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Investigations on Measurement Uncertainty and Stability of Pressure Dial Gauges and Transducers

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Several commercial instruments are available for pressure measurements. As per ISO stipulations, whenever such instruments are used for precise and accurate pressure measurements, it is obligatory on the part of measurement authority to indicate the quality of results. Stability of the pressure measuring instruments over the years is one of the important parameters in defining the quality of results quantitatively. Also, it helps the users to decide the optimum calibration interval of the particular instrument. In the present investigation, we have studied a number of analogue / digital pressure transducers / transmitters / calibrators and pressure dial gauges. The present paper describes the results of the studies carried out on several pressure dial gauges and transducers in the pressure range up to 500 MPa, calibrated several times over the years, as examples. A new approach is proposed for the establishment of measurement uncertainty for such instruments by characterizing the data obtained during calibration over the years using curve fitting.

Keywords: Pressure metrology, pressure dial gauge, pressure transducer, calibration, measurement uncertainty, stability

1. INTRODUCTION

THE SIMPLE, cost effective, reliable, precise and highly accurate knowledge of one of the most important physico-mechanical quantities i.e. pressure is essentially required in all walks of human life including that of science, engineering, trade, commerce, efficiency, quality and safety. The extensive and vital role of pressure measurements is now well established in many applications in industries such as nuclear, thermal and gas based power plants; manufacturing of fertilizers, pesticides, chemicals, petro-chemicals, pharmaceuticals and drugs; forging of hot and cold steels; synthesis of super hard materials like diamond; optimization of domestic appliances like pressure cooker and filling of cooking gas cylinders; assessment of health like blood pressure monitors, ventilation, filtration and process control in general. Such diversified applications witnessed focused and considerable research and development activities in pressure metrology during the last 4-5 decades that have resulted into development of various types of improved industrial hydraulic pressure measuring instruments such as piston gauges or dead weight testers, pressure transducers based on various physical effects and mechanical dial type gauges, commonly known as Bourdon gauges.

Whenever repeated measurements of a physical quantity are made, the observations are found to vary due to assignable and controllable causes like improper / incomplete measurement method, improper selection and bias in the equipment / apparatus used, wrong recording of measurement data etc. A measurement process cannot produce meaningful results unless all such assignable causes of variability are eliminated. For chracterising the quality of measurements, well established, readily implemented, easily understood and generally accepted procedures have been published as ISO Guide [1] and EAL Document [2]. These procedures stipulate that the measurement results should be reported with some indication of quality of results. Without such indication, the measurement results can not be compared, either among themselves or with reference values or standard. So any measurement which has no valid calibration is meaningless. Further, the measurement uncertainty of reference standard should be better than or equivalent to that of the instrument under calibration. Accurate measurement of pressure is an important subject of considerable interest in recent days. Several instruments nowadays are commercially available with much improved measurement uncertainty i.e. liquid column manometers (LCM), dead weight testers (DWT), quartz resonators (QR), pressure dial gauges (PDG), resistance / capacitance / inductance type pressure transducers / transmitters (PT). LCM and DWT measure pressure based on primary principle having well defined mathematical expression / model for measurand and are categorized as primary / reference instruments [3-4]. The evaluation of measurement uncertainty for such instruments is readily evaluated and can be characterized by the estimation of Type A and Type B standard uncertainties [5-7].

The mathematical model of the measurement that transforms the set of repeated observations into the measurement results also includes various influence quantities that are not exactly known. Ignorance of these quantities contributes to the uncertainty of the measurement results where well defined models are not available as in the case of QR, PDG and PT. Establishment of measurement uncertainty for such instruments is a very tedious and difficult task. In such cases, the Type B standard uncertainty of the equipment can only be characterized by an estimate obtained from a curve that has been fitted to the experimental data by method of least square and Type A standard uncertainty through a series of repeated measurements. In the present work, computer software has been developed that is used for curve fitting and data regression using least square method for simple polynomial. More than fifty PDGs and PTs have been studied and results are discussed. It has been observed that by using curve fitting and data regression, the uncertainty of such types of equipment can be improved relative to the uncertainty specified by the manufacturer of the gauge.

