward. Of particular interest is the manufacturing of diesel injection components such as nozzles and rails. Also precision water jet cutting as well as high-pressure sterilisation, as a method of conservation in the food industry, have growing importance, mainly in Japan and the USA.

For these emerging fields traceability of the measuring equipment with the highest possible accuracy is also a must for these ultra high pressures.

Keywords: ultra-high pressure measurement

1. THE NEW DESIGN AND INHERENT ADVANTAGES

The paper describes a new type of pressure transducer (patent pending, [1]) providing accurate and at the same time dynamic pressure measurement for, at the moment up to 15000 bar, using foil type strain gauges. Still higher pressure ranges are possible. The strain gauge is the smartest choice for measuring ultra-high pressure, as the measuring body which is made from special steel can be designed freely according to the requirements of maximum pressure resistance plus the overload protection, as well as maximum sensitivity. The relationship between the two quantities is given by the shape, the thickness and the material choice of the measuring body.

The strain gages are only applied after the measuring body is finalised, which offers the advantage of not limiting possibilities in design and hindering certain technology steps. This is different with other pick-up principles. Lower pressures are mainly measured using the piezoresistive principle [2] or the capacitive pick-up [3]. These principles have a lot of advantages in the very low pressure range, but they fail to be of practical use in the high and ultra-high pressure range. In addition they often require also a design out of 2 or even 3 components causing the well-known problems in firmly joining them together, especially critical to withstand ultra-high pressure. To counteract these problems the new transducer has a monolithic design, i.e. it is made of only one piece of steel, which is the most common material used in reference transducers for calibration [4].

The most remarkable result of the new design and the choice of material is the high number of load cycles that can be performed. The measuring body, the combined element for sealing/tightening and reduction of the dead volume, as well as the whole housing are especially designed to provide good performance and comply with safety requirements for such high pressures.

2. REALISATION

Based on our experience in manufacturing pressure transducers for more than 30 years we have used construction components that have proven reliability for long [5] in the sensor design (Fig. I.) as well as the electronics such as the use of custom made chips for the signal conditioning.

Fig. I. Outer shape of the transducer

Table I shows some key technical data of the different ranges that can perform with a very high number of load cycles and still sufficient accuracy.

Table I. Key technical data

Nominal range	5 000 bar	10 000 bar	15 000 bar
Nominal sensitivity	1 mV/V	1 mV/V	1 mV/V
Initial accuracy	0.2%	0.4%	0.5%

This new type of pressure transducer was to provide accurate and at the same time dynamic pressure measurement for up to 15000 bar at the moment, using foil type strain gauges. In the future still higher pressure ranges were to be possible. A decision had taken to be made and we decided to give the transducer a higher overload protection, to withstand a higher number of load cycles, essential to serve especially the test equipment for diesel injection technology, the by far most important application of ultra-high pressure measurement.

Currently the transducers with a nominal range of 5000 bar are in practical use by standard institutes as well as reference standard customers while transducers with a nominal range of 10000 bar are already tested by some of them. 5000 bar and 10000 bar transducers are available from stock. Transducers with 15000 bar are presently undergoing a wide variety of in-house tests and will be available before the end of 2003.

3. DYNAMIC BEHAVIOR

Dynamic measurements are of particular importance for the applications that have already been mentioned in the introduction and the chapters above. The new applications have brought about a shift in requirements: In addition to an appropriate static behavior precise statements on the dynamic load are increasingly often required, for example, with components testing applications.

As a result of the research we are now able to present a systematically structured report which is summarised in diagram 1.

