MEASUREMENT PERFORMANCE OF CAPACITANCE DIAPHRAGM GAGES AND ALTERNATIVE LOW-PRESSURE TRANSDUCERS

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Abstract

The most important factors that limit measurement performance of high-accuracy low-pressure transducers are: short-term instabilities in the zero-pressure readings, long-term shifts in the transducer calibration with time and, in the case of heated gages, the effect of thermal transpiration at absolute pressures below 100 Pa. A comprehensive study of capacitance diaphragm gages (CDG's) of the types currently being used by calibration laboratories as transfer standards has been carried out. Several hybrid CDG systems, developed at NIST by using thermoelectric heating/cooling modules to control the CDG's near room temperature, have demonstrated that this approach can improve their measurement performance. Somewhat more limited data on alternative low-pressure transducers based on other technologies (e.g., helical quartz tube, resonant structures, etc.) have been obtained and are presented as well.

1. Introduction

During the past two decades, capacitance diaphragm gages (CDG's) have played an important role in the development and operation of primary standards for vacuum, low pressure, and low-flow rates at the National Institute of Standards and Technology (NIST). These transducers have served and continue to serve both as check standards and transfer standards and therefore an accurate knowledge of their performance limitations is critical not only in their use but also in the assessment of overall uncertainties of NIST primary standards.

The first systematic study at NIST on CDG measurement performance was published more than a decade ago[1]. This study found that zero instabilities of different temperature-controlled gages were largely correlated with changes in room temperature and the magnitude of the instabilities for different gages differed by as much as three orders of magnitude. It was also reported that changes in CDG calibration do not occur as a monotonic drift with time but as random shifts between calibrations.

Since that time, a considerable amount of additional data has been accumulated on performance of commercial CDG's as well as several hybrid CDG systems developed at NIST. For example, in the area of calibrations alone, the number of records on repeat calibrations performed at NIST has increased tenfold, from 31 to 320, and the number of CDG's that have been calibrated more than once has more than quadrupled, from 17 to 79.

This paper describes a comprehensive study of major factors that limit measurement performance of CDG's of the high accuracy type used by calibration laboratories as transfer standards. Somewhat more limited data on the performance of two other types of low-pressure transducers, quartz Bourdon spiral gages (QBG's) and resonant silicon diaphragm gages (RSDG's), are also included.

2. Basic Operation of the Transducers

The different types of transducers considered in this study can all be classified as mechanical deflection gages that measure pressure directly as a force per unit area. The basic difference between them lies in the mechanical element used as a sensor and the manner in which its deflection is converted into an analog or digital output. Mechanical deflection gages are inherently differential in that they measure differences between an unknown applied pressure and a reference pressure. In constructing differential gages, the reference side of the sensor is left open allowing both differential and gauge mode measurements to be made directly, or absolute mode measurements by evacuating the reference side. Absolute gages are constructed by evacuating the reference side to less than 10^{-5} Pa and sealing it. In some gages, a chemical getter is used to maintain the low pressure.

2.1. Capacitance Diaphragm Gages

An example of a capacitance diaphragm gage and its operation is illustrated schematically in Figure 1. A difference between applied pressure, P_X, and reference pressure, P_{REF}, causes the stretched thin metal diaphragm inside the sensor capsule to deflect. This, in turn, changes the capacitances, C_1 and C_2 , between the diaphragm and two fixed electrodes deposited in a concentric "bull's eye" arrangement on a ceramic disc. The capacitances, which form two arms of an AC bridge, undergo unequal changes thereby unbalancing the bridge. The output of the bridge is converted into either analog or digital outputs by signal conditioning circuitry.

The sensor capsule is mounted inside a cast aluminum shell that is heated and controlled at an elevated temperature, usually near 45 °C. The primary purpose for this arrangement is to attenuate the effect of room temperature changes on zero stability. However, the operation of a pressure sensor at elevated temperatures gives rise to another undesirable side effect known as thermal transpiration[(2)], which manifests itself as a non-linear gas-species-dependent response of the gage at absolute pressures below 100 Pa (see Section 3.2).

Other electrode configurations and sensor geometries used in capacitance diaphragm gages are discussed in a recent review[(3)] that describes the calibration and use of capacitance diaphragm gages as transfer standards.

