Chapter 6
The Impact Calibration Technique for Piezoelectric Force Sensors

Michael Mains, Derrick Hollins, and Chad Kallmeyer

Abstract This paper is an expansion upon a previous IMAC paper which compared calibration techniques for piezoelectric force sensors [1]. In this paper, the dynamic impact calibration technique will be further explored and verified with additional testing. We will retake some of the same data taken in the original paper with the same sensor models and test procedures tested to investigate repeatability of the technique.

In the original paper force was applied to the sensor under test similar to the way an impact hammer is calibrated, this is similar in many ways to how an impact test is performed for modal testing. The use of an impact hammer is convenient and commonly used for modal testing, but known to not provide the best data for modal analysis. Many of the same issues that affect impact modal testing, such as alignment of the hammer to the surface of the structure to be impacted are known to affect accuracy. We will look at using the mass extenders that come with the impact hammer and using a larger hammer that what was used in the original paper. Additionally, a MATLAB app using the DigiDAQ was used in the original paper, we will also acquire data with a higher quality lower noise DAQ card and use The Modal Shop (TMS) 9961 software the is traditionally used for impact hammer calibration.

All results will be compared back to the tradition hydraulic force sensor calibration that is currently used for calibrating force sensors.

Keywords Force · Sensor · Calibration · Impact Hammer

Background

The available methods of calibrating piezoelectric force sensors have limitations. The simple to use and accessible Gravimetric Drop Calibration may not adequately test a high range sensor while the use of deadweight and hydraulic systems is set up intensive and costly. The Impact Calibration technique provides both a simplified set up and higher force input for calibration of higher measurement range force sensors.

The Gravimetric Drop Calibration rig is shown in Figs. 1 and 2 was discussed in detail in the original paper. A typical time history is shown in Fig. 3. This measurement is repeated with several weights. The limitation of this method is limited to the maximum weight that can be supported by the monofilament line. In The Modal Shop calibration lab weights of approximately 1, 2 and 3 lbs. are used.

A representative hydraulic force sensor calibration system is shown Fig. 4. This method was discussed in detail in the original paper.

In this paper we continue to investigate the impact method as a third option to calibrate force sensors. Impact testing had been used in trouble shooting and impact hammer calibration for a number of years. It is also receiving renewed interest in the research of National Metrology Institutes (NMI's) like Germany's Physikalisch-Technische Bundesanstalt (PTB) [2] and the United States' National Institute of Standards and Technology (NIST) [3]. Figures 8 thru 10 show their respective test systems for hammer calibration. They have not yet tried to extend this to general purpose force sensors and impedance heads as we do in this paper. It is interesting to note that both systems implement a pendulum setup for there hammer to mitigate operator error that might occur during testing. PTB's system specifically notes the use of a scale to help maintain a consistent application of force. TMS is evaluating is currently evaluating these designs as well as investigating a dual

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Fig. 1 The Modal Shop Gravimetric Calibration rig