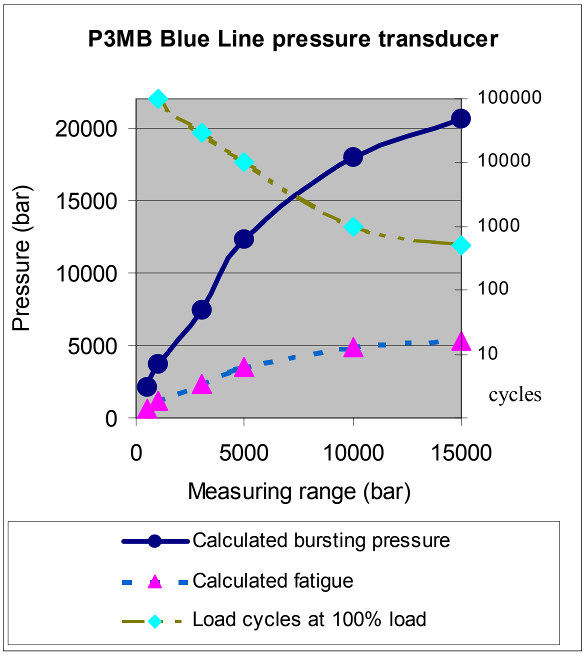

Diagram1 P3MB Blue Line pressure transducer series

How have these results been achieved? Table II which is based on diagram 1 has been verified at some points by fatigue tests and by the experience gained during operation. At the same time the table confirms the correct dimensioning of the pressure transducers.

Table II Fatigue strength

Nom. measuring range / Static load capacity (bar)	Fatigue strength at nominal pressure (load cycles)	Fatigue / 10^7 load cycles (bar)
500	10^6	350
1000	10^6	700
2000	10^6	1400
3000	3×10^4	2100
5000	1×10^4	3500
10000	10^3	5000
15000	5×10^2	6000

For the measuring ranges of 500, 1000 and 2000 bar the fatigue pressures exceed the value of 70% given in the specifications.

For 500 and 1000bar the fatigue pressure even amounts to a value exceeding the nominal pressure. The value of 70 % is explained by the uncertainty resulting from the substantial relative weakening of the wall thickness caused by potential notches, the more so as the measuring body hole for these pressure ranges is prepared in the “standard” way.

For the higher measuring ranges of 5000 bar, 10000 bar and 15000 bar, plain values have been chosen (with regard to the application of the specifications).

The mathematical interpretation accounts for the theoretical relationship of material characteristics, load, fatigue and service life.

Knowledge of these relationships and the test results allow us to make reliable statements of load capacity and service life.

Measuring bodies based on the hollow spring principle are designed similar to autoclaves.

For thin-walled autoclaves, the maximum stress is the tangential stress

$\sigma_t = p * d / (2\ s)$ "cylinder formula"

with p = pressure
d = inside diameter
S = wall thickness

The elastic calculation of a thick-walled autoclave shows the substantial loading of the thick wall's internal diameter. Therefore, the " cylinder formula" can only be applied for actually thin-walled autoclaves (s/d < 0.1).

The following applies for the internal diameter of a thick-walled autoclave with

D = outside diameter
$q_a = (d/D)2$

$\sigma_t = 3^{1/2}\ p / (1 - q_a)$

Designing a measuring body for stain gauges requires dimensioning for a specific strain at the outside diameter. The strain required from the meteorological point of view is determined by the quality requirements and the amplifier technology used.

The requirements to the strain on the outside diameter and elastic stress on the internal fibre can be complied with consistently using the common materials up to about 6000 bar. For higher nominal pressures another principle is used which is popular in high pressure technology:
Owing additional outer material of the wall takes part to bear the load - the exceeding of plastic limit at the autoclaves's internal diameter range is admitted. After stress removal, the exceeding of plastic limit results in an internal pressure stress of the inner part of the wall. (see diagram 2).

σ_S = permissible stress
ra = outside radius
ri = inside radius
c = limiting radius between
plastic and elastic range
The permissible pressure p can be calculated as

$p = \sigma_S / 3^{1/2}\ (2 * \ln(c/r_i) + 1 - (c^2 / r_a^2))$

In practice, only a partial plastification is permissible. In this case, a plastification of about 30% of the wall is allowed. With 100% plastification there is no more additional material supporting the wall. This case allows an excellent assessment of the bursting pressure that is to be expected.