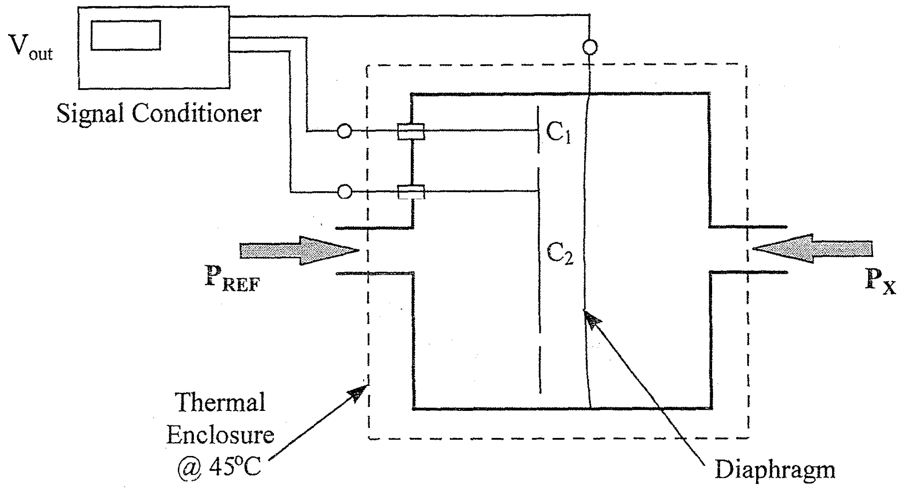

Figure 1. Schematic diagram of a capacitance diaphragm gage (CDG).

In order to minimize this effect, we have developed several hybrid CDG systems at NIST that enable transducers to be operated near room temperature while significantly attenuating the effects of room temperature changes. Each hybrid system consists of one to three CDG's mounted inside a commercially-available thermal enclosure that uses a thermoelectric (TE) module to control its interior temperature (see Figure 2). An external power supply and bridge circuitry developed at NIST are used to control the electrical current to the TE heating/cooling module. This arrangement enables the interior temperature of the enclosure to be controlled to better than ±20 mK for room temperature changes of up to several degrees.

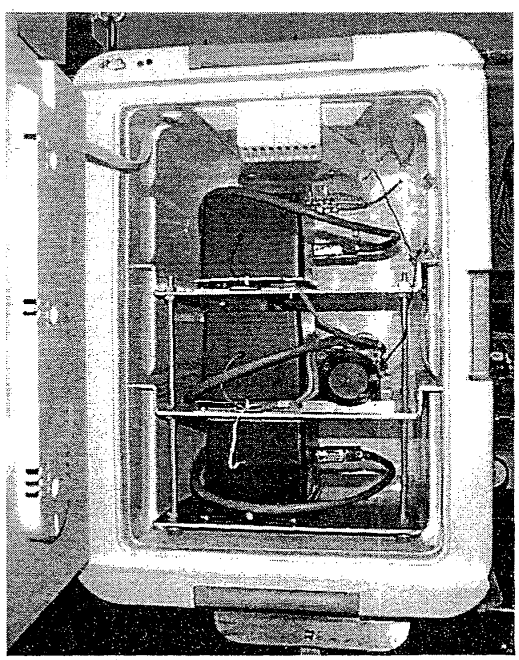

Figure 2. Photograph of a three-CDG hybrid system developed at NIST.

2.2. *Quartz Bourdon Spiral Gage*

The operation of a quartz Bourdon gage is illustrated schematically in Figure 3. The mechanical deflection element consists of a helical quartz tube with a mirror attached near its closed end. The mirror reflects a light beam onto two identical photocells, which are equally illuminated when the mirror is in its "zero" position. An increase in pressure, P_X, applied to the open end of the tube causes it to unwind thereby rotating the mirror. The unequal illumination of the photocells produces an error signal that is converted by a control amplifier to a proportional current. The current passes through a force-balancing coil assembly that restores the mirror/quartz tube assembly to its "zero" position. The current, which is therefore proportional to the differential pressure, is converted to an output voltage by means of a precision resistor.

The effect of room temperature changes on zero stability is significantly attenuated by mounting the sensor capsule in a machined aluminum/steel housing that is controlled at a nominal temperature of 50 °C.

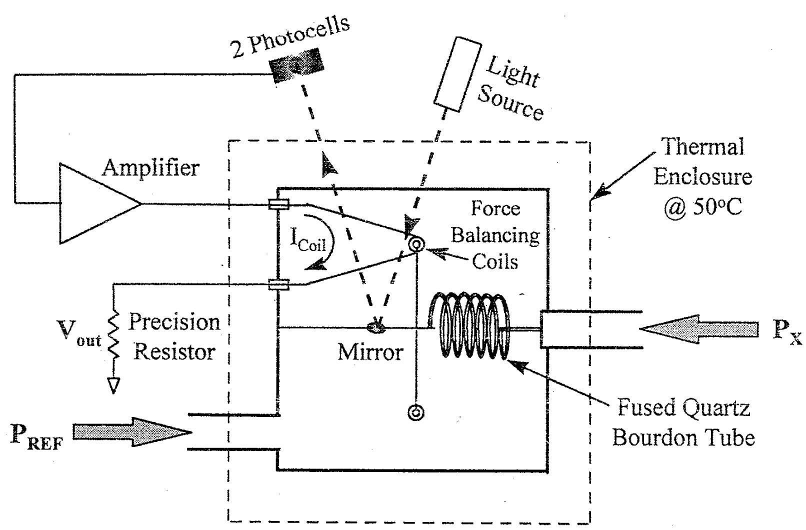

Figure 3. Schematic diagram of a quartz Bourdon gage (QBG).