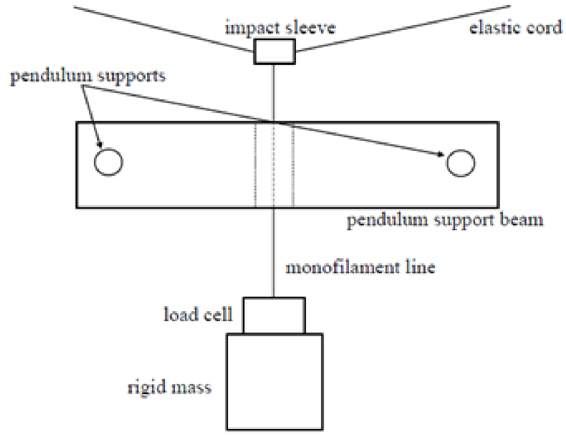

Fig. 2 Gravimetric Load Cell Calibration

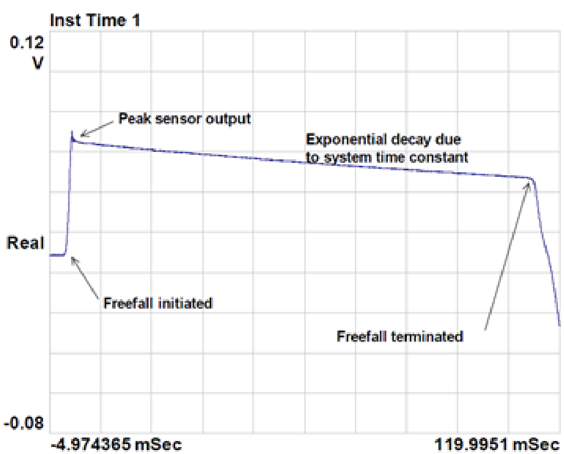

Fig. 3 Time history of a gravimetric force cell calibration

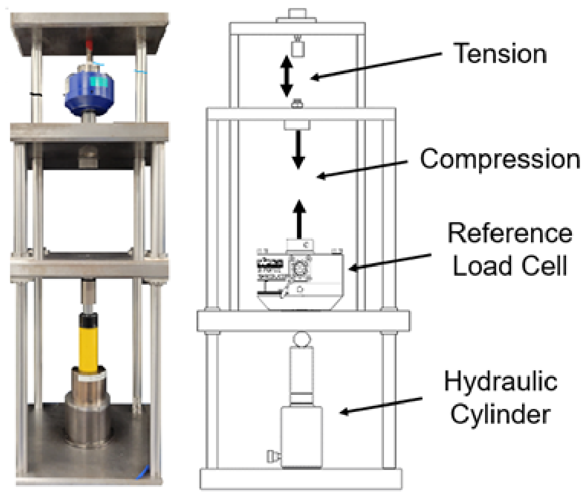

Fig. 4 Force Calibration Rig

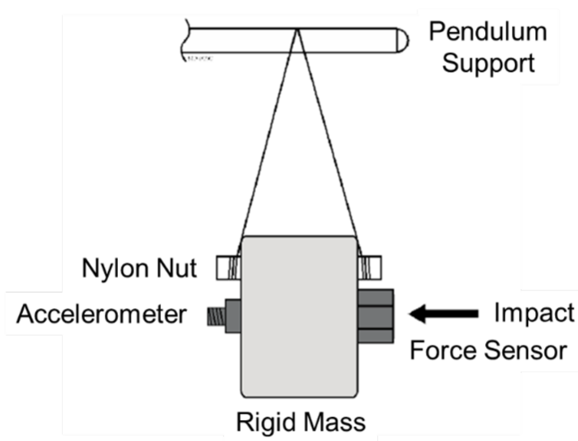

Fig. 5 Impact Force Sensor Calibration

pendulum impactor that would use two weights with both pendulums supported by monofilament line. Figure 5 illustrates the setup using the pendulum of the Gravimetric Calibration rig that is typically used for calibration of impact hammers. With this method, instead of calibrating the impact hammer we mount the force SUT on the rigid mass and install an impact cap on the force SUT. The impact hammer is used to apply the force to the SUT and the acceleration is measured using a reference accelerometer. The force is calculated multiplying the measured acceleration by the mass of the rigid mass of the pendulum. Several impacts were made at varying force levels.

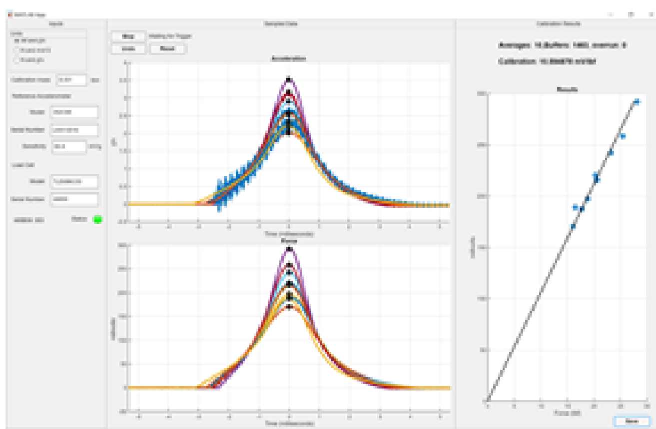

Fig. 6 MATLAB application

Fig. 7 DigiDAQ Model 485B39

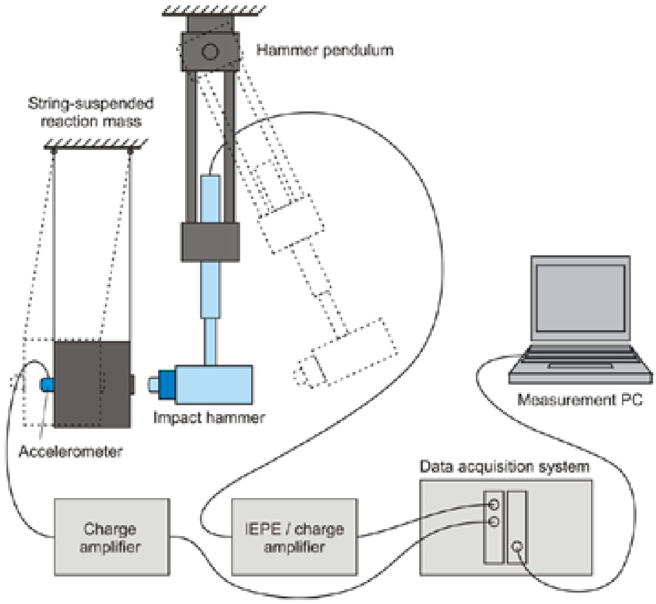

Fig. 8 Impact Hammer Calibration Device at PTB

Testing

Application and DAQ

The measurements were made with two different acquisition setups. The first is a continuation of what was used in the previous paper and was comprised of a custom MATLAB app (Fig. 6) written for the DigiDAQ Model 485B39 (Fig. 7). The second setup was the TMS Impact Hammer Calibration System 9155-961 software option which uses a National Instruments (NI) 4461 DAQ card. Acceleration measurements were made with 353B04 ICP Accelerometers. Force impacts were applied with a PCB TLD086C03 or TLD086D05 impact hammer with and without mass extender. Hammer tips included the red (super soft), black (soft), white (medium) and steel (hard) hammer tips included with TMS and PCB impact hammers. The steel hammer tip was not always used with the MATLAB DigiDAQ app because the DigiDAQ is limited to a 48kHz sample rate. Typically, 10 to 16 impacts were made taken per test. A test consisted of a specific force sensor, hammer tip and either a slow, rapid or mixed application of force. Unlike hammer calibration, hammer tips don't seem to bias the results of calibrating the force sensor. For hammer calibration a different sensitivity is often specified for different hammer tip and extender configuations.

