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Static and Dynamic Calibration for *FlexiForce* Sensor Using a Special Purpose Apparatus

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Abstract:

This paper introduces an experimental apparatus to be implemented for calibrating the ***FlexiForce*** sensor both statically and dynamically. This sensor uses a resistive – based technology and it has force range of (0-111N). The static calibration is done with static weights under static conditions, also these sensors are calibrated dynamically with the use of an inertial force of a mass as the known dynamic force; the acceleration of the mass is measured by an accelerometer board attached to the oscillating mass. These sensors are calibrated with the same conditions under which force sensors are supposed to be used, as to measure the force on the fingertip of a robotic manipulator. Results of both calibration methods are presented and discussed herewith.

Keywords: Force sensors, dynamic calibration, special apparatus

1. Introduction

In a wide variety of applications (Sheplak *et al.*2001) (Kalamdani *et al.*2006) (Abu-Faraj *et al.*1997), force measurement has five basic mechanisms, namely,

(a) Balancing the unknown force with a standard mass through levers mechanism.
(b) Measuring the acceleration of a known mass.
(c) Converting the force to electrical signal by different methods (magnetic field, optical cells, variable resistance or capacitance).
(d) Using the force to generate pressure on a specific area and then measuring the pressure.
(e) Converting the applied force into deformation in an elastic element.

But all of these mechanisms need to be calibrated both statically and dynamically. Statically, by using static weights under static conditions, and dynamically by using known reference varying forces, such as, impact force, oscillating force or step force. The state of dynamic force calibration must cover all conditions under which force sensors are supposed to be used for proving the validity of the calibration procedure under different types of dynamical load.

In this field, Jensen *et al.*(1991) used a thin force sensor to measure the grasping force for the human hand injury rehabilitation; this sensor was calibrated with a strain gage dynamometer and the results of this calibration were similar to those when using static method. Kumme *et al.* (2000)(2001) used an oscillating force as reference force for dynamic calibration, since the force transducer to be calibrated was mounted on a shaker and a load mass is screwed to the head of transducer. This procedure shows that in many cases the force indicated by the force transducer can noticeably differ from the force which must be determined in dynamic application and this is due to the effect of resonance behavior of the force transducer and resonance behavior of the surrounding mechanical structure of the calibration devices. Fujii (2006)(2009) has proposed the Levitation Mass Method (LMM); in this method the inertial force of a mass levitated by using a pneumatic linear bearing was used as a reference force for dynamic calibration and its results showed that the differences between the static and the dynamic calibration results are derived mainly from the difference between the static and dynamic characteristics of the sensor.

Sun *et al.*(2006) has proposed and developed a new design of two-axis MEMS (microelectromechanical system), this sensor was calibrated by mounting the sensor in different situations (vertically and horizontally), since the weight of the movable parts of the sensor acts as a constant-magnitude load to the sensor in x and y directions. Link *et al.*(2009) described a linear least-squares fit method for system identification to estimate the transfer function from sinusoidal force calibration measurements.

In this paper, the ***FlexiForce*** sensor is calibrated statically and dynamically for comparative study to satisfy the identity between the static and dynamic sensitivity for this sensor.

2. Sensor Description

The ***FlexiForce*** (Force sensor user manual 2012; Calibration guide 2001) sensor depicted in figure.1 , is an ultra-thin and flexible printed circuit, which can measure force between any two contacting surfaces and is durable enough to stand up to most environments with force rang (0 to 111N). It is constructed from two layers of substrate; this substrate is composed of polyester film (or Polyimide in the case of the High-Temperature Sensors). On each layer, a conductive material (silver) is applied, followed by a layer of pressure-sensitive ink. Adhesive is then used to laminate the two layers of substrate together to form the sensor.

The sensor acts as a variable resistor in an electrical circuit. When the sensor is unloaded, its resistance is very high (greater than 5 MΩ); when a force is applied to the sensor, the resistance decreases. Table.1 indicates the properties of this sensor.

3. Calibration Apparatus

Specific devices have been designed to satisfy the experimental conditions which the force sensors are supposed to be used. In other words, these devices are not compatible with another type of application, since this application represents measuring the grasping force for multi fingers robotic hand.