2.3. *Resonant Silicon Diaphragm Gage*

The resonant silicon diaphragm gage (RSDG) included in the present study is a MEMS (micromachined electromechanical sensor) type of device that has a small diaphragm (nominally 7 x 7 mm x 0.5 mm thick) micromachined into a silicon substrate[4]. A change in the pressures, P_X and P_{REF}, applied to opposite sides of the silicon diaphragm changes the strain in two single crystal silicon resonators attached to the diaphragm and this, in turn, changes the natural frequency of each resonator. The two resonators are located on the diaphragm in such a manner that the strains (and therefore resonant frequencies) change in the opposite direction. The differential pressure is derived from the difference of the two resonant frequencies and is converted to a digital output. The use of two resonators in a differential mode provides compensation for changes in room temperature.

Oil interfaces are used between the silicon diaphragm and two secondary diaphragms in contact with the pressurizing fluid in order to damp out unwanted resonances. The two resonators are isolated from the oil by encapsulating them in small vacuum cavities on the silicon diaphragm.

The oil interface significantly increases the tilt sensitivity of the RSDG and can adversely affect the performance of the low-range units. The tilt sensitivity of a 1 kPa RSDG was measured at NIST and found to be 400 Pa/rad, which is more than two orders of magnitude larger than the tilt sensitivity of a 1.33 kPa CDG (~ 1 Pa/rad). In order to minimize this effect, the instrument case of this RSDG was mounted on a base with a tilt adjustment and precision level.

3. Factors Limiting Measurement Performance

The measurement performance of low-pressure transducers is limited by several factors. The most important of these for transducers used as transfer standards are the short-term instabilities in zero-pressure readings, the effect of thermal transpiration at absolute pressures below 100 Pa, and long-term shifts in the transducer calibration with time.

3.1. Zero Instabilities

At lowest pressures the accuracy of a transducer is limited by the short-term (hours to days) instability of its zero pressure reading. A measure of this instability can be obtained by applying a "zero" pressure to the transducer and recording its output as a function of time. Figure 4 presents such data for three absolute CDG's, each having a full scale (FS) range of 10 torr (**1 torr = 133.322 Pa**). The gages were connected to a manifold, evacuated to a pressure less than their

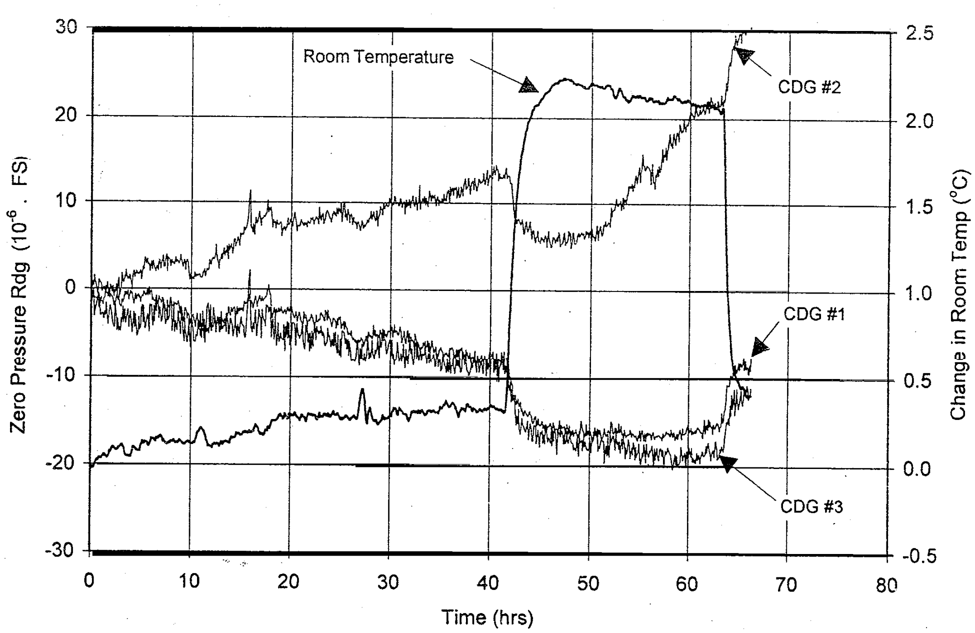

Figure 4. Stability of zero pressure readings of three 10 torr absolute CDG's.

sensitivity (< 10^{-6} torr), and then zeroed. During the course of measurements over a period of nearly three days, the gages were subjected to a room temperature cycle of approximately 2 °C.

These data illustrate two types of zero instabilities: (1) zero **shifts** that correlate directly with changes in room temperature, and (2) zero **drifts** that appear to vary randomly in both sign and magnitude and are probably due to drifts in the electronics and/or mechanical structure of the gage. The latter type of zero instabilities cannot be easily quantified, yet our experience at NIST indicates that they are a qualitative characteristic of a given transducer, i.e., some transducers exhibit significant zero drift while others are relatively stable. Zero shifts, on the other hand, are proportional to room temperature change and can be described in terms of a zero-pressure temperature coefficient.