Table 1 Table of Sensors

Range (lbf)	Sensitivity (mV/lbf)	Type	Normalized Error E_N		Normalized Error $\|E_N\|$		Sample Size (Sensors)		Model
			2025	2024	2025	2024	2025	2024	
10	500	Force	-1.27	0.07	1.35	0.80	72(3)	8(2)	208C01
100	50	Force	-0.45	-0.20	0.46	0.20	98(2)	10(2)	208C02
500	10	Force	-0.66	-0.82	0.67	0.82	98(3)	10(2)	208C03
1000	5	Force	-1.16	-1.74	1.17	1.65	98(3)	10(2)	208C04
5000	1	Force	0.36	2.10	0.38	2.10	72(3)	8(2)	208C05
50	100	Impedance Head	-	0.07	-	0.73	-	10(2)	TLD288D01
100	50	Impedance Head	-	0.30	-	0.37	-	10(2)	TLD288M25

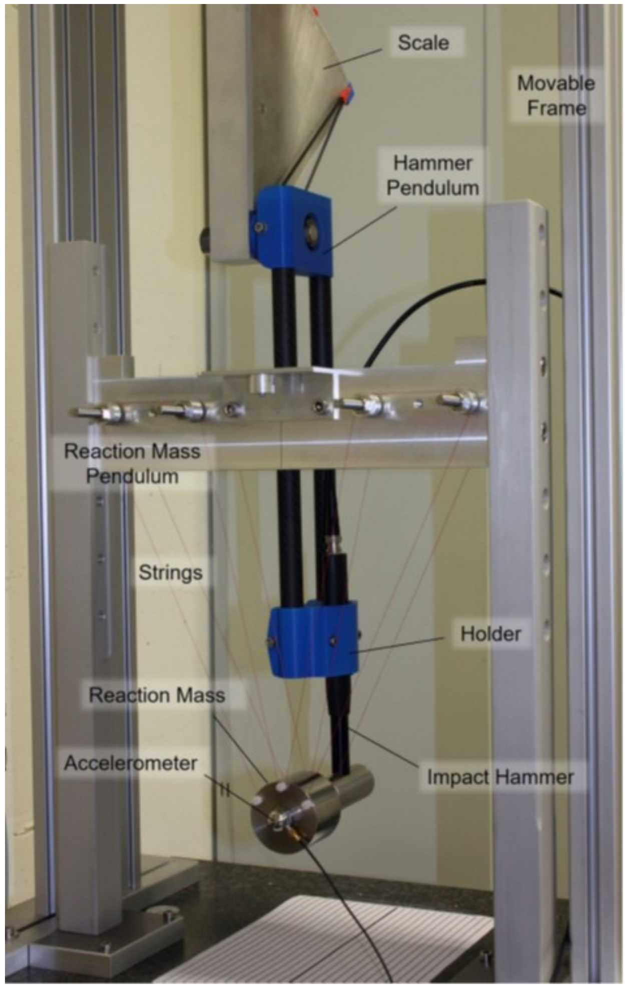

Fig. 9 Photo of PTB Device

Sensors

Two to three sensors each for seven different models of sensor were tested for a total of 18 different sensors pulled from the TMS rental pool. The maximum force level for each sensor model varied from 10 lbf to 5000 lbf. Two of the force sensors used were impedance head type sensors which include force and acceleration measurement capability. These sensors are typically used for making driving point FRF measurements for modal testing where shakers are used for excitation.

Analysis

To determine the force sensor's sensitivity a simple least squares regression is performed. Since the y-intercept between the known acceleration and the unknown force is zero for ICP sensors the least-squares regression simplifies to:

$$x_n = \frac{\overline{V}_p}{m\bar{a}_p} \tag{1}$$

where: x_n = sensitivity of the new method
$\overline{V}_p$ = is the mean of the peak Voltages measured by the force sensor
m = mass of the pendulum
$\bar{a}_p$ = is the mean of the peak accelerations measured by the accelerometer