A special purpose calibration apparatus is constructed from a plastic frame which consists of two parts, namely cover and base frame. The cover has been fastened to the base frame by two bolts which let the distance between the cover and the base frame to be adjustable; the base frame has a curvature portion to simulate the shape of the finger tip, and at this portion the ***FlexiForce*** sensor is installed. This frame has the ability to be fastened with the head of the shaker as shown in the figure.2.

Other part of the apparatus is the oscillating mass which is installed between two identical helical springs. This mass has the ability to vibrate and then generate the inertial force which is calculated from measuring the acceleration of the mass by using an accelerometer board (ADXL 330) (Accel Board Manual 2006) which is attached to the side of the mass as shown in figure. 2.

The oscillating mass is inserted between the two springs thus generating an initial compression in both springs, hence to satisfy the transferring of inertial force to the plastic frame continuously and passing through the force sensor.

4. Mathematical Model

From the model illustrated in figure.3 the following equilibrium relation can be obtained,

$$m\ddot{x} = -K_1(x-y) - K_2(x-y) \tag{1}$$

The inertial force is,

$$F(t) = m\ddot{x} \tag{2}$$

And the transmitted force to the force sensor is,

$$F_s = -K_1(x-y) \tag{3}$$

In addition to that, both springs have the same stiffness, $K_1 = K_2$, from this and the above equations, the relation between the inertial force and the acting force at the force sensor can be derived as follows:

$$F_s = 0.5\,F(t) \tag{4}$$

$F(t)$ can be determined from the product of the measured acceleration with the oscillating mass in continuous form with time. This can be repeated for various magnitudes of mass (60 gr, 81.5gr, 95gr) to generate a wide range of inertial forces.

5. Experimental Procedure

The schematic diagram, shown in figure.4, represents the calibration apparatus setup for measuring the inertial force to be calibrated with the reading data of the force sensor dynamically. Figure.5 shows the photograph for the experimental instruments.

A ***FlexiForce*** sensor is attached to the curved portion of the plastic frame, and the accelerometer board is mounted at its base on the oscillating mass. The plastic frame with its contents fixed at the head of the shaker which is excited by the function generator and power amplifier units to generate an excitation with various frequencies, amplitudes and function shapes.

The procedure begins with setting the function generator at the sinusoidal wave form and then increasing the frequency gradually until the data passing to the PC through the analogue to digital convertor, ADC, of the force sensor and the accelerometer board shows a behavior similar to the function shape as appeared on the oscilloscope thus maintaining a case of minimum noise. At this moment the sample of data is saved as digital data. This procedure is repeated for different magnitudes of mass (60 gr, 81.5gr, 95gr). The mass considered, in this investigation, is the total effective mass by taking into account the effect of the accelerometer mass and the virtual effective mass of its wires.

For static calibration, the same plastic frame is used (without mass, springs, accelerometer and its cover) with the digital weighting device and lever mechanism to transfer the weights effect to the force sensor.

6. Results

The data obtained from the static calibration procedure is presented in figure.6. Since the behavior of the flexiforce sensor is linear within the given range of loading, hence a linear regression procedure is adopted to fit the results, from which the obtained calibration equation can be listed as below,

$$F_{measured} = 0.0404\,ADC_{counts} \tag{5}$$

where ADC_{counts} is the output of the analogue to digital convertor.

Peak to peak values were considered as parameters describing each signal in the dynamic calibration procedure. Where these signals show a variation in amplitude in the same sample, for this reason and referring to figure.7, the definition of the peak to peak statistical relation (Oscilloscope User Manual) is used to obtain the amplitude of this signal as follows:

$$Peak\ to\ Peak\ Amplitude = \frac{1}{n}\sum_{i=1}^{i=n} Rmax_i \tag{6}$$

$$Rmax_i = Peak_i - Valley_i \tag{7}$$

A selected sample for the dynamic calibration at a frequency 7.46 Hz and oscillating mass of 81.5 gr, is presented in Figure.8. Applying eqs. (6)(7) on this selected sample, hence obtaining the average peak to peak measured force and the ADC_{counts} as 1.667 N and 36 respectively.

Applying this procedure for all the cases tabulated in Table.2, hence the dynamic calibration chart can be obtained as presented in figure.9. Using the linear regression analysis to fit the results, the calibration equation is obtained as listed below,

$$F_{measured} = 0.0414\, ADC_{counts} \qquad (8)$$

From the obtained results, namely equations (5) and (8), which both show good agreement between the static and dynamic calibrations, and since both calibration methods show approximately the same behavior for this specific condition, hence a static calibration procedure will satisfy the relation between the applied load and the measured load.