Figure 5 presents the zero-pressure temperature coefficients that have been measured for a large number of low-pressure transducers: a total of thirty-six commercial CDG's with FS ranges of 1, 10, 100, and 1000 torr, six hybrid CDG's with FS ranges of 1 and 10 torr, one QBG with a FS range of 7.5 kPa and one RSDG with a FS range of 1 kPa. In general, CDG's with the lowest FS range and therefore highest sensitivity also have the largest zero-pressure temperature coefficients, though there is a significant variation among CDG's with a given FS range. The zero stability of the six hybrid CDG systems appears to be better, at least on average, than that of CDG's being temperature controlled by their internal heaters.

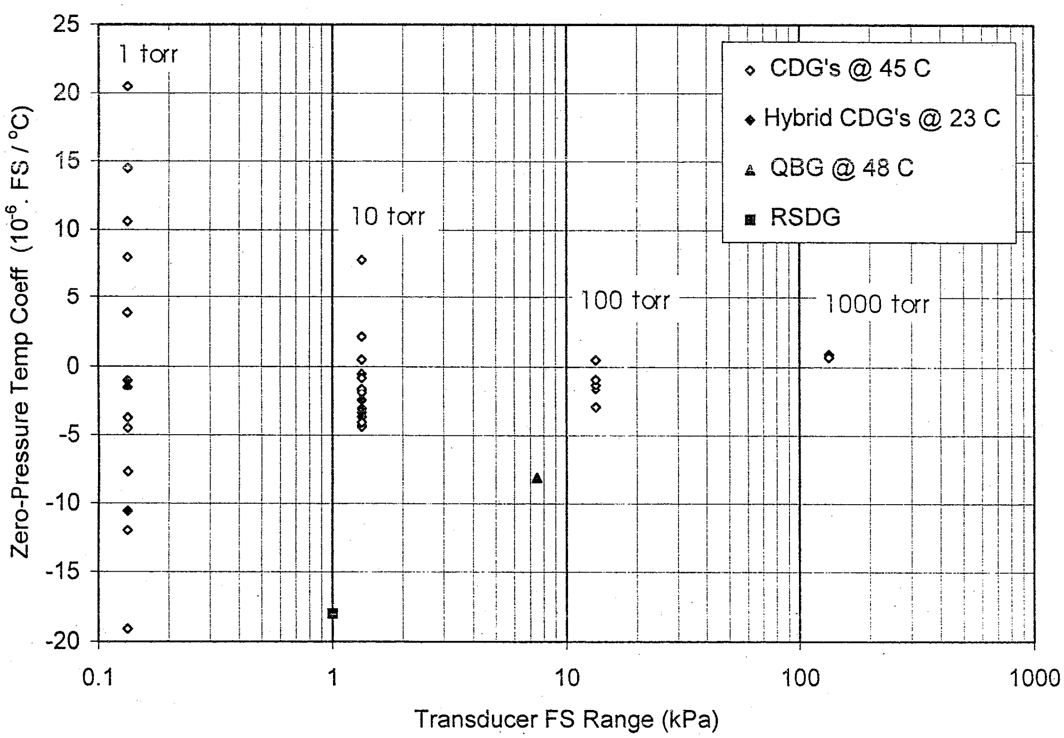

Figure 5. Zero-pressure temperature coefficients for different types of low-pressure transducers.

The data on the QBG and the RSDG indicate that these gages are significantly more sensitive to room temperature changes than CDG's with equivalent FS ranges, perhaps by a factor of two or three.

3.2. Thermal Transpiration Effect

The thermal transpiration effect[2] is illustrated in Figure 6, which presents several sets of data obtained during calibration of a 1 torr absolute CDG by comparison with a NIST primary standard[a]. In the upper two sets of data obtained with helium and with argon, the CDG was maintained at an operating temperature of 45 °C by means of its own internal heater. These data show that the CDG response becomes highly nonlinear as pressure is decreased and, at lowest pressures, the CDG reading is nearly 4% too high. At intermediate pressures, in the transition region between molecular flow (≲ 10^{-4} torr) and viscous flow (≳ 1 torr) conditions, the gage response is also gas-species dependent. The dashed and continuous lines represent calculated values based on a semi-empirical equation proposed by Takaishi and Sensui[6] that approximates the nonlinear behavior.

The lower two calibration data sets were obtained after this CDG was mounted inside a thermal enclosure as part of a three-CDG hybrid system. These data clearly show that the effect of thermal transpiration is significantly reduced by controlling the CDG at near room temperature.