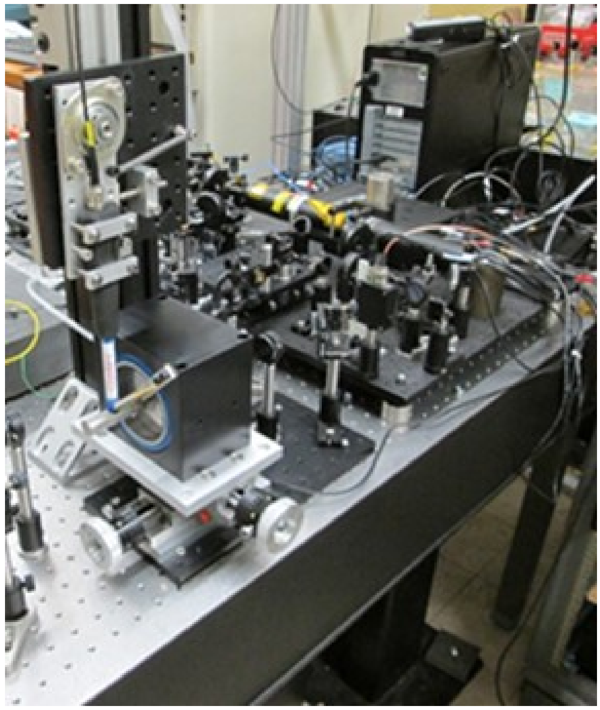

Fig. 10 NIST Impact Force Standard

Normalized Error

It is common when comparing calibration results between laboratories to use normalized error [4]. This is often done with laboratories participating in proficiency tests or interlaboratory comparisons. Normalized error is a statistical evaluation where the uncertainty in measurement result is included.

$$E_n = \frac{\frac{x_n}{x_R} - 1}{\sqrt{U_n^2 + U_R^2}} \tag{2}$$

where: x_R = sensitivity of the existing method

U_n = Uncertainty percentage of the new calibration procedure

U_R = Uncertainty percentage of the existing calibration procedure

For this analysis, similar to coherence, values between ± 1 are considered acceptable.

Results

The Normalized Error calculation was applied to 457 of 462 tests that were performed on 18 different sensors. 4 of 6 data sets for 5000 lbf. sensor were omitted from this study because the sensitivities were over 20 mV/lbf for a sensor with a nominal sensitivity of 1 mV/lbf. Since the other 2 data sets were reasonable, they were retained. 1 of 64 data sets for a 10 lbf. were omitted because the sensitivity was 171 mV/lbf when the nominal is 500 mv/lbf.

The difficulty with using Normalized Error is assigning an Uncertainty percentage to the new calibration method. This is primarily because there hasn't been any data acquired for this method. The first attempt was to assume that the Uncertainty percentage of the new method would be equivalent to PCB's uncertainty for their hydraulic calibration method which is stated at $\pm 1\%$. When applying 1% to both Uncertainties the histogram shown in Fig. 11 with a range of –5 to 10 can be plotted. Realizing that the Uncertainty for impact testing is typically stated at 5% the histogram was replotted and shown in Fig. 12 with a more reasonable range of –1.58 to 2.94. Noting that there a positive bias in data, the question was raised as to whether the mass of the reference accelerometer and force sensors included in the overall system mass. Realizing that this wasn't the case the nominal mass of the Force, Impedance Head and Reference accelerometer were included and the sensitivities for each sensor were recalculated. The mass of each item in the system are listed in Table 2.

Table 2 Masses

	Mass (lbm)	Mass (grams)	Model
Pendulum	1.94	880.0	N/A
Force	0.050	22.7	208C
Impedance Head	0.042	19.2	TLD288
Accelerometer	0.023	10.5	353B04

Looking back at Table 1 we see have added the 2025 data to the 2024 data and presented the 2024 data for comparison. For the 2024 data the force sensors in the 10 to 500 lbf range have the best average normalized error of −0.07, −0.20 and 0.82 respectively with the worst results for the 1000 and 5000 lbf sensors, of −1.58 and 1.31 respectively. This can be partially explained by trying to impact these sensors that hardest, trying to introduce higher force and thus introducing more human error in impacting perpendicular to the sensor and to the center of the sensor. The average of the absolute value of normalized error gives similar result with 10 to 500 lbf force sensors ranging from 0.20 to 0.82. Again, the 1000 and 5000 lbf sensors have the worst average of the absolute value of normalized error of 1.65 and 1.31. Adding the 2025 data to the 2024 date we see that the 10 lbf sensors an excellent normalized error of −0.07 to −1.27, for the worst change. The 100 lbf sensors went from −0.20 to −0.45 in normalized error, but not a significant difference. The 500 lbf sensor improved slightly from −0.82 to −0.66. The 1000 lbf sensor also improved from −1.58 to −1.16. The 5000 lbf sensor improved the most from 1.31 to 0.36 in normalized error. We see similar trends with the absolute value of the normalized error. Note that no additional data was taken in 2025 for Impedance Head sensors.

Comparing the 2024 data sets with 66 samples (Fig. 13) with the combined 2024 and 2025 data sets of 457 samples (Fig. 14) we see a normalized error still between −2 and 2. Most of the new data sets are falling between normalized errors of between −1.5 and 0.5. If we remove the data from 2024 from Fig. 14 we produce a sample size of 391, shown in Fig. 15. Here we accentuate the negative Bias in the data seeing no normalized errors above 0.5 in the new data. Since we introduced a new DAQ and Software Figs. 16 and 17 make the comparison between the 257 MATLAB/DigiDAQ and TMS 961/NI 4461. Note the negative bias in the uncertainty is present in both, so the negative bias is not created by the introduction of the new software and hardware combination.

Figures 18 through 20 group the data by operator. In 2024 Operator A performed all of the tests and Operator B and C conducted the tests in 2025. It seems that Operator B is contributing more to the negative bias than Operator C that we see 2025 data. Operator A seems to have a more Gaussian-like distribution in their Normalized Error. Perhaps operator error is the biggest cause of variation. An obvious error in not allowing the accelerometer to settle was show in the previous paper.