2. EXPERIMENTAL SET-UP

All the pressure measuring instruments studied in the present investigation were calibrated against National Physical Laboratory, India (NPLI) secondary pressure standards. The primary and secondary pressure standards maintained are controlled clearance type piston gauges [4, 8-9]. Fig.1 shows schematically the usual circuit for the calibration of PDGs and PTs.

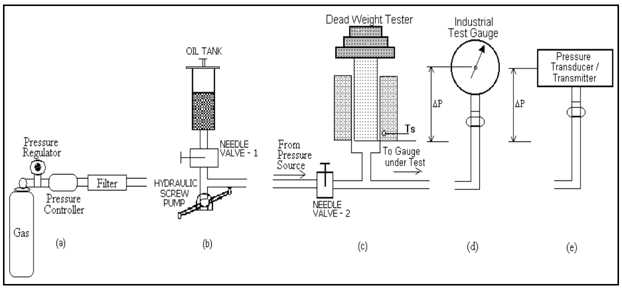


Fig.1. Experimental set up for calibration of pneumatic PDGs (a+c+d); hydraulic PDGs (b+c+d); pneumatic PTs (a+c+e) and hydraulic PTs (b+c+e)

The calibration procedure for these instruments starts with leak testing, zero adjustment and the selection of a reference or datum level. After connecting the instrument under test, the pressure in both the standard and test instruments is raised to the full scale pressure of the test gauge; the pressure is then released slowly to zero. This process is repeated at least three times to ensure that there are no leaks in the system. In this way the compressibility of the transmitting fluid, packing of the valves, pump plunger and O-ring seals is stabilized to reach an optimum level. Zero setting of the pressure gauges was performed using the zero adjustment knobs (mechanical or electrical). If a zero adjustment knob is not available, the initial bias in the measurement (zero shift) is recorded, and the necessary correction is applied at the appropriate level. A precise reference or datum level is then established for the PDGs and pressure transducers. Usually, this is noted in the operational manual. If no such information is available, the center point of the elastic sensor is considered as the reference or datum level.

For calibration of a PDG, the full-scale pressure is divided into at least 10 equally- spaced pressure points. The needle of the PDG is transferred to a chosen point and the mass on the pressure standard is adjusted so that the piston of the pressure standard floats at the reference or equilibrium level. The pressure measured by the standard is then computed using computer software [10], which is based on pressure balance theory reported in the literature [11-12]. At least 20 observations, both in increasing and decreasing pressures are taken to evaluate hysteresis in the pressure cycle. After reaching full scale pressure by increasing pressure, ten minutes were allowed to pass before repeating the observations by decreasing pressure. Sufficient time (approximately 15-20 minutes) is kept between successive observations to allow the system to reach a state of thermal equilibrium. Three pressure cycles are employed for each instrument so that minimum number of observations at each pressure point is 6 and there are at least 60 observations as a whole. The mean value of the observations at each pressure point is used to fit a curve showing the reading as a function of nominal pressure for those gauges in which hysteresis is not studied. To examine the hysteresis effect, all the observations are taken into consideration when fitting the curves, and the deviation of the observations at each particular pressure point in both the increasing and decreasing pressure cycles is considered as the random scattering of the data. In case of pressure transducers, the output is recorded as a function of the applied pressure as determined by the pressure standard. The rest of the calibration process is similar to the one used for PDGs.