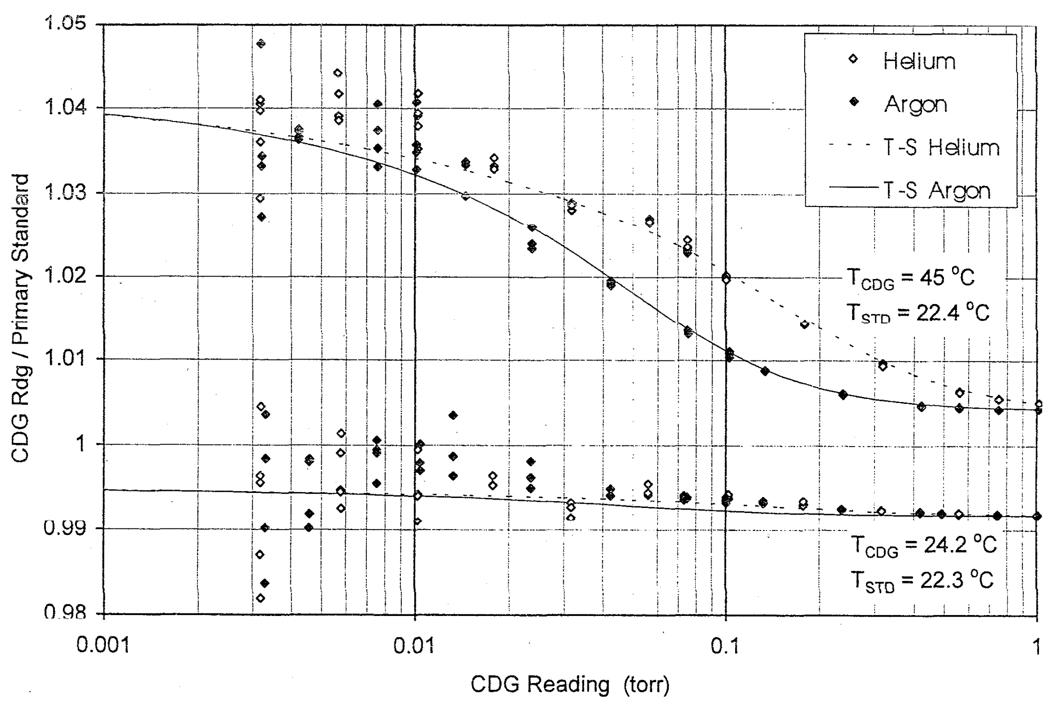

Figure 6. Calibration data for a 1 torr absolute CDG when controlled at 45 °C and 24.2 °C.

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[a] NIST operates UIM (Ultrasonic Interferometer Manometer) primary standards[5] for calibrations over the nominal range 0.1 - 3.6×10^5 Pa (0.001 - 2700 torr).

3.3. *Calibration Instability*

At higher pressures the accuracy of a transducer is limited by long-term (months to years) instability of its response function or calibration factor. This instability can only be determined by repeat calibrations of the transducer against a reliable standard over a period of time.

Figure 7 presents the calibration history at NIST of a 1 torr absolute CDG belonging to a calibration customer. This gage was recalibrated once each year over a period of eleven years. A relatively large calibration shift (~ 0.6%) is observed between the first and second calibrations followed by more moderate calibration shifts (≤ 0.2%) for the next six calibrations. This behavior is a common characteristic of many CDG's, that is, the largest calibration shifts occur early in their calibration histories.

The last four calibrations of this gage show a significant decrease in its stability, following the return of the sensor to the manufacturer for repair of a reference-side vacuum leak. This illustrates how the performance of a gage can be seriously affected when subjecting the sensor to unusual stresses (e.g., major repair, over-pressurization, etc.). Clearly, the prior calibration history is no longer valid for this CDG and so, in effect, the data in Figure 7 describes stability data for two different transducers.

The repeat calibration data on high accuracy CDG's accumulated at NIST during the past twenty years were analyzed. The shifts in gage response function or calibration factor between