Figures 21 through 25 group the data by sensor model. These histograms display some of the most Gaussian-like distributions suggesting that there be some dependency on the sensor models. The 10 lbf (Fig. 21) and 1000 lbf (Fig. 24) sensor are the biggest contributors to the negative bias in the data. The 5000 lbf sensor (Fig. 25) has the most positive bias with the largest positive outliers from the 2024 data.

Figure 26 shows the data from 2024 with Impedance Heads. We simply need to take more data for these sensors.

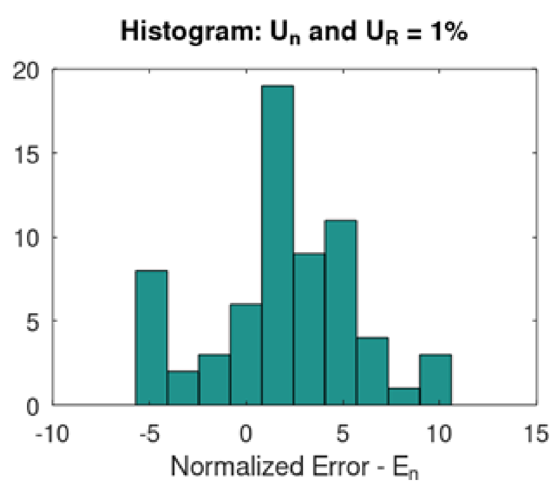

Fig. 11 Histogram with Uncertainty for both methods set to 1%

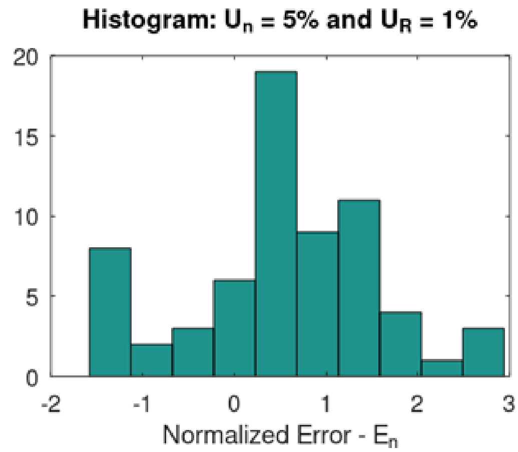

Fig. 12 Histogram with New method uncertainty set to 5%

Table 3 gives a general overview of how force is affected as we harden the tip and increase mass of the hammer. As expected, the harder the tip, the harder the force and heavier the hammer the more force is applied. For the hardest tip and larger hammer with extender mass, we achieved a max measured force of 320.80 lbf, getting much closer to the full mass range of the 500 lbf, Model 208C03 force sensor. While this was a "well selected" example, this was the general trend for all the sensors involved in this study. It's believed that a proper setup could be developed to optimize the force applied to various model sensors. Perhaps optimizing a setup for a 5000 lb force sensor could be dialed back for lower capacity sensors so as not to damage them and apply optimal force. Again a pendulum used for applying the force could be setup to swing at different heights for different loads.