7. Conclusions

This paper demonstrates the ability of depending on the static calibration procedure without the need to apply the dynamic calibration, which can be applied for a specific force sensor and under oscillating load conditions. Since the static calibration is simpler than the dynamic calibration and hence there is no need for sophisticated instruments for signal processing. Finally, this work needs in future to take into account different types of dynamic force as a reference force used in the calibration to satisfy the validity of the identity between the static and dynamic characteristics for this sensor.

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Table1. Properties of the *FlexiForce* sensor

Sensor Properties	**Model A201**
Operating Range	15°F (-9°C) to 140°F (60°C)
Linearity (Error)	<+/- 5%
Repeatability	<+/- 2.5% of full scale (conditioned sensor, 80% force applied)
Hysteresis	<4.5% of full scale (conditioned sensor, 80% force applied)
Drift	<3% per logarithmic time scale (constant load of 90% sensor rating)
Temperature Sensitivity	Output variance up to 0.2% per degree F (approximately 0.36% per degree C). For loads >10 lbs., operating temperature can be increased to 165°F (74°C).

Table 2. The considered oscillating masses and their frequencies for thirteen samples of experimental data.

Oscillating mass (gr)	**Frequencies of oscillating mass (Hz)**
60	2 , 8 , 17.24
81.5	4.167 , 6.5 , 7 , 7.46 , 10.42 , 11.5 ,11.63, 13 , 15
95	3.7

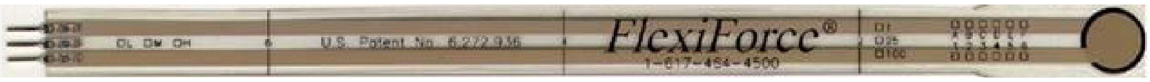

Figure 1. The *FlexiForce* sensor

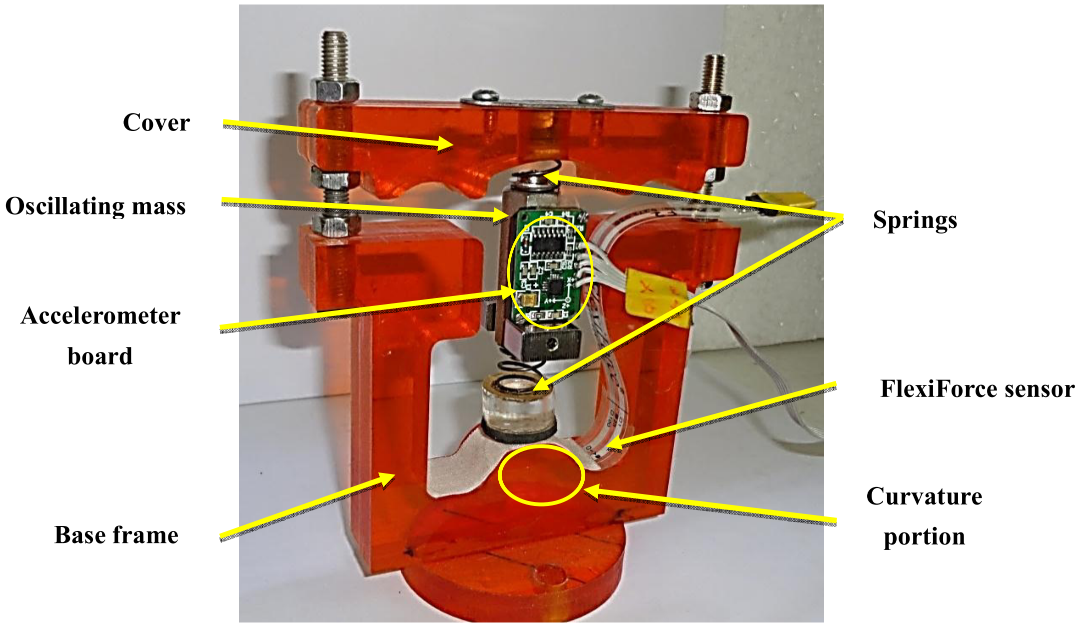

Figure 2. The apparatus construction.

