Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 05, May-2019

Validation of a 3-Component Force Dynamometer

Akshay M. Patel[1]
Advanced Manufacturing Lab in the Department of Mechanical Engineering
at Dalhousie University in Halifax, NS Canada.

***Abstract*:- This paper aimed to validate a 3- component force dynamometer used for the fine measurements of cutting forces on the workpiece during grinding operations. A set of expected sensor characteristics were pre-established and the sensor was tested experimentally to verify if it met the required performance criteria. Multiple experiments were conducted to find the sensor's resolution, precision and hysteresis. The sensor was calibrated in a static condition to determine its accuracy. The sensor met all predefined requirements satisfactorily. It was later tested for its performance in dynamic condition using an impulse hammer. It was found that the sensor's output was close to actual input in the dynamic state for the normal axis. The other two axes, tangential and transverse were observed to be deviating in their outputs by around 10 N; this could be attributed to human errors in controlling the input of hammer and improper transmission of force to the sensor because of flanges. The sensor was found to be efficiently responsive to inputs in a dynamic state. Static tests verified the sensor performance, and dynamic tests validated its use as a perfect sensor for grinding research.**

Index Terms— Calibration, Dynamometer, Accuracy, Resolution, Precision, Hysterisis, Grinding and Impulse.

I. INTRODUCTION

The motivation for this project came from the fact that the Kistler force dynamometer, which has continuously served Dalhousie University's grinding lab since 2001, is planned for more rigorous use for the next two years. It was thus important to check its validity for being suitable for the task that lies ahead. Grinding, which is used for improving surface finish, is a field of abrasive machining that deals with removing material from the workpiece using a grinding wheel rotating at high speeds. It is important for the grinding process to be efficient, with as low power consumption as possible. The measure of power consumed is the product of cutting forces and cutting speed. While the cutting speed is determined by the operator, cutting forces are a result of multiple parameters involved and are hence necessary to be known for determining the power consumption. [1]
Grinding lab at Dalhousie University uses Quartz 3-component force dynamometer for measuring the forces applied by grinding wheel on the workpiece in the normal, tangential and transverse direction. In order to verify the sensor's performance, a set of sensor requirements are identified that needs to be met by the sensor.

A. Working principle of Force Dynamometer

Quartz 3-component Force Dynamometer Type 9257 B provides a dynamic and quasi-static measurement of the 3 orthogonal components of a force (F_x, F_y, and F_z) acting from any direction onto the plate. With the aid of optional evaluation devices, the three moments M_x, M_y and M_z can be measured as well.
Force is introduced at the top plate and distributed between four 3-component Quartz force sensors arranged between the base and top plates. For the force measurement in 3 components, the individual signals are led together in the connecting cable.

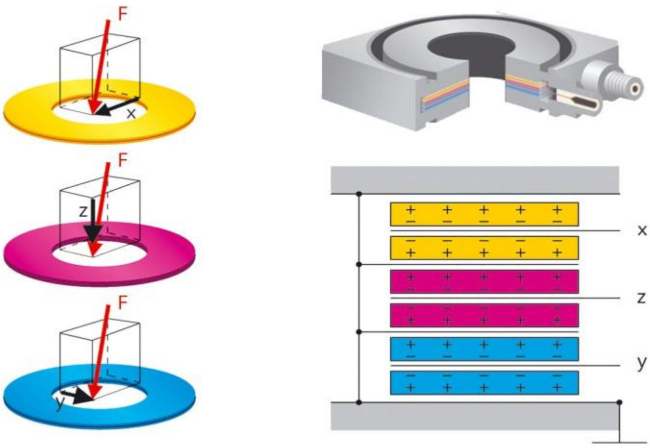

Fig. 1: Working Principle

The Force Dynamometer functions on the piezoelectric principle, in which mechanical loading produces a proportional electrical charge. Depending on the direction of the force, positive or negative charges occur at the connections. Negative charges give positive voltages at the output of the charge amplifier, and vice versa. The sensitivity of the sensor in the normal axis is 3.7 pC/N and that for the tangential and transverse axis is 7.5 pC/N.

B. Requirements

For the sensor to be verified, the following performance criteria should be fulfilled as per its planned future workload:

1. The resolution of the force sensor should be less than 0.1 N for all axes.
2. The output of the force sensor should be precise within 0.05 N for the same input applied repeatedly in the normal direction.
3. The sensor should not exceed the hysteresis of

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 05, May-2019

0.5 N limit while operating under 100 N scale in the normal direction.

4. The outputs of the force sensor should be accurate within -1 N to 1N for all axes.

Above criteria were tested with a force sensor under static condition.