After computing the pressure measured by pressure standard for each nominal value, the characteristics of the pressure gauges are expressed in the form of $p = f(r)$ where p represents the standard pressure, r the test gauge reading and f is a polynomial function. The calibration data are then analyzed to study the behavior of pressure gauges and plotted so as to show calibration factors and percentage residuals of fitted values versus gauge reading. As noted earlier, the evaluation of uncertainty in the measurements for DWTs and LCMs can be characterized by estimating Type A and Type B standard uncertainties. In case of PDGs and PTs, where well defined models are not available, the estimation of standard uncertainty can be obtained from a curve that has been fitted to the experimental data by the method of least squares. The estimated variances and resulting standard uncertainties of the fitted parameters characterizing the curve are computed using a computer software using least square method for simple polynomial as follows;

$$y = a_0 + a_1 x + a_2 x^2 + ... + a_n x^n \tag{1}$$

where y is the calculated (fitted) value obtained from experimental value x using a_0, a_1, a_2........and an as zero order, Ist order, 2nd order ....and nth order constants of the fitted curve. The uncertainty of the instruments under calibration was obtained by plotting percentage residuals against gauge reading for the same gauge/gauges. The residuals R are obtained by subtracting calibration factor of fitted values from the calibration factor of experimental values as follows;

$$R = \left(C_{fe} - C_{ff}\right) \tag{2}$$

where $C_{fe} = \left(\dfrac{x_e}{x_g}\right)$ and $C_{ff} = \left(\dfrac{x_f}{x_g}\right)$ are defined as calibration factors of fitted and experimental values, respectively, x_e and x_f are the experimental and fitted values for the gauge reading x_g. Finally, relative residuals are obtained by multiplying values of residuals R by 100.

The relative residuals indicate the uncertainty of each measurement point and the maximum span of the residuals is considered to be the overall uncertainty of the pressure measuring instrument. For a gauge that displays hysteresis, the curve for increasing pressure differs from that for decreasing pressure. In such cases, fitted curve generally, but not always, passes through the mean of all gauge readings taken for each nominal pressure. The deviation of relative residuals in increasing and decreasing pressure of a one pressure cycle describes the effect of hysteresis and deviation of relative residuals in different pressure cycles is due to random effects. The maximum span of relative residuals, including hysteresis and random effects may be considered as overall uncertainty of the pressure gauge. When the measurand is computed using the fitted equation, most of the errors due to nonlinearity are eliminated whereas the random component of the error may still persist. The random component is caused mainly due to the environmental condition, the method of measurement used, the properties of the gauge tested and the operator engaged in the measurement. Therefore, by proper control of the complete measurement process and the operator with ample knowledge of the process, the random effects can be reduced to a minimum value. No electrical / electronic equipment is used with pressure balance standards to measure corrected pressure except measurement of temperature of piston cylinder assemblies. The temperature of piston cylinder assembly is measured using the attached mercury thermometer or platinum resistance thermometer. The uncertainties of temperature measuring equipments used in the present investigations are much less compared to those of the pressure gauges under calibration. Since the effect of such contributions is not considerable on the overall uncertainties of the pressure gauges under calibration, they are ignored in the computation of overall uncertainties. However, if any electrical / electronic equipment is used to record the output of the transducers and for the measurement of temperature, the electrical quantities may certainly influence the uncertainty budget. In such cases, the root mean square method may be used to compute overall uncertainty taking into consideration all the uncertainty contributions.