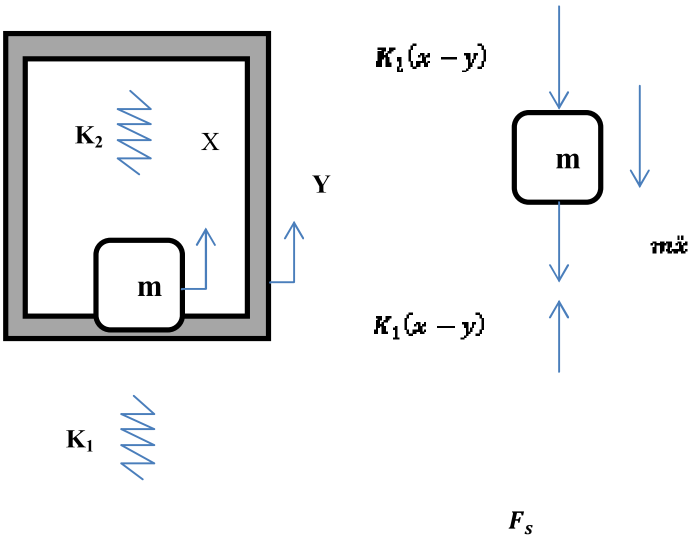

Figure 3. The mathematical model for the apparatus

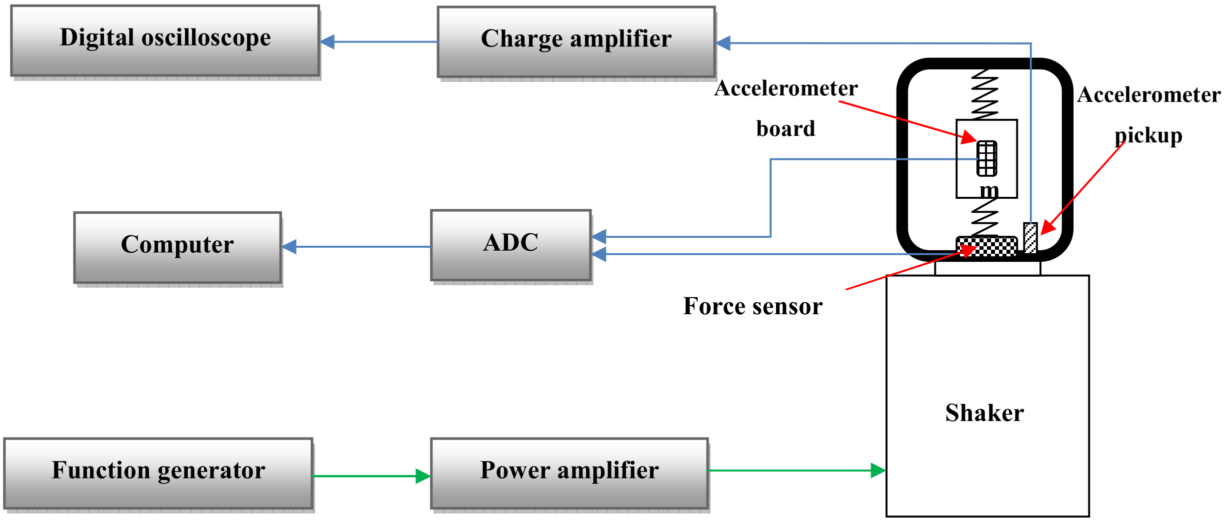

Figure 4. Calibration instruments connection scheme