II. VERIFICATION USING STATIC EXPERIMENTS

A. Experimental setup for Static Experiments

Force data is generated at Kistler type 9257 B Force dynamometer. The signal from the dynamometer is sent to a Kistler model 5019A charge amplifier. Finally, the signal is captured using a National Instruments BNC-2120 connector block attached to an in-computer PCI-MIO-16XE-10 data acquisition card and is processed with Labview software.

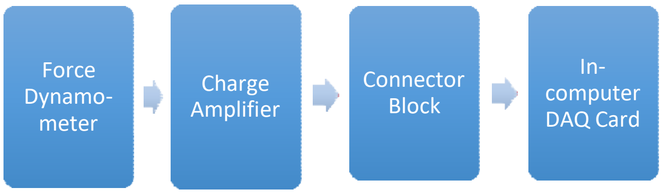

Fig. 2: Experimental setup

This setup remained unaltered for all static experiments for determining resolution, precision, hysteresis and accuracy of the force sensor.

B. Determination of Resolution

Resolution of a sensor is the smallest theoretical change in input that can be detected and measured by a sensor. It was observed that the sensor picked some noise from the surrounding and gave a constant non-zero reading for zero load i.e. when the sensor was under the no-load state. This non-zero reading can be thought of as the lowest values that sensor measures. Data Acquisition system was started, and the sensor data was allowed to stabilize under the no-load state. Data was collected and its Root means square was taken to obtain the final value of resolution for all axes.

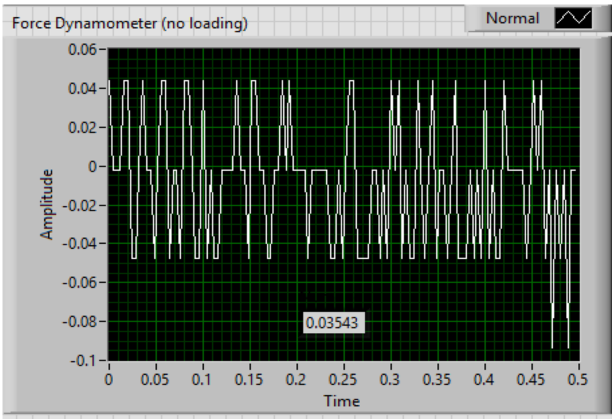

Fig. 3: Resolution for Normal axis

As shown in fig. 3, the RMS value of the signal acquired under no-load was 0.03543 N, which is the resolution of force sensor for its normal axis. A similar approach was adopted for determining the resolution of the tangential and transverse axis.

Axes	Normal	Tangential	Transverse
Resolution (N)	0.035	0.038	0.038

Table. 1. Resolution of different sensor axes

Resolution values for all the three axes are tabulated above in table.1. It is clearly evident that the resolution values for all the three axes are less than 0.1 N, which means that the sensor meets resolution criteria.

C. Determination of Precision using Repeatability

Precision is the degree of reproducibility of the same measurement by a sensor. Five trials with ten known forces were taken after an interval of every 30 seconds. Force sensor's output was noted for all the 50 trials in total. However, the table. 2. shows only the trials with lowest, medium and highest values of forces for getting a general insight of sensor repeatability.

Known Forces (N)	Trial 1 (N)	Trial 2 (N)	Trial 3 (N)	Trial 4 (N)	Trial 5 (N)	Max deflection (N)
2.22687	2.319	2.3141	**2.324**	**2.311**	2.322	**0.013**
49.05	48.942	48.971	**48.941**	48.968	**48.984**	**0.0422**
95.5494	96.211	**96.251**	**96.210**	96.229	96.251	**0.0415**

Table.2. Repeated trials for checking the precision

As shown in table.2, the values in red are the maximum output readings and blue values are minimum output reading over all five trials for the same input of known force. Maximum deflection is generally considered as the precision of the sensor.

The maximum deflection was calculated by taking the difference between the maximum and minimum output readings of the sensor for all the ten known forces. It was observed that precision was always almost 0.042 N from 13 N force inputs up to 95.5 N force inputs. The precision was observed to be less than 0.015N for the input forces below 13 N. This shows that the sensor is more precise below 13 N measurements and starts to deflect in its output by 0.042 N above 13 N. This can be thought to have happened because of added effect of flanges which are mounted on sensor as the input force increases. The metal flanges mounted on the sensor are strong and heavy. As the force increase while loading the senor, mechanical vibrations rise in the flanges that are bolted to the sensor plate. These vibrations can be considered a strong source of deflection in sensor output.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 05, May-2019

It is clear from the repeatability tests that the force sensor gives precise measurements within 0.042 N for the same, repeated inputs. This precision value is less than the pre-specified limit of 0.05 N; this proves that the sensor meets precision criteria.

D. Determination of Hysteresis

A sensor is said to have hysteresis when its output changes for same input depending on its sequence. An ascending and descending input situation was created for the sensor to check for any hysteresis. Starting with the minimum load of 2.32 N, other known loads were added in ascending order without removing any initial loads till a total of 95.61 N. The measured ascending outputs were recorded. After allowing the sensor data to stabilize, the sensor was unloaded in descending order and the resulting outputs while unloading was recorded too.