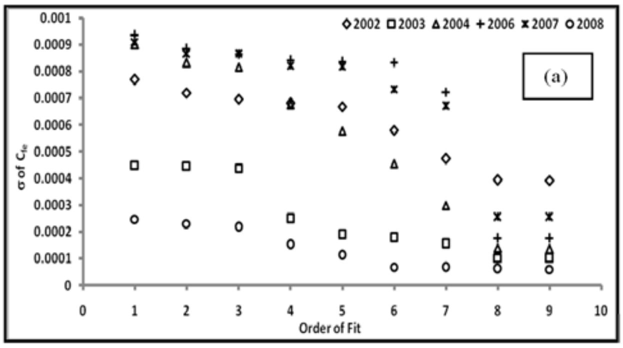
3. RESULTS AND DISCUSSION

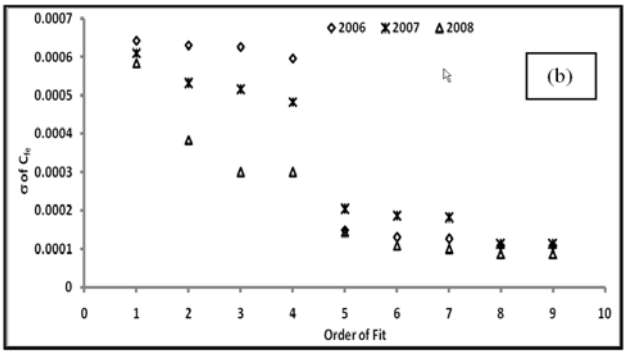
In the present investigation, more than fifty gauges were studied in the way of calibration against NPL primary and secondary pressure standards. It is not possible to report results of all the gauges due to obvious reasons. However, results analyzed for some of the selected gauges are discussed in detail. The secondary standards are periodically calibrated against NPL primary pressure standards and their uncertainties in measurement are established through in house calibration and by participating in the international intercomparisons [13-15].

The different pressure ranges covered are 0 to 500 MPa. In most of the cases of PDGs, it has been observed that 8th order fitted values are much closer to the experimental values as suggested in our earlier findings [16]. Further extensive studies carried out over the years conclude that it is true for most of the PDGs independently of the type of gauge, measurement range, pressure transmitting fluid and the measurement standard used in the calibration. Such preliminary results were presented elsewhere [17]. It is not possible to include all the results in this paper due to obvious reasons. However, the results of some gauges studied over the years are included in this paper.

The identical trend is obtained when the same gauge is calibrated several times over the years. Although, in some of the PDGs, 7th order fit was also observed but 8th order fit was found suitable in 90% of the cases. In order to arrive to the conclusion of 8th order fitting, the standard deviation of fitted values has been plotted against order of fit for two hydraulic PDGs of 0 – 70 MPa (PDG1) and 0 – 60 MPa (PDG2) in Figs.2(a) and 2(b), respectively for the calibration data collected over the years. These two PDGs were also used as artifacts for the proficiency testing experiments conducted by NPLI for Indian pressure accredited calibration laboratories [18-20]. We can clearly see in Figs.2(a) and 2(b) that 8th order fit is most suitable with minimum standard deviation. The same behavior is observed for other PDGs irrespective of different pressure ranges with least relative residuals which are well below the specified uncertainty of the gauge reported by manufacturers. This conclusion of 8th order fit is achieved after studying more than 50 pressure dial gauges of different ranges.

It is clearly evident from Figs.2(a) to 2(b) that standard deviation of fitted value improves with the increase in order of fit but it nearly saturates after 8th order with no considerable improvement in the standard deviation and hence it is concluded that 8th order fitting is most suitable irrespective of pressure range and transmitting fluid used. The fitted values are almost superimposing to the values of [Fig.2(c) - primary x-axis] having relative residuals within ± 0.06% [Secondary y – axis] for both PDG1 and PDG2.