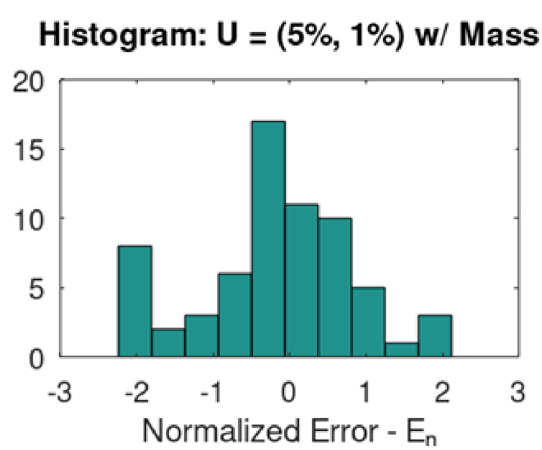

Fig. 13 Histogram with values adjusted for mass

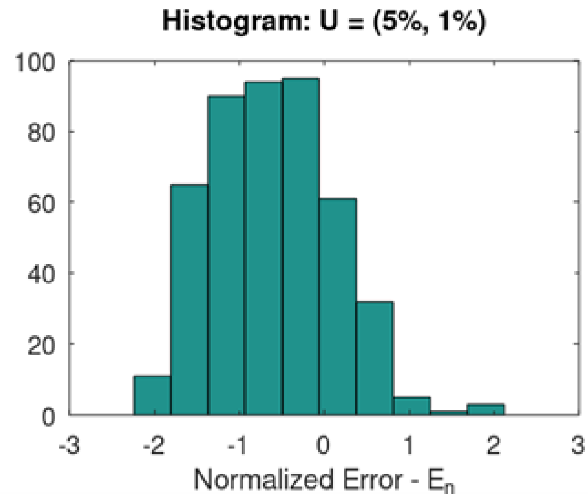

Fig. 14 2024 and 2025 Data, Sample Size 457

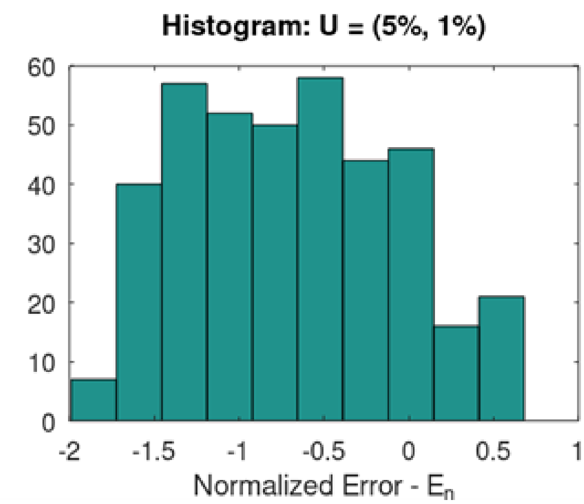

Fig. 15 2025 Data, Sample Size 391

Conclusions

The Impact Calibration Technique for Piezoelectric Force Sensors continues to show promise as a less expensive method to calibrate sensors than what has traditionally been done with a force calibration rig. This method can also apply more force that what can be accomplished with the gravimetric (drop) calibration method. The force applied via impact is also more representative of how the sensor is used in actual testing than the static hydraulic method or gravimetric method.

Operator error and model type (force capacity) have shown been shown in the data as areas that introduce uncertainty. Certainly, the setups at PTB and NIST where a pendulum is used to reduce operator error merit attention. Interestingly enough an inexpensive setup with the DigiDAQ provides adequate data quality compared to the more expensive NI 4461, with its only limitation being sample rate to accommodate the hard tip hammer.

The Impact Calibration Technique for Piezoelectric Force Sensor has shown that appropriate forces can be applied to sensor under test (SUT) and can be controlled with various hammer tips, hammer size and addition of a mass extender. The more massive the hammer and the harder the tip allows for larger forces to be applied to the sensor.

Future research should be done to reduce the uncertainty in the measurement and more data needs to be taken with more sensors in the specific model range and sensor type.