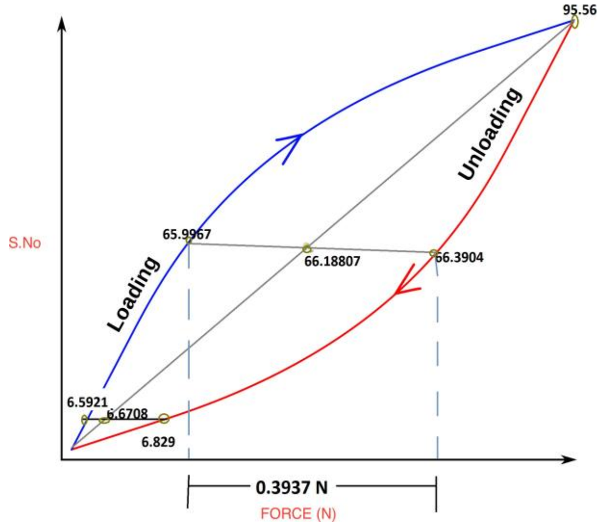

Fig. 4. Hysteresis graph

As shown in fig. 4, the sensor outputs deviated from its ascending-state outputs while unloading. The descending output data was checked thoroughly for maximum deflection. It was found that, at 66.18807 N of actual applied load, the difference between ascending and descending outputs was maximum. It also meant that the outputs in reverse condition deflected maximum from its ascending state performance at 66.18807 N of input load. Thus, the difference between loading output 65.9967 N and unloading output 66.3904 N was calculated, which was found to be 0.3937 N.

Hysteresis was found to be 0.3937 N for normal axis using sequential loading and unloading of the sensor. This value of hysteresis is lower than the hysteresis limit of 0.5 N defined earlier. It can be rightly said that the force sensor under study has passed the criteria for its hysteresis performance.

E. Determination of Accuracy using Static Calibration

Accuracy of the sensor is the maximum difference that exists between the actual value and measured value at the output of the sensor.

i. Static Calibration for Normal Axis

A set of known masses were used whose mass values were converted to force values for using them as known inputs to the sensor.

Fig. 5. Static loading in Normal direction

Different known forces were applied to the sensor after an interval of 30 seconds and the corresponding sensor outputs were recorded. Errors in measured outputs were calculated for each load case by taking the difference between actual applied load at the input and the measured value of the load at the output.

Known Weights (kg)	Actual Force (N)	Measured force (N)	Error
0.227	2.22687	2.32	-0.09313
0.453	4.44393	4.42012	0.02381
0.47	4.6107	4.66934	-0.05864
1.331	13.05711	13.035	0.02211
2	19.62	19.57	0.05
2.266	22.22946	22.313	-0.08354
3	29.43	29.54	-0.11
5	49.05	48.945	0.105
7.266	71.27946	71.692	-0.41254
9.74	95.5494	96.2788	**-0.7294**

Table. 3. Datasheet for Static Calibration of Normal axis

ii. Static Calibration for Tangential and Transverse axes

Sensor's tangential and transverse axes were loaded using a pulley system. The loads were applied at an angle of 45 degrees. Resolving the forces theoretically gave the value of known inputs which were later compared with the sensor outputs. Using a similar technique as shown in table 3, errors in measured data were found for both the axes.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 05, May-2019

iii. Accuracy results of Static calibration

Maximum error for all the axes outputs was identified, which shows the range of fluctuations in the output of the sensor from an actual value. Table. 4 summarizes the accuracies obtained for normal, tangential and transverse axes.

Axes	Normal	Tangential	Transverse
Accuracy	± 0.7294	± 0.7301	± 0.7214

Table. 4. Accuracies for all three axes of the sensor

It is clear from static calibration that the values of accuracies are less than ± 1 N for all the three axes of the sensor. Hence, it is proved that the sensor has fulfilled its performance criteria for accuracy.

Static experiments have proved that the sensor meets all the pre-established performance criteria of resolution, precision, hysteresis and accuracy. Hence, the verification process was successful.

III. VALIDATION USING DYNAMIC CALIBRATION

It is important to check the sensor's performance dynamically. In order to compare the sensor's dynamic output with actual input, an impulse hammer was used to generate a known amount of instantaneous force as input to the force dynamometer.

