# Design, Manufacturing, and Calibration Process of One Piece Lathe Dynamometer for Measurement in Two Axes

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*Many pieces in structure of a dynamometer may negatively affect the accuracy of the measurements since each piece may display a different strain and stress depending on its material and construction. A one piece dynamometer has been designed to eliminate these negative effects and to facilitate reliable force measurements. A dynamometer that its dimensions were confirmed following strength calculations was manufactured and calibrated in two different ways. The first one was multipoint calibration method in which certain loads were applied to the dynamometer and strain values corresponding to these loads were matched. The second calibration method was implemented using Kistler dynamometer that its results are accepted to be accurate by everyone and it was based on equivalency of force values resulted from work piece processing and force values resulting from machining work pieces with the same parameters to the manufactured dynamometer. The manufactured dynamometer was capable of measuring cutting forces and feeding forces.* [DOI: 10.1115/1.4024532]

*Keywords: dynamometer, measurement, machinability, CAD-CAM*

## 1 Introduction

Researches have been focused on cutting forces since these forces directly influence generation of heat, tool wear, power consumption, surface quality, and geometric tolerance of the processed work piece [1,2]. Many theoretic models were developed to measure cutting forces. These models do not provide reliable results since machining has many complex parameters. Therefore, measuring cutting forces by experimental methods in unavoidable. There are many research works regarding measurement of cutting forces in literature and many various dynamometers have been developed for various machining methods. In a work in which the effects of cutting tool rake angle on cutting forces in turning process was studied, it was indicated that cutting forces reduced as rake angle increased. Cutting forces were measured by a dynamometer that was manufactured using two beam type load cells [3]. It was noticed that a dynamometer, which could be used in turning and metal cutting, manufactured in shape of an octagonal ring was capable of measuring static and dynamic cutting forces accurately [4]. A particular type lathe tool dynamometer, which could be used in ultra sensitive machining to measure statical and dynamical forces was designed, manufactured and tested [5]. A piezo-electric cell based dynamometer capable of measuring forces in three axis during turning process was installed to a computer numerically controlled (CNC) counter for this work. The software was capable of analyzing, confirming, observing and recording data in real time [6]. A strain gauge base power dynamometer was designed and manufactured for this work. Alternative tool method was produced by developing a recovery method with computer support using balances that were produced to display the relationship between cutting forces and dimension errors [7]. It was observed that majority of these models use ring shape octagonal spring elements with strain gauges attached to them. Negative effects of connection elements used in attaching construction elements together when assembling tool holder type dynamometers are substantial with respect to sensitivity of the dynamometers. A one piece turning dynamometer with strain gauge capable of measuring cutting forces in two dimensions (axis) was designed and manufactured in this work and its calibration tests were implemented.

## 2 Materials and Methods

**2.1 Design and Strength Calculations of the Dynamometer.** The dynamometer was designed (DM) as a one piece material (Fig. 1(*a*)) [8,9]. Solid-Works program was used for design works. Dimensions of the tool holder section that held the cutting tool, which was used, were planned as 25 mm × 25 mm. Therefore, flexibility to bring the tool's edge into same level with the mobile tailstock's edge was provided by designing the section on which the tool holder will be located with 31 mm × 31 mm dimensions. Standard length of the tool holder passes through the neck located inside the dynamometer and it establishes a tight connection with dynamometer's body. The two perpendicular internal surfaces of the tool holder are completely full and void free. The other two surfaces were connected to the dynamometer's body using a total of ten screws. Flow strength of AISI 1020, which was accepted as dynamometer material in the equation, was considered with double safety. The maximum load value to be applied to the system was calculated to be 12883.904 N based on the safety strength. For cutting depth of 2.5 mm in a work safe bending strength was calculated to be 19.2 MPa in section strength control considering that the value of the forces to be encountered were estimated to be 2000 N. Stress and strain were calculated to be 0.234 MPa and $1.112 \times 10^{-6}$ for 100 N. When these strain values were taken into consideration the dynamometer design used here was concluded to be compatible with necessary criteria for measuring the smallest strain values. The deflection in the edge point was calculated as follows when the tool holder was loaded at the edge point of a bar with square cross section [1,2]. Maximum load was taken into consideration hereby and a deflection valued at 0.001776 mm may result in the edge point. This value was a lot less than acceptable deflection values that must occur at the edge of the tool. Spring constant was calculated as 9241.573 MN and it was placed in Eq. (3) and the value of the