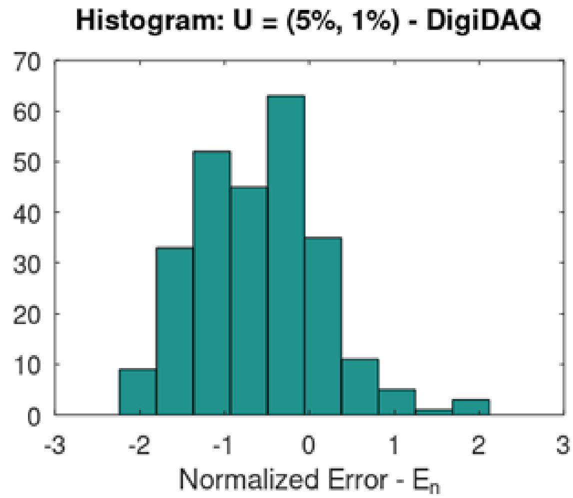

Fig. 16 MATLAB App, Sample Size 257

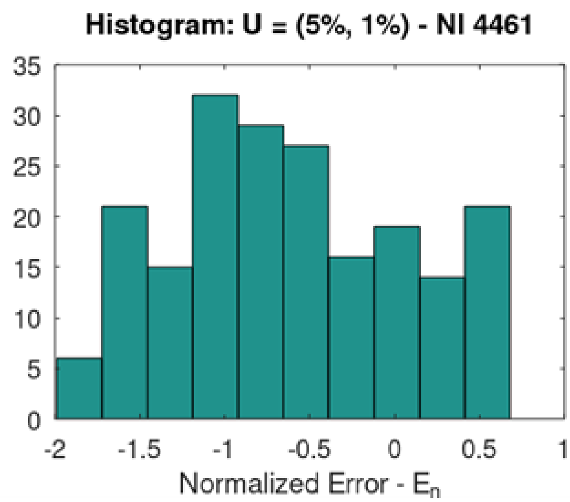

Fig. 17 TMS 9961 Application, Sample Size 200

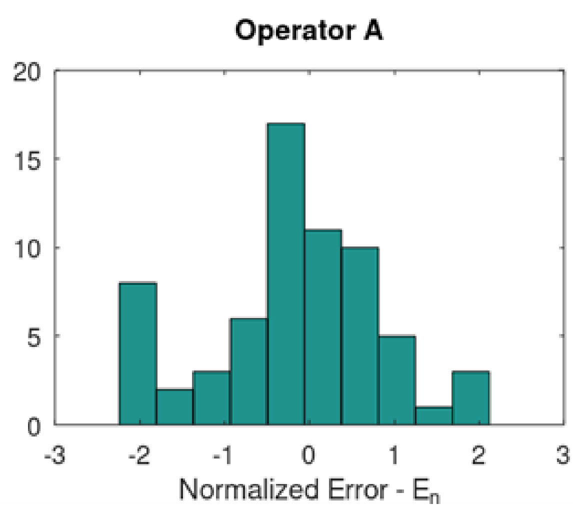

Fig. 18 Sample Size 66

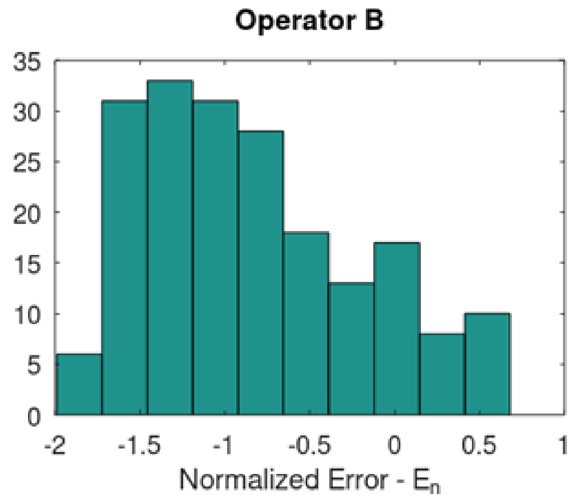

Fig. 19 Sample Size 195

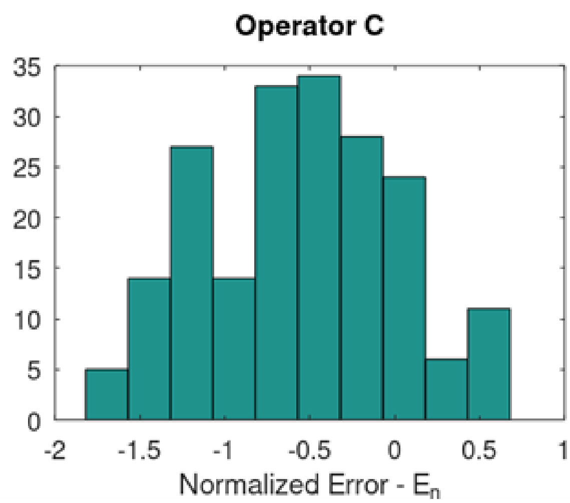

Fig. 20 Sample Size 196

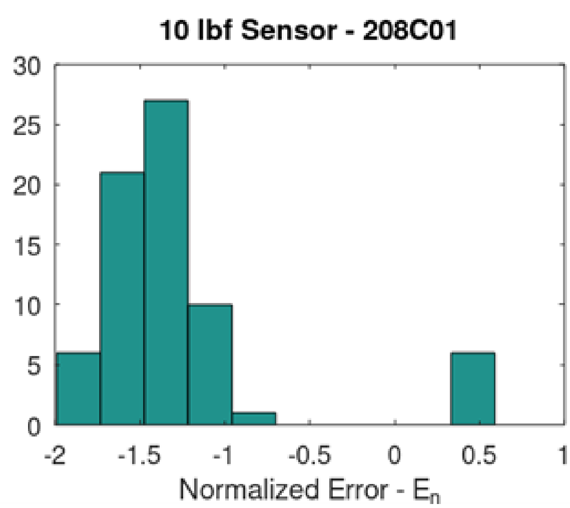

Fig. 21

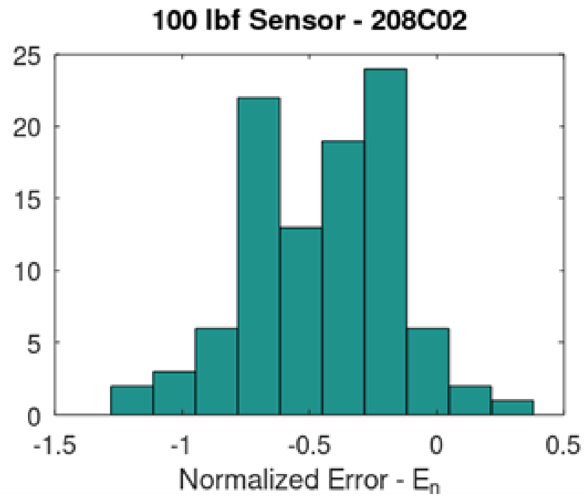

Fig. 22

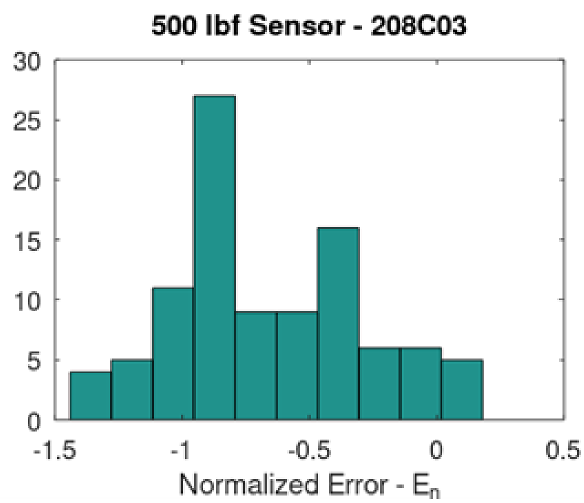

Fig. 23

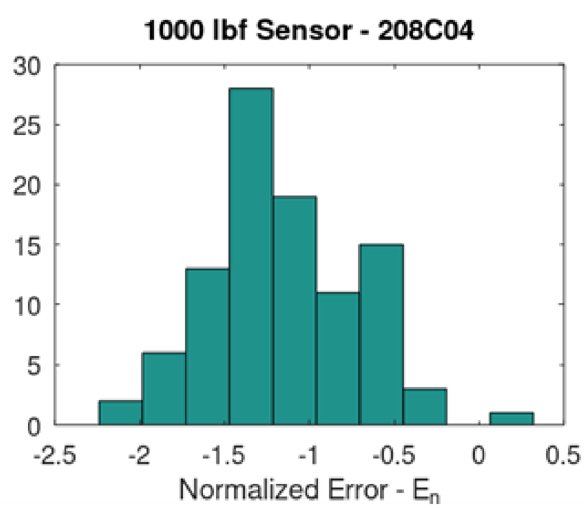

Fig. 24

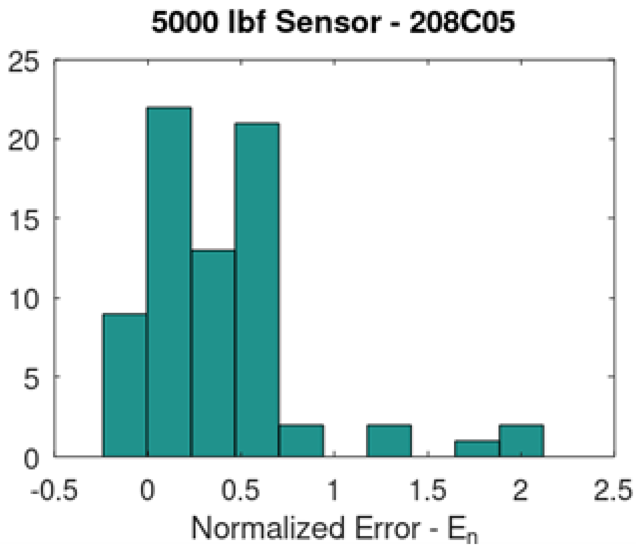

Fig. 25

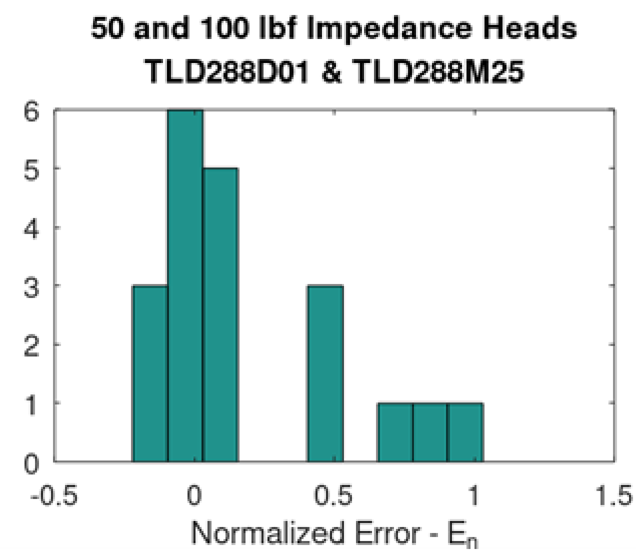

Fig. 26

References

1. Mains, M., Peres, M., Kallmeyer, C., Dillon, M., Weaver, C., Bono, R., "Comparison of Calibration Techniques for Piezoelectric Force Sensors", International Modal Analysis Conference (IMAC) XLII, January 2024.
2. Kobusch, M., Klaus, L., "Uncertainty in Measurement for the Calibration of The Shock Sensitivity of Impact Hammers", XXIV IMEKO World Congress, August 2024.
3. The NIST Impact Force Standard, https://www.nist.gov/programs-projects/dynamic-mechanical-metrology-acceleration-force-and-acoustics/impact-force