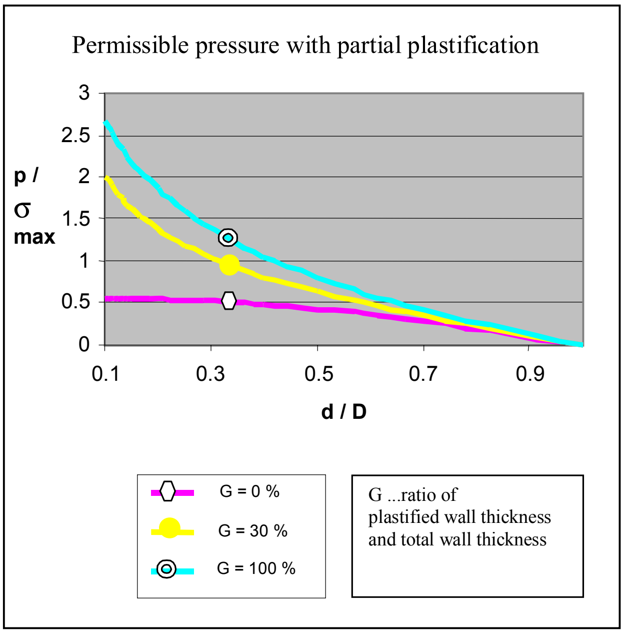

Diagram 2 permissible pressure with partial plastification

4. CONCLUSIONS

The strain gauge, in the classical shape as a foil-type strain gauge, is perfectly dedicated for the measurement of ultra-high pressure if a suitable measuring body shape is chosen and a good compromise in between thickness and sensitivity of the construction is found. 15000 bar are only a first goal and no firm border for possible realisations.

Applications in the ultra-high pressure field, who are of increasing importance, can now be actively supported by a pressure transducer, who can perform with a very high number of load cycles and still sufficient accuracy. This opens new possibilities for progress in this field.

At the moment the 1-P3MBP Blue Line Transducers can be combined with the DMP 40 precision unit that enables the user to input a linearisation table and we recommend to use this feature, the software programme CATMAN has more possibilities.

To give an outlook of further developments, especially issues surrounding a higher accuracy of the transducers including ideas for an integrated temperature compensated electrical circuit is given. This is most important for the field of calibration uncertainties.

Finally the design of the transducer could prove, that it is possible to create a transducer suitable to promote ultra-high pressure application fields with very high dynamic requirements, which are very much on the move forward.

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AUTHORS:

André Schäfer, Dr.-Ing.
(presenting author and contact person for paper)
Dept. M-M, Hottinger Baldwin Messtechnik GmbH
Im Tiefen See 45, 64293 Darmstadt, Germany
Tel.: +49-6151-803-224, Fax: +49-6151-803-630
e-mail: andre.schaefer@hbm.com

Wolfgang Viel, Dipl.-Ing.
Dept. T-D, Hottinger Baldwin Messtechnik GmbH
Im Tiefen See 45, 64293 Darmstadt, Germany
Tel.: +49-6151-803-468, Fax: +49-6151-803-604
e-mail: wolfgang.viel@hbm.com

Christoph Rapp-Hickler, Dipl.-Ing.
Dept. T-D, Hottinger Baldwin Messtechnik GmbH
Im Tiefen See 45, 64293 Darmstadt, Germany
Tel.: +49-6151-803-308, Fax: +49-6151-803-604
e-mail: christoph.rapp-hickler@hbm.com

Karl Mikulecki
Dept. T-D, Hottinger Baldwin Messtechnik GmbH
Im Tiefen See 45, 64293 Darmstadt, Germany
Tel.: +49-6151-803-534, Fax: +49-6151-803-604
e-mail: karl.mikulecki@hbm.com