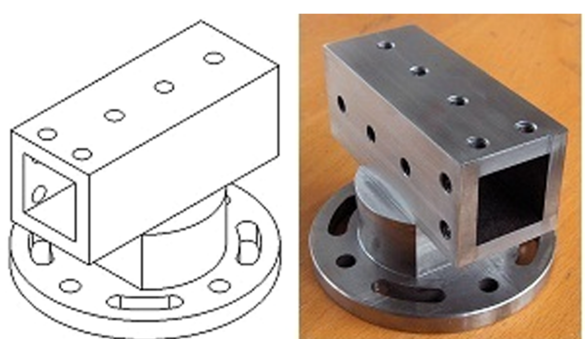
(a) (b)

**Fig. 1 Designed (*a*) and manufactured (*b*) dynamometer**

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natural frequency was calculated as 784.482 Hz. For example, when the largest value of revolution was 1000 rev/min (rpm) and the frequency was 16.667 Hz the natural frequency of the dynamometer shall approximately be at least 21 times larger than the normal working frequency. Thus, the criteria in which the natural frequency of the dynamometer must be at least 4 times less than its normal working frequency was fulfilled greatly.

**2.2 Manufacturing of the Dynamometer, Wheatstone Bridge Circuit, and Data Collection System.** The dynamometer was manufactured using lathe, CNC milling machine, electro erosion machine and columnar drill workbench (Fig. 1(*b*)). Manufacturing steps of the dynamometer in order: Turning front surfaces of cylindrical raw material in lathe, changing dimensions of the cylindrical raw material into the desired dimensions in lathe, machining the lower section to which the tool holder will be connected using lathe. CNC milling machine processes: Machining the outer surfaces of the section to which tool holder will be connected in CNC milling machine, machining the lower section of the dynamometer in the CNC milling machine. Drill workbench process: The interior of the quadrangle section was removed by drill as a process prior to square cross sectioning. Electro erosion machine processes: The interior surface of the section to which the tool holder would be connected was removed in square cross section throughout its length by electro erosion. Drill workbench processes: Opening screw holes on two surfaces on the rectangular section by drill and tapping in order to fix the toll holder properly.

A total of four strain gauges including one under and one on top of the dynamometer to measure the cutting forces and one at right and one at left to measure the feeding force were fixed using an adhesive with appropriate components. The specifications of the strain gauge were as follows: type FLA-10-11, gauge factor 2.09 ± %1 and its resistance was 120 ± 0.3 Ω. In order to connect the strain gauges in the form of a half Wheatstone bridge circuit a particular data cable was used. Specifications of the data cable were as follows: 120 ± %0.1 resistance, trimmer potentiometer with 15 turns and 50 Ω. The connection terminals located on the cable were appropriate for half or quarter bridge connections. Strain zeroing adjustment trimmer potentiometer, bridge completion resistances and screwed terminals were inside the cable. A clear container made of Plexiglas material with 4 mm width was designed to keep strain gauges from getting damaged by metal chips and external effects. The dynamometer with strain gauges attached, completed solder connections and connected container, tool holder and tool are shown in Fig. 2 [8,9]. The specifications of the data collection system were: measurement resolution 16 bit (±10 V/65,536 steps/8 channels), data collection speed eight samples/second, channel gain may be adjusted between 1 and 890, data recording in MS Excel, dynamic graphic axis adjustment, multi-channel zeroing, establishing mathematical processes between the channels and multipoint calibration. One channel was arranged for cutting forces and another was arranged for feeding forces. The data collection system was connected to the computer using a USB cable. Specifications of this device connector were USB 2.0 and RS485 interface and it was controlled with a microprocessor. Software that was supplied with the data collection system was installed on the computer. This facilitated real time observation and recording of the data transferred from the dynamometer.