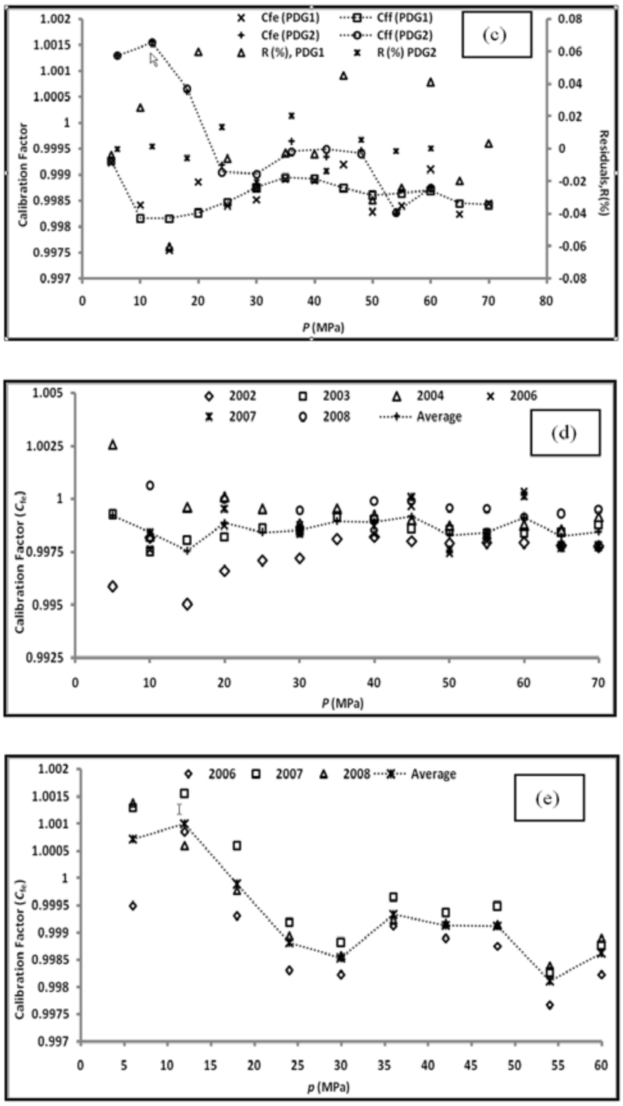


Fig.2. Plots showing the standard deviation of calibration factor versus order of fit for (a) PDG1, (b) PDG2, (c) plots showing experimental and fitted values of calibration factor using 8th order fitting along with relative residuals for both PDG1 and PDG2 for the year 2008, (d) stability of calibration factor as a function pressure for PDG1 and (e) stability of calibration factor as a function pressure for PDG2.

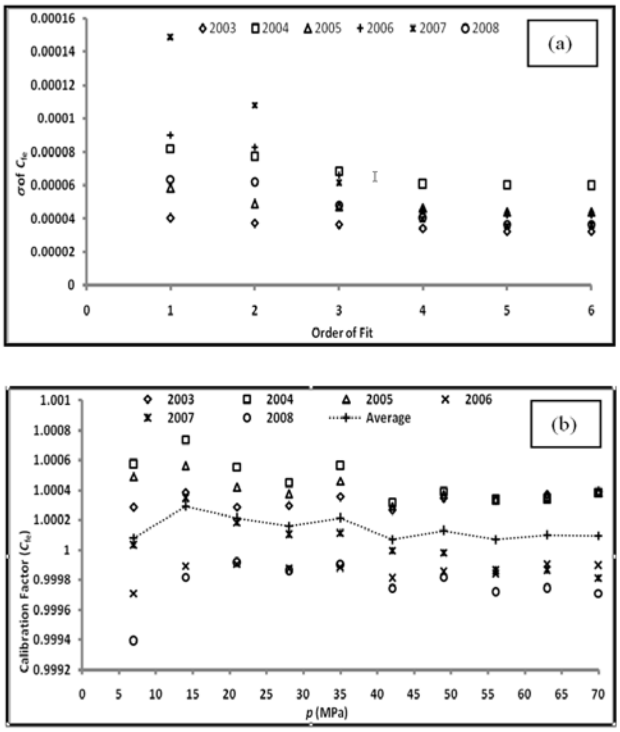
In order to study the stability and behavior of gauges over the years, the data collected for 6 calibrations and 3 calibrations, performed from 2002 to 2008, are shown in Figs.2(d) for PDG1 and 2(e) for a PDG2. Almost identical behavior of both gauges is observed over the years, which leads to the conclusion that the gauges remained stable during these years. Since these plots are obtained by taking the mean of several observations at one particular pressure point to include random effects, deviations of the experimental values with fitted values are considered as "systematic". The percentage residuals are obtained by approximating the characteristic of the gauge through curve fitting to a precision well below the level of random uncertainty. Therefore, the percentage residuals are treated as Type B uncertainty of the gauge.