4. Hogan, R., "How to Calculate Normalized Error", www.isobudgets.com/how-to-calculate-normalized-error/

Table 3 Tip and Hammer Effects on Force: 500 lbf sensor - 208C03

Hammer Tip	Hammer Model	Extender Mass	Normalized Error E_N	Mean Force	Min Force	Max Force
red	086C03	No	0.038	8.82	4.58	12.69
red	086C03	Yes	-0.121	12.93	6.42	17.09
red	086D05	No	0.177	14.76	4.08	28.07
red	086D05	Yes	0.137	17.81	3.24	27.79
black	086C03	No	-0.181	15.39	7.65	21.54
black	086C03	Yes	-0.339	25.02	21.32	32.02
black	086D05	No	0.058	25.92	6.01	36.14
black	086D05	Yes	-0.062	20.80	1.02	38.13
blue	086C03	No	-0.121	24.63	4.67	38.54
blue	086C03	Yes	-0.161	35.45	14.97	46.00
blue	086D05	No	-0.101	24.43	6.39	44.18
blue	086D05	Yes	-0.081	44.00	13.07	61.08
white	086C03	No	-0.379	97.10	64.41	135.70
white	086C03	Yes	-0.399	97.04	65.09	119.75
white	086D05	No	0.177	125.38	35.04	174.96
white	086D05	Yes	-0.220	146.53	61.26	188.90
steel	086C03	No	-0.637	152.04	91.28	211.69
steel	086C03	Yes	-0.399	199.78	115.44	274.35
steel	086D05	No	-0.200	212.74	120.15	290.87
steel	086D05	Yes	-0.181	249.96	145.48	320.80