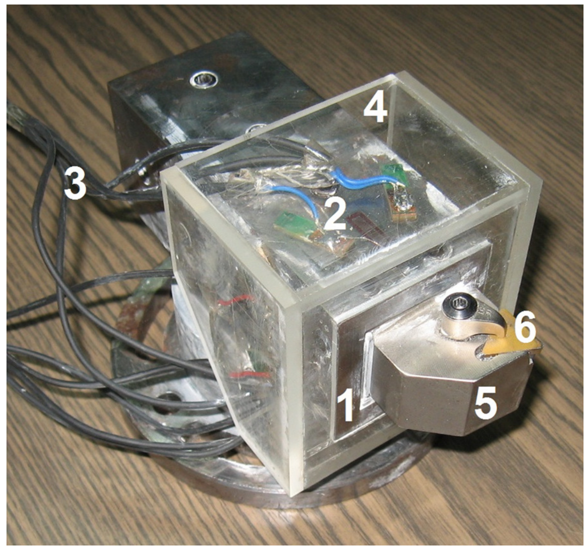


**Fig. 2 Cabled dynamometer with identified strain gauge that its strain gauge safeguard, tool holder, and tool are attached (in the figure: 1- dynamometer, 2- strain gauge, 3- cable, 4- container, 5- tool holder, and 6- tool)**

**2.3 Calibration Apparatus for Statical Loading Systems.** A calibration apparatus was designed and manufactured (Fig. 3(*a*)). In order to calibrate the dynamometer with regard to cutting forces it was fixed to horizontal table (Fig. 3(*b*)) and it was fixed on perpendicular plate while being turned for 90 deg for calibration with respect to feeding forces (Fig. 3(*c*)). Cutting force of the dynamometer was initially calibrated in the statical loading system. Multipoint calibration method was used in the software. Weight of the experimental mechanism was arranged to be 100 N and loading had started from 0 N and it had continued until accomplishing 1000 N in intervals of 100 N. Microstrains corresponding to each 100 N were recorded. The loads were reduced in

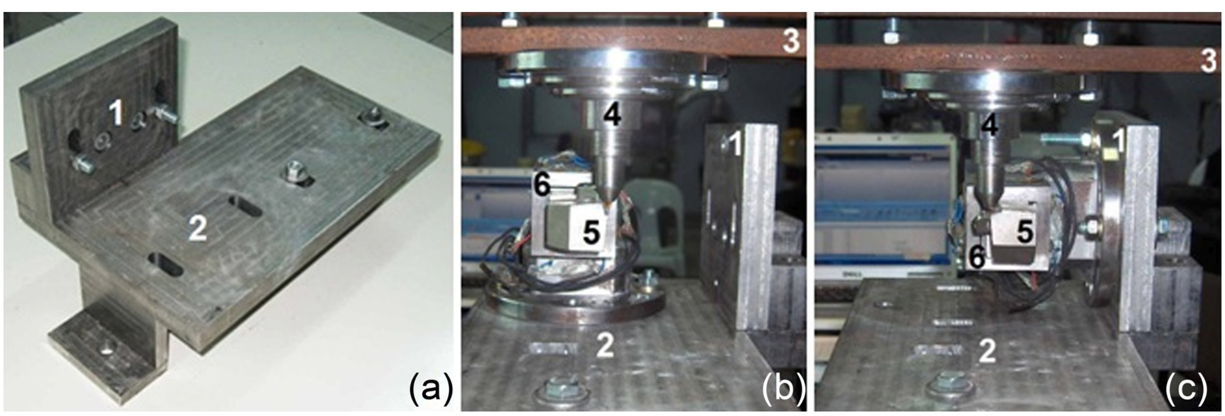


**Fig. 3 Calibration apparatus (*a*), cutting force calibration (*b*), and feeding force calibration (*c*) (in the figure: 1- feeding force calibration table, 2- cutting force calibration table, 3- load frame, 4- load heading, 5- tool holder, and 6- dynamometer)**