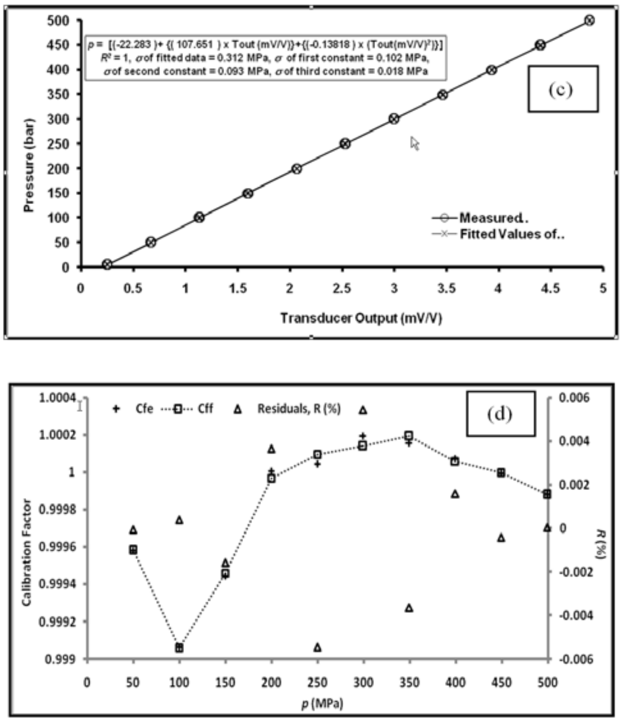
It is clearly evident from Figs.2(d) and 2(e) that both gauges behaved almost in a similar fashion during all the six calibrations (PDG1) and 3 calibrations (PDG2) except at the slightly lower pressure points which are obviously below or equal to the 10 % of the full scale pressure. The relative deviations are found to be well below 0.06 % [Fig.2(c)]. These relative deviations are well within the manufacturer specifications of 0.1 %. We can conclude that both PDGs remained stable during these successive calibrations.

The contribution of hysteresis on overall uncertainty of PDGs was also studied in some of the gauges where it was considered prominent. We have observed that in some of the gauges, the maximum contribution of hysteresis on uncertainty is within 10 % of full scale pressure of the gauge under test.

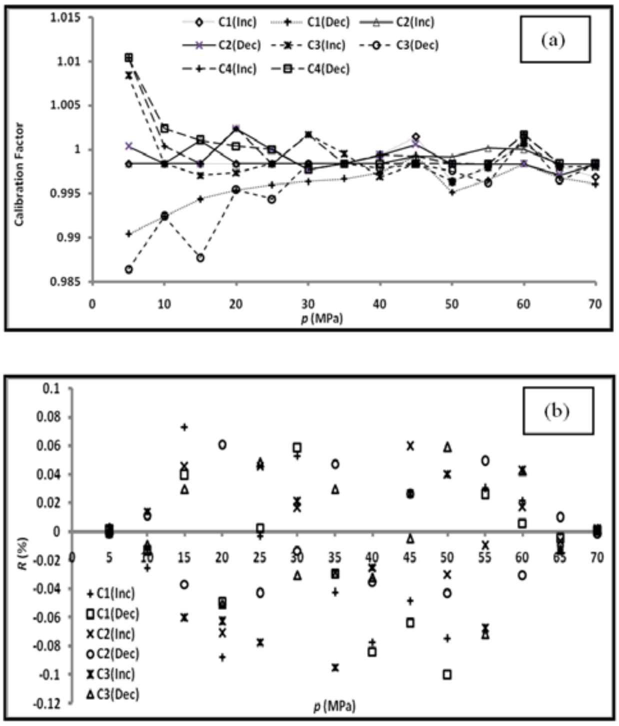
The higher error at initial points is mainly due to the limited sensitivity of the gauges, small force error and viscosity of transmitting fluid. Therefore, if initial points of 10 % of full-scale pressure are ignored, the uncertainty is found to be improving in comparison with the uncertainty reported by manufacturers.