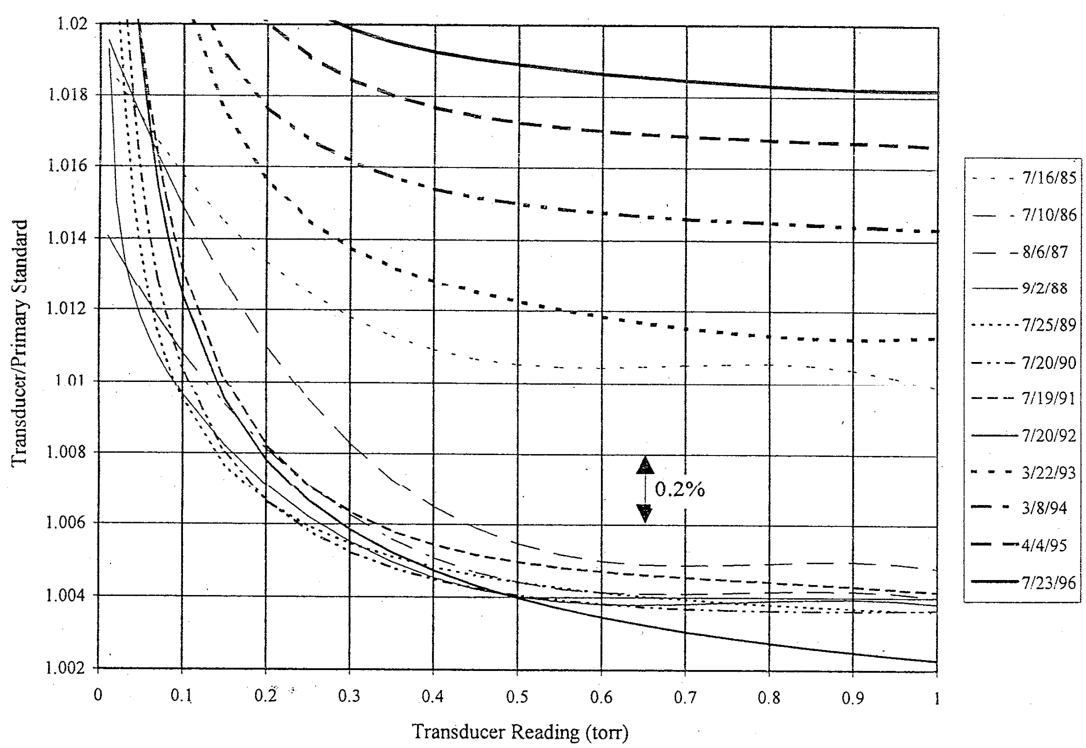

Figure 7. Calibration history at NIST of a customer 1 torr absolute CDG.

successive calibrations were determined for 79 different CDG's with full scale (FS) ranges of 1, 10, 100 and 1000 torr. For the purpose of calculating shifts, the "cal" factor for each calibration was taken as the average at three transducer readings, specifically at 0.3 FS, 0.5 FS and 1 FS.

The results for 1 torr CDG's are presented in Figure 8, where the shift (in percent) from the previous calibration is plotted as a function of calibration number; the shift for the first calibration is zero by definition. The average period between calibrations is approximately one to two years for most CDG's. The data in this plot exhibit three characteristics also seen in data for CDG's with other FS ranges. First, the largest shifts occur early in the calibration history of a CDG. Second, the calibration changes do not appear as a monotonic drift with time but as random shifts between calibrations. Third, there is a significant difference in the calibration stability of gages belonging to calibration customers and those belonging to NIST. This difference is unexpected since (a) customer and NIST gages are fairly representative of the different manufacturers, models and types (absolute and differential units) of high accuracy CDG's, and (b) most NIST calibration customers are other calibration laboratories whose personnel are presumably familiar with the proper care and handling of their gages. A plausible explanation may be rough handling during shipment to and from NIST between calibrations.

The degree of scatter among calibration shifts provides an indication of the calibration instability for each group of gages, customer-owned and NIST-owned. A quantitative measure of the instability is given by twice the standard deviation of the calibration shifts about the mean shift, which is nominally zero. The results for customer and NIST gages with full-scale ranges of 1, 10, 100, and 1000 torr are presented in Table 1. The table shows that shifts in CDG response functions differ significantly for gages with different full-scale ranges, the largest shifts occurring

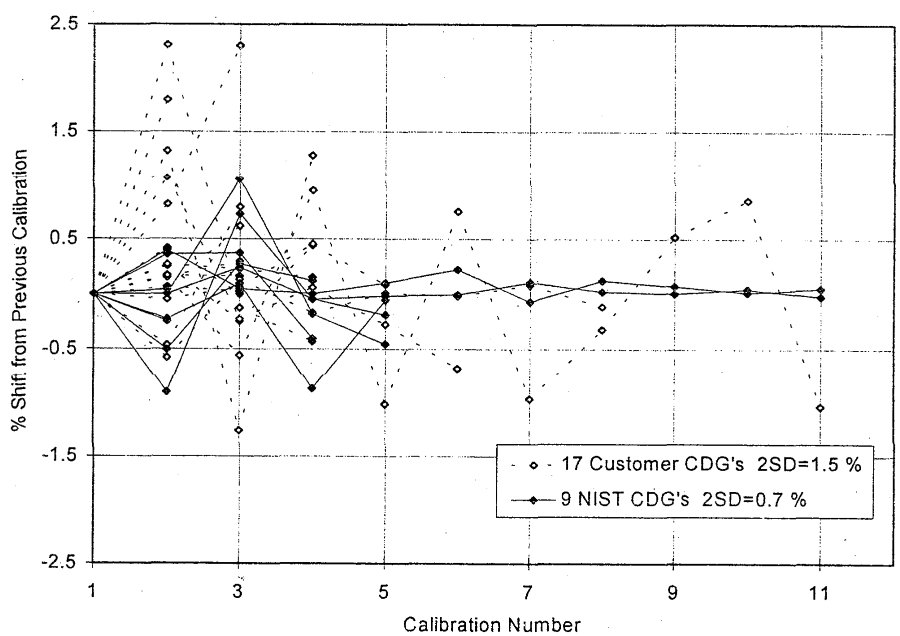

Figure 8. Calibration instability of 1 torr CDG's calibrated at NIST.

Table 1. Calibration instabilities of high-accuracy CDG's calibrated at NIST.