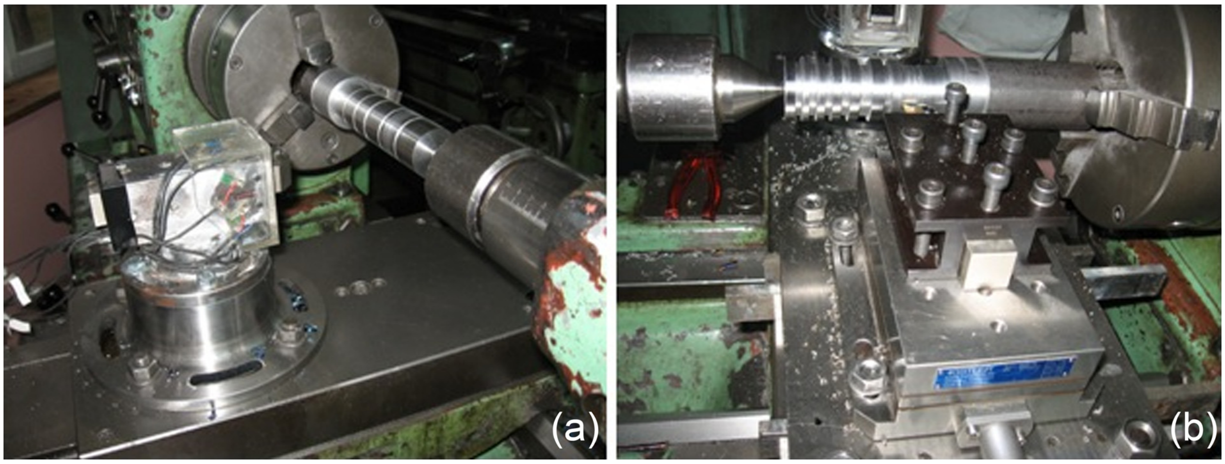


**Fig. 4 Machining using (DM), the manufactured dynamometer (*a*) and Kistler-9257B (*b*)**

**Table 1 Parameters used in machining with DM and Kistler dynamometers**

| | | | | |
|---|---|---|---|---|
| RPM (rev./min.)<br>1000 | Cutting speed (m/min.)<br>146.143 | Rake angle (deg)<br>6 deg | Inclination angle (deg)<br>0 deg | Approach angle (deg)<br>90 deg |
| Diameter (mm)<br>49 | Last diameter (mm)<br>44 | Tool holder<br>CTGPR-2525M16 | Tool and coating<br>TPGN-160308-M30 | Unit specific cutting force<br>1750 N/mm$^2$ |
| Cut of depth (mm)<br>2.5 | Work material<br>AISI 1050 | Tool length (mm)<br>150 | Tool coating materials<br>TiCN-$Al_2O_3$-TiN | Material coefficient<br>0.27 |
| Feed (mm/rev.) | 0.08 | 0.12 | 0.24 | |

**Table 2 Statical calibration values of DM dynamometer**

| Force (N) | 0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cutting ($\mu\varepsilon$) | 0.0000 | 0.6523 | 1.3639 | 1.8976 | 2.5499 | 3.2023 | 3.8546 | 4.5069 | 5.0999 | 5.6336 | 6.3452 |
| Feed ($\mu\varepsilon$) | 0.0000 | 1.0679 | 2.0764 | 3.1443 | 4.3901 | 5.1613 | 6.1698 | 7.1190 | 8.0094 | 8.9581 | 9.7293 |

intervals of 100 N to accomplish 0 N once again after 1000 N was accomplished. Microstrains corresponding to each 100 N reduction were recorded. The waiting time for each loading was 30 s. The experiments were repeated for 3 times for each loading and their average values were taken into consideration. The same processes were repeated for calibration of the feeding force.