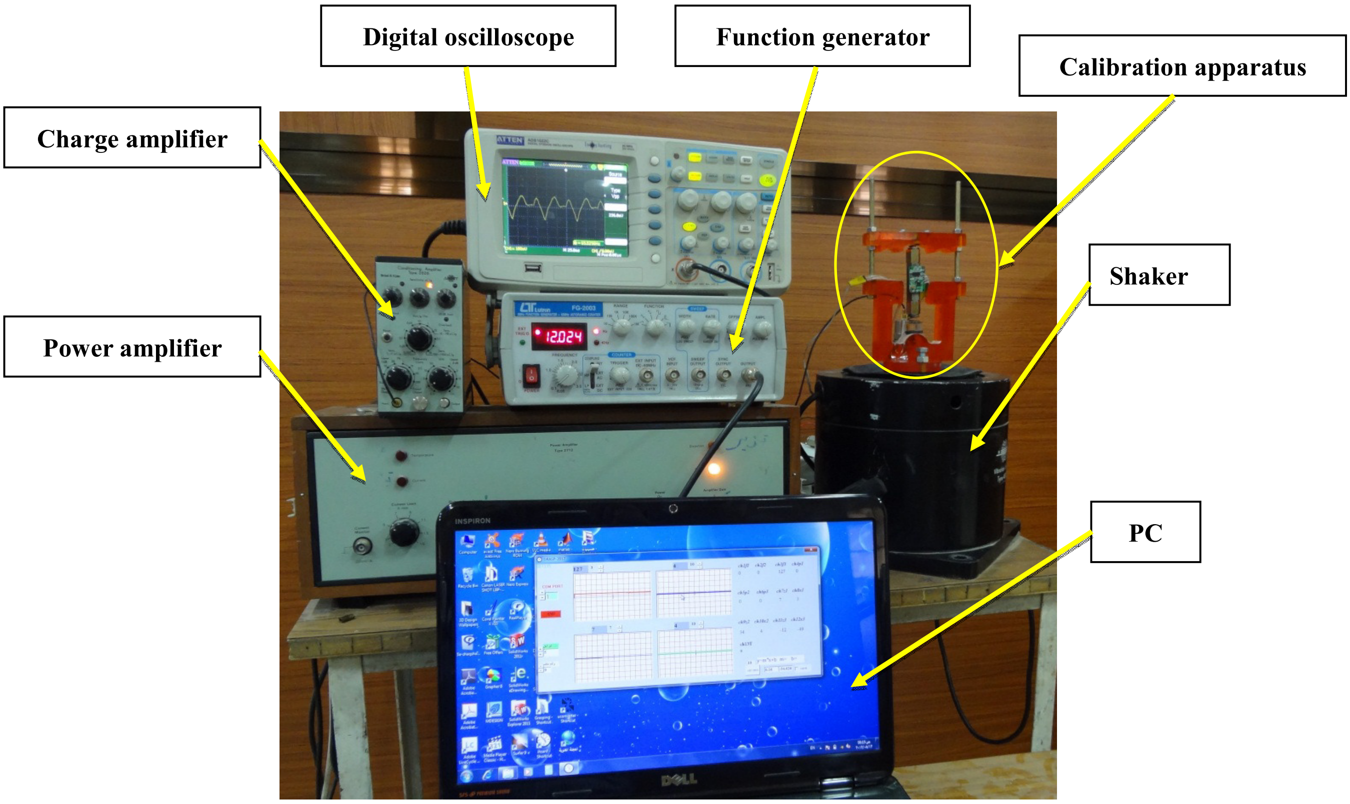

Figure 5. The experimental devices setup.

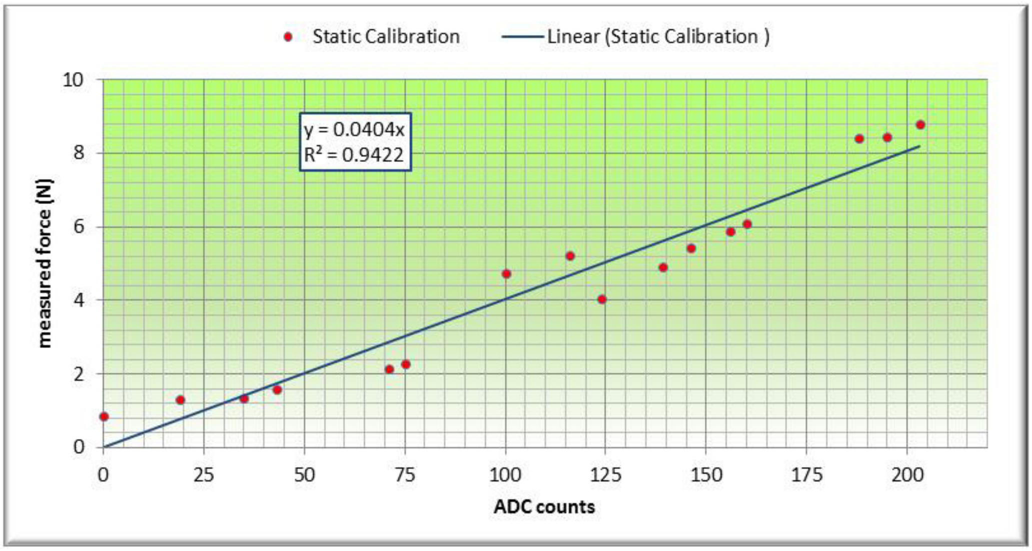

Figure 6. Static calibration results.