	Full Scale Range	Number of Gages	Number of Calibrations	2 Std. Dev. (% Shift)
Customer CDG's	1 torr	17	71	1.5
	10 torr	19	67	0.8
	100 torr	11	40	0.5
	1000 torr	8	20	0.3
NIST CDG's	1 torr	9	49	0.7
	10 torr	9	53	0.5
	100 torr	4	14	0.4
	1000 torr	2	8	0.3
	Totals	79	322	

for gages with the lowest full-scale range. The difference in stability between customer and NIST gages is also largest for the lowest range gages. The results obtained for the NIST gages are believed to be more representative of the inherent calibration stability of capacitance diaphragm gages since circumstances of their calibration and use are better known.

High range quartz Bourdon gages and resonant silicon diaphragm gages have been commercially available for several years as absolute, differential, and gauge mode units and, as a result, a history of their use has been established at NIST and elsewhere. A recent development has been the availability of low range versions of these gages for differential or gauge mode measurements. At NIST, a 7.5 kPa QBG and a 1 kPa RSDG have been adapted for absolute measurements and several repeat calibrations have been performed.

Figure 9 presents the history of absolute-mode calibrations performed at NIST on the 7.5 kPa differential QBG. The average shift, evaluated at 0.1 FS, 0.5 FS, and 1 FS, between successive calibrations over a period of one year is 0.003%. At pressures less than 0.1 FS the shifts are somewhat larger, yet less than 0.02%. The results indicate that the stability of this gage is of the order of 0.01% per year or better. This is consistent with calibration stabilities seen in higher range QBG's at NIST.

Similar data for a 1 kPa differential RSDG is illustrated in Figure 10. The average shift between four successive calibrations during a period of approximately a year is 0.005%, though the last calibration revealed a somewhat different trend in the response function with a shift of about 0.02% at a transducer reading of 0.1 FS. Although somewhat more limited, these data suggest that the calibration instability of this gage is of the order of 0.01% per year. Repeat calibrations of a 130 kPa RSDG at NIST have shown that the instability of a higher range RSDG is about 0.01% or better.

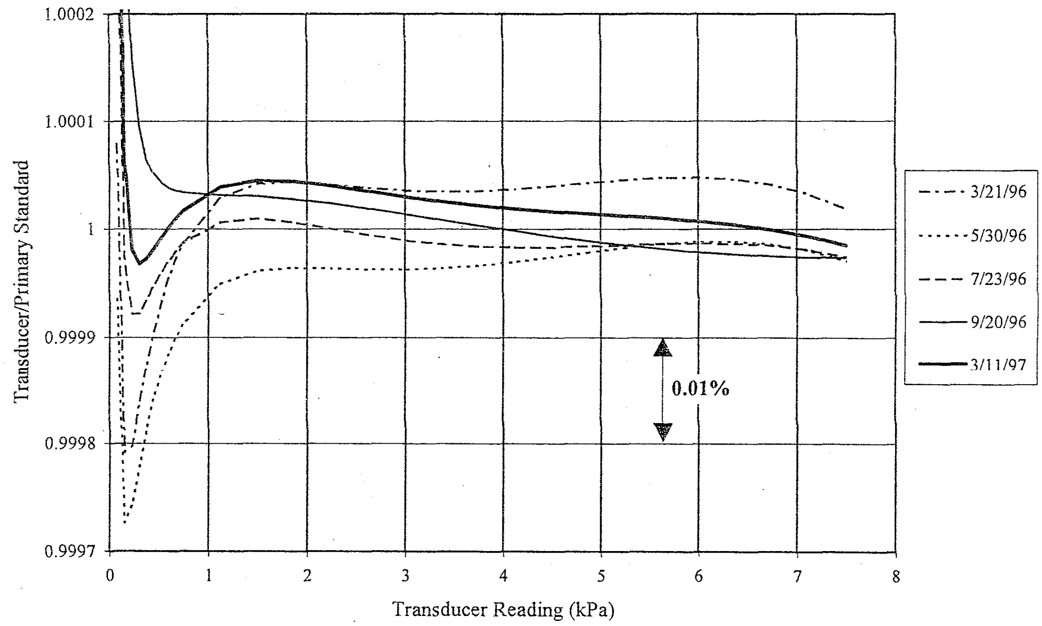

Figure 9. History of absolute-mode calibrations at NIST of a 7.5 kPa differential quartz Bourdon gage.