**2.4 Metal Chip Removing Processes.** The dynamometer, which was designed and manufactured, was defined as DM (Fig. 4(*a*)). Results of machining manufacturing (external surface turning) implemented using DM dynamometer were compared to the machining results using Kistler-9257B dynamometer (Fig. 4(*b*)). The experiment set included Kistler-9257B dynamometer, Kistler Multichannel Charge Amplifier-5070 and DynoWare-Data Acquisition. The bench used for machining processes was the Universal lathe Bench. The tool holder and tool displayed in Fig. 2 were used for processes using both dynamometers. The work bench used for the two dynamometers was the same based on cutting speed, revolution number, cutting depth and machining length parameters and it wasn't changed. The only parameter that had changed was feeding Machining parameters are provided in Table 1.

## 3 Results and Discussion

**3.1 Statical Calibration of DM Dynamometer.** Forces corresponding to cutting and feeding related to DM dynamometer are provided in Table 2, the average strain calibration results are provided. Maximum strain values in loading data were 6.35 $\mu\varepsilon$ for cutting and 9.73 $\mu\varepsilon$ for feeding. R2 value of the certainty coefficient was used in explaining the variety observed in the data as a scale for efficiency of the regression equation. R2 value was calculated as 0.9996 for cutting force and it was calculated as 0.9979 for feeding force in this experiment [10]. Regression lines, regression equations and R2 values for cutting and feeding forces are provided in Fig. 5. The R2 values were rather close to ideal values and this indicates that the relationship between the data was positive and strong. The dynamometer has displayed the expected behavior in the process and it was observed that it could be a reliable tool to measure cutting and feeding forces after completion of calibration process.

**3.2 Work Piece Machining for Calibration of Kistler and DM Dynamometer.** Machining values used in this experiment are provided in Table 1. Diameter of AISI 1050 work piece was reduced to 49 mm from 50 mm by turning its outer surface prior to the experiment. A cutting tool with width of 5 mm was used on the work piece with diameter of 49 mm channels were created in intervals of 7 mm to reduce the diameter to 42 mm. The dynamometers and their data collection systems were different, although all other parameters were the same during the machining process. The cutting (Fc) and feeding (Fv) forces measured by Kistler and DM dynamometers as a result of machining the work piece are provided in Table 3.