A similar behavior was observed in case of pressure transducers except that the 3rd or 4th order fitting is the most suitable. The graphs plotted to judge the suitability of the fitting order for SGT1 (0 – 70 MPa) are shown in Fig. 3(a) by plotting the standard deviations of fitted values against order of fit as in case of PDGs and thus the suitability of 4th order fitting is well established irrespective of type of transducer, pressure range and transmitting fluid used. Fig.3(b) clearly reveals that SGT1 remained stable and behaved in a similar fashion during all the six calibrations performed form year 2003 to 2005. A pressure calibrator based on SGT1 was also used as artifact for the interlaboratory comparisons conducted for Indian pressure accredited calibration laboratories [21-23].





Figs.3. Plots showing (a) standard deviation of calibration factor versus order of fit for SGT1,(b) behaviour and stability of calibration factor as a function of pressure for direct pressure indicating device (SGT1), (c) calibration curve for an indirect pressure indicating device (SGT2) using 3rd order fitting and (d) calibration factor and percentage residuals for SGT2



Figs.4. Plots showing (a) calibration factor of PDG1 for three pressure cycles, C1, C2 and C3 in increasing as well as decreasing order of pressure, (b) residual R (%)

SGT1 is a direct pressure indicating device. For the indirect pressure indicating devices, as in case of strain gauge pressure transducer of 0 – 500 MPa (SGT2), the output of the transducer in mV/V was recorded as a function of applied pressure. The 3rd order fitting was found most suitable in this case also as shown in Fig. 3(c). However, if calibration factor is used, then third order fitting is not suitable here. However, our observations reveal that 8th order fit is most suitable in such cases [Fig.3(d)]. In such cases, the uncertainty of the calibration curve is estimated from the calibration coefficients [24-25] and is root-sum-squares of residuals obtained as suggested above for the computation of the overall uncertainty associated with pressure measurement.

As discussed earlier, in case of PDGs these plots were obtained by taking several observations at particular pressure point to include random effects, while Fig.4(a) is the clear representation of random as well as systematic effects. These calibration factors are plotted for four cycles (C1, C2, C3 and C4) of observations at one point over the entire range for PDG1 to include random effects in increasing as well as decreasing order of pressure. The mean relative residuals of C1, C2, and C3 vary from -0.09 % to 0.07 %, -0.07 % to 0.06 % and -0.09 % to 0.06 %, respectively which is shown in Fig.4(b). Thus, the spans of residuals given above for each cycle are treated as systematic components and the total systematic error is brought to the level of maximum span of all residuals which is due to random effects i. e. ± 0.09 % and this has been considered as relative uncertainty of the gauge which is well within the manufacturer specification of ±0.1%. Similar improvement in uncertainty is observed for most of the gauges and transducers.

4. CONCLUSIONS

Extensive studies are carried out on more than 50 pressure dial gauges and transducers using calibration factor, stability and percentage residuals obtained during their calibrations over the years. A novel approach is proposed for the estimation of measurement uncertainty of such devices. Our studies reveal that curve fitting can be utilized for the establishment of uncertainties of various pressure measuring instruments. The 8th & 3rd (4th) order fitting are most suitable for PDGs and pressure transducers, respectively. Our investigations suggest that using curve fitting, one can improve the uncertainty of the pressure measuring equipment. We have only reported our observations of 8th and 3rd order fitting for PDGs and pressure transducers, respectively but this would certainty open new lines for researchers to predict some mathematical models.

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