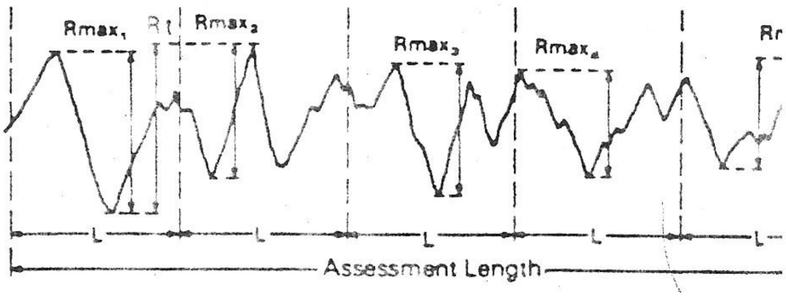

Figure 7. Example for signal has different peaks.

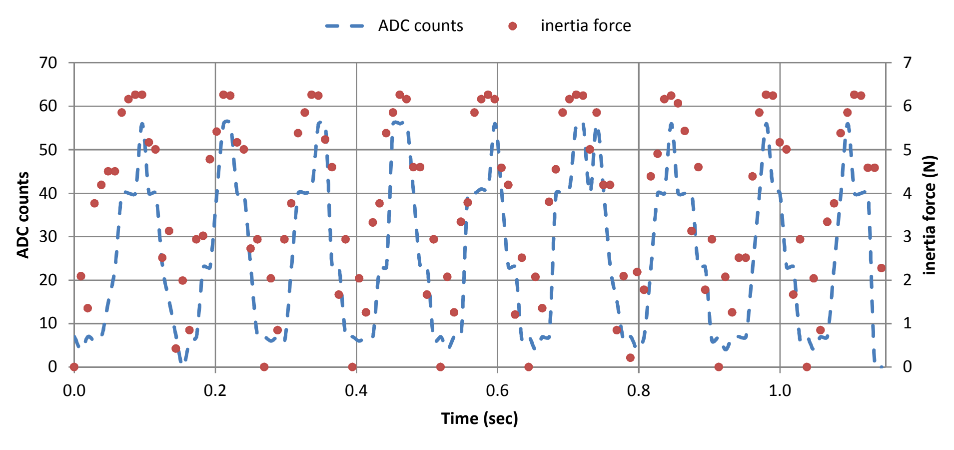

Figure 8. Selective sample for dynamic calibration.

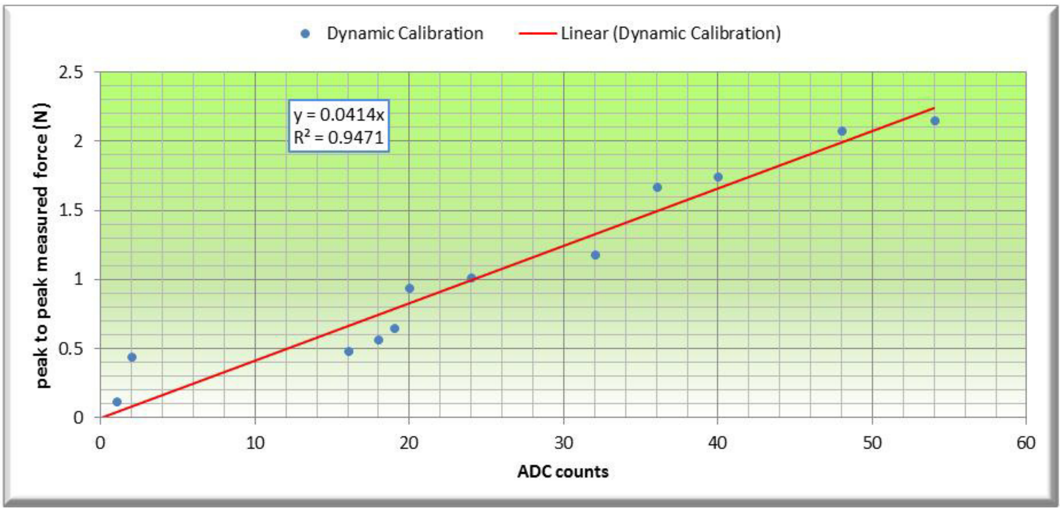

Figure 9. Dynamic calibration results.

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