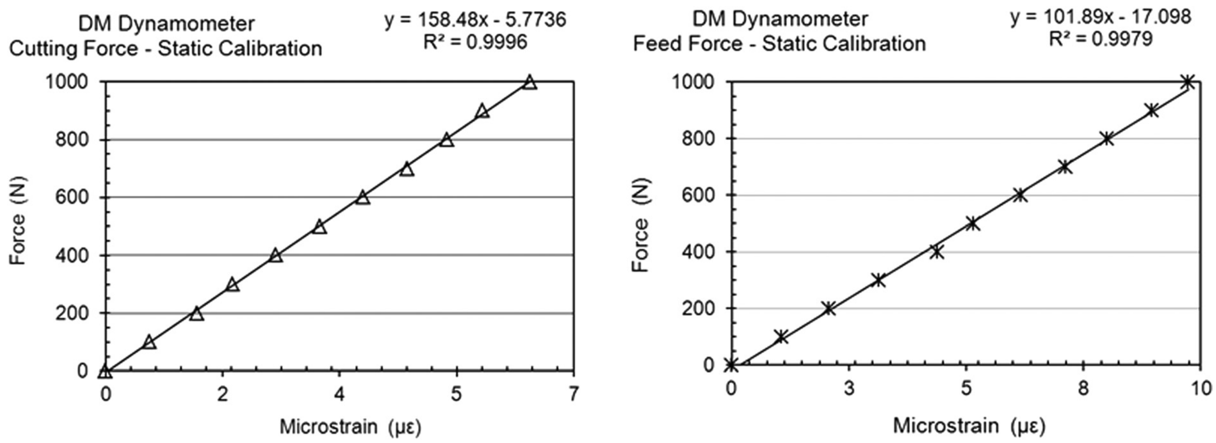


**Fig. 5 Variation of cutting and feeding forces with microstrain for DM dynamometer calibration**

**Table 3 Force and strain values accomplished with Kistler and DM dynamometers during machining**

| Feed (mm/dev.) | Kistler dynamometer (force) | | | DM dynamometer (microstrain) | | |
|---|---|---|---|---|---|---|
| | Fc (N) | Fv (N) | Fc/Fv | Fc ($\mu\varepsilon$) | Fv ($\mu\varepsilon$) | Fc/Fv |
| 0.08 | 672.99 | 434.91 | 1.547 | 2.556 | 1.345 | 1.900 |
| 0.12 | 869.14 | 507.81 | 1.712 | 3.268 | 1.672 | 1.955 |
| 0.24 | 1404.09 | 652.95 | 2.150 | 7.132 | 2.936 | 2.429 |

**Table 4 Comparison of the theoretical and experimental cutting forces**

| Feed (mm/rev.) | Fc (N) | | (%) Difference |
|---|---|---|---|
| | Theory | Kistler | |
| 0.08 | 653.286 | 672.990 | 2.93 |
| 0.12 | 878.314 | 869.140 | −1.06 |
| 0.24 | 1456.806 | 1404.090 | −3.75 |

Fc and Fv values were indicated as microstrains for DM dynamometer in order to calibrate DM dynamometer based on Kistler dynamometer. The strain values that resulted from DM dynamometer under load effects were recorded along with the force values (Fc and Fv) produced by Kistler into a calibration file using multipoint calibration method by the software. It was concluded that the feeding and cutting forces obtained by DM dynamometer were exact matches for cutting and feeding forces measured by Kistler. Behaviors of the dynamometers under load effect were different. Values obtained by DM dynamometer were changed into force values using Kistler dynamometer and the calibration was implemented. When DM dynamometer was used with the said calibration file the same strain values were obtained under the same machining conditions and therefore, the force values corresponding to these values were also the same with the force values measured by Kistler dynamometer. Fv values that were measured in this experiment recoded a change depending on raise in values of the feeding. All feeding forces were smaller than cutting forces. In order to determine the ratio between the cutting and feeding forces values calculated based on Fc/Fv were provided in Table 3. When Fc/Fv ratios were studied it was noticed that these ratios increased as feeding during machining with Kistler and DM dynamometers increased. The smallest and largest ratios for Kistler were calculated to be 1.547 and 2.150 and these values were 1.900 and 2.429 for DM dynamometer. Theoretical cutting forces were calculated using the machining parameters indicated in Table 1 and these values were indicated in Table 3 as comparisons to force values measured by Kistler dynamometer. Statically talking 5% error was an acceptable error rate for engineering calculations [10]. Should the theoretical cutting forces be considered as reference values and should the % differences between the values be studied, the largest would be −3.75% and the smallest would be −1.76%. Table 4 shows that there were differences between values obtained for cutting forces calculated based on theoretically accepted values and the experimental values. Therefore,