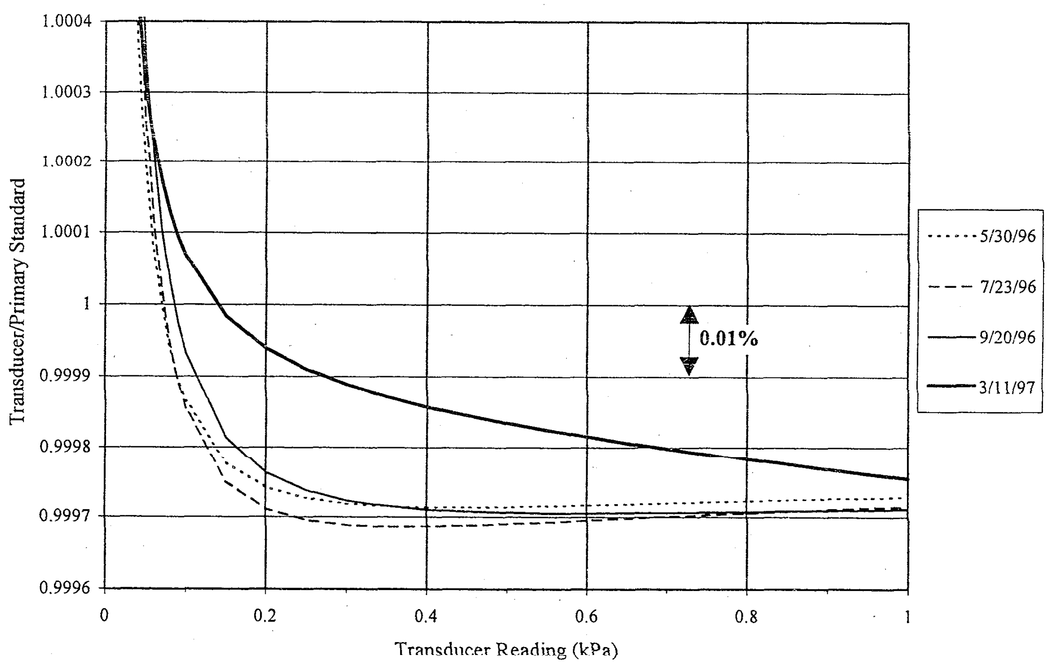

Figure 10. History of absolute-mode calibrations at NIST of a 1 kPa differential resonant silicon diaphragm gage.

4. Discussion of Results

A comparison of present results on CDG's with those of the earlier study[1] indicates the most significant improvement in measurement performance of high-accuracy commercial gages is their zero stability. The key to this appears to be the method used to control the sensor's operating temperature. Ten of the fourteen gages studied earlier used two different methods for temperature control of the sensor, either a proportionally-controlled heater wrapped around the sensor or a temperature-controlled thermal base on which sensor and electronics were mounted. The zero-pressure temperature coefficients of these gages are approximately an order of magnitude larger than those of the gages in the present study. The other four gages in the earlier study had their sensors mounted in a temperature-controlled cast aluminum shell similar to gages in the present study. Not surprisingly, they exhibited zero-pressure temperature coefficients of the same magnitude as those seen in this study.

The calibration data on CDG's from the earlier study (31 repeat calibration records for 18 gages) were also included as part of the present NIST calibration database (320 repeat calibration records for 79 gages) that forms the basis for results given in Table 1. The database was also analyzed by grouping records for CDG's with a given FS range by "age" (date of the first calibration) and model. However, the data was not sufficiently conclusive to suggest that calibration stabilities of gages currently in use at NIST and by our calibration customers are better than those of gages in use more than a decade ago.

Calibration stabilities of high range QBG's have also been studied at the Physikalisch-Technische Bundesanstalt in Germany, where the stability of two gages was observed to be better than 0.02% over a period of one year[7]. This is consistent with results obtained at NIST.

5. Conclusions

The present study has shown significant differences in the nominal measurement performance of different transducer types. Capacitance diaphragm gages have relatively good zero stability with zero-pressure temperature coefficients of $\sim 5 \times 10^{-6}$ FS/°C or better. Zero stability can be further improved with hybrid CDG systems developed at NIST. These systems, when controlling the CDG's near room temperature, can also significantly reduce the effect of thermal transpiration. The calibration stabilities of CDG's differ significantly for gages with different FS ranges, from 0.3% to 0.7% per year, the largest shifts occurring for gages with the lowest FS range.

The low-range quartz Bourdon gage and resonant silicon diaphragm gage considered in this study both exhibited reasonable zero stability with zero-pressure temperature coefficients of $\sim 1 \times 10^{-5}\cdot$FS/°C and $\sim 2 \times 10^{-5}\cdot$FS/°C, respectively. Although based on rather limited data, their calibration stabilities appear to be of the order of 0.01% per year or better, which is at least an order of magnitude better than that for CDG's.

This study has also shown wide variations in measurement performance among individual CDG's with a given FS range, by as much as a factor of 4 or 5 in some cases. For applications requiring highest accuracy, it is imperative that users establish the performance limitations of their gage. Zero instabilities should be evaluated from repeated measurements of room temperature and gage output at a stable low pressure (less than the sensitivity of the gage), taken over a time interval longer than that used for pressure measurements. Long-term calibration instabilities of the gage should be determined by direct comparisons with a reliable standard. With or without historical calibration data, confidence in the stability of the CDG can be improved if it is periodically compared with one or more check standards (other instruments with comparable or better stability)

Capacitance diaphragm gages will continue to be a transducer of choice for many applications because of their high sensitivity, all-metal construction and ruggedness. However, low pressure transducers based on other technologies are becoming commercially available in ever decreasing full scale ranges and, for selected measurement applications, they can provide a viable or, in some cases, a superior alternative to the CDG.

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