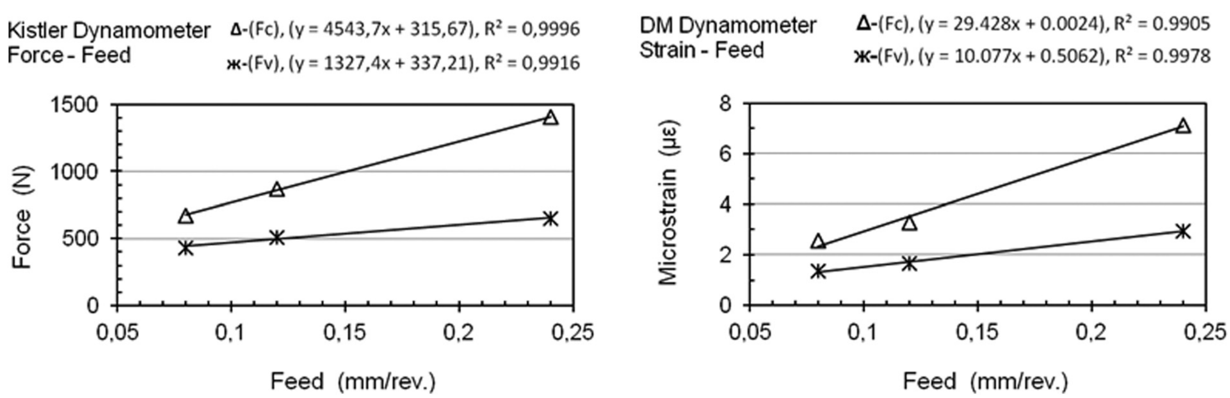


**Fig. 6 Variation of the cutting (Fc) and feeding (Fv) forces based on feeding in machining using Kistler dynamometer and variation of the strain value based on feeding in machining using DM dynamometer**

when DM dynamometer was calibrated using Kistler dynamometer these differences were transferred into DM dynamometer during calibration process.

Figure 6 shows the regression analysis results corresponding to cutting and feeding forces related to Kistler dynamometer that were indicated in Table 3. R2 values for cutting and feeding were 0.9996 and 0.9916. The relationship between the data was positive and rather strong. Results of the regression analysis implemented using DM dynamometer cutting and feeding force values are provided in Fig. 6. R2 values for cutting and feeding forces corresponding to DM dynamometer were 0.9905 and 0.9978. Data corresponding to DM dynamometer also display a positive and pretty strong relationship similar to Kistler dynamometer. It was possible to calibrate DM dynamometer with Kistler force values. The data collection system and the software played rather substantial role in this process. Each corresponding x and y value pairs were entered into the Software using multicalibration method during calibration process, a different linear equation was applied to each point, all points were processed using more than one linear equation and therefore, great flexibility was provided in obtaining the load-microstrain information based on these.

## 4 Conclusion

A one work piece dynamometer was designed and manufactured with lots of sensitivity. The dynamometer does not include any additional work pieces except for tool connecting process. In the first calibration process, the strain values measured by the dynamometer after application of certain loads were recorded as multicalibration principles. This process was a rather reliable and explicit process and the data obtained through this method could be used when deemed necessary. The second calibration process was the machining functionality test that shows the actual functionality of the manufactured dynamometer. The cutting and feeding values obtained by Kistler dynamometer, which was accepted to be reliable by everyone, were matched to the strain values obtained by the manufactured dynamometer under the same working conditions. The process was implemented, but it was concluded to be inappropriate since the difference between the theoretically and experimentally obtained results naturally affected the accuracy of the manufactured dynamometer. It shall not be forgotten that the manufactured dynamometer shall display deviation from theoretically obtained values due to its characteristics and therefore, error rate increased when the deviations resulted from the other device were also added to these deviations. The process was completed successfully. It was possible to implement the calibration process using this method as well. Theoretical and experimental cutting forces' % differences were calculated the largest $-3.75\%$ and the smallest $-1.06\%$. It was observed that the results obtained from the manufactured dynamometer when it was calibrated using the first method were a lot more reliable that the results obtained after the second calibration method was used. As a result, the manufactured dynamometer measured the cutting and feeding forces reliably as a complete system including the data collection system and the software.


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