A. *Experimental setup for Dynamic tests*

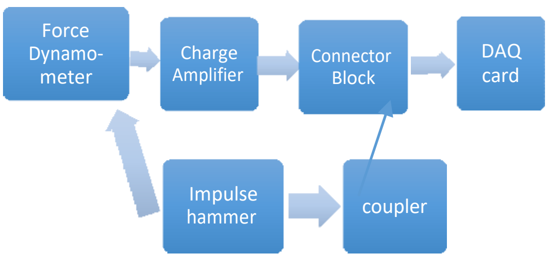

Fig. 6. Connection diagram for dynamic tests

An impulse hammer is mainly used to deliver a measurable force impulse to excite a mechanical structure for its test. The stainless steel head of an impulse hammer is equipped with quartz, low impedance force sensor which accepts impact tips varying in hardness. A selection of steel, plastic, PVC and rubber tips along with an extender mass allow the hammer to be tailored to impart to the test structure, a desired magnitude of forces. The sensitivity of the impulse hammer used in these tests is 1 mV/lbf.

For dynamic testing, additional components were required to be used along with the static experiments setup. Initial setup was kept unaltered. Using BNC cables, an impulse hammer of Kistler Type 9726A20000 was connected to a Kistler coupler that acted as an exciter for impulse hammer. The output of the coupler was connected to BNC-2120 connector block which was attached to an in-computer PCI-MIO-16XE-10 data acquisition card. The data acquired is processed using Labview software.

B. *Dynamic Calibration of the force sensor*

An impulse hammer was used to trigger an impulse on the force dynamometer. Depending on the axis of calibration, the impulse hammer motion was directed parallel to the axis line and impact was made on the flanges that covered force dynamometer. This procedure was followed for calibrating all the three axes of force dynamometer. The signal acquired from an impulse hammer was processed to determine the input value of impulse which was later compared to the output value of measured impulse from the force dynamometer.

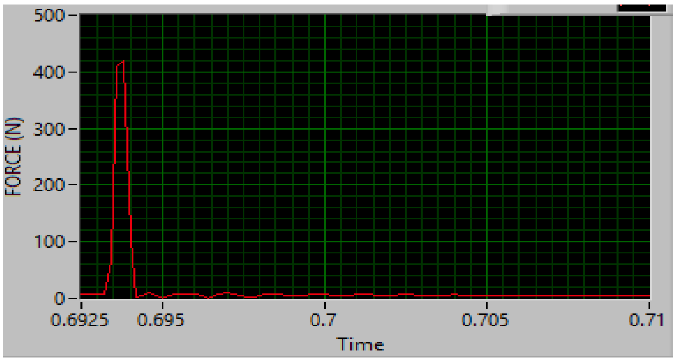

Fig. 7. Input from impulse hammer on the normal axis

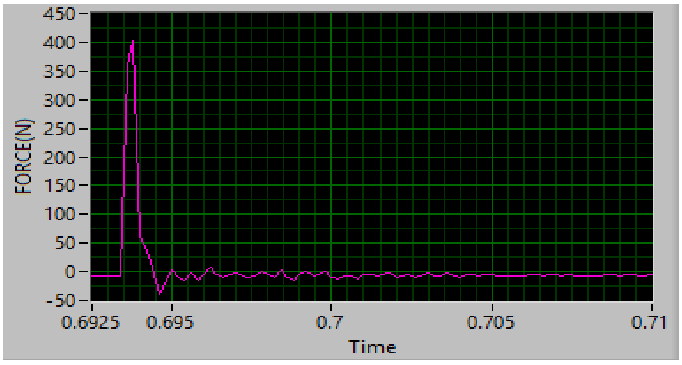

Fig. 8. Measured output by Force dynamometer on the normal axis

As evident from fig. 7, in normal axis, applied input force by impulse hammer was 411.616 N while the dynamometer output shows an impulse of 410.250 N. Difference between the input and output values is 1.366 N. This result suggests that the dynamometer is pretty close in measuring forces on its normal axis in dynamic conditions.

Similarly, inputs and outputs values from impulse hammer and force dynamometer were compared for tangential and transverse axes. Input force on tangential axis was 124.798 N whereas the dynamometer outputted an impulse of 112.338 N. The difference between input and output was 12.46 N for tangential axis. Using the same procedure, the difference between input and output was found to be 8.276 N. Higher deflection in the measurement of forces in the tangential and transverse direction can be attributed to human errors in controlling hammer motion after impact. It gets difficult to pull back the hammer after impact due to its initially-acquired inertia and hence the applied force readings are generally higher than the actual force applied. Another strong reason that affects the dynamometer output is the inadequate transmission of force to the sensor due to the flanges that are clamped above the sensor. Flanges mounted on the sensor absorb some force due to the vibrations that cause relative motions between flanges and bolts. The error of about 10 N can be caused by both the reasons mentioned above; and by that understanding, sensor outputs in tangential and transverse directions are reasonable.

Response time of the sensor was checked by careful investigation of obtained data. It was found that there was a difference of 0.000125 seconds in peak generation time in input graph and output graph. This suggests that the sensor responds to the applied inputs in 0.000125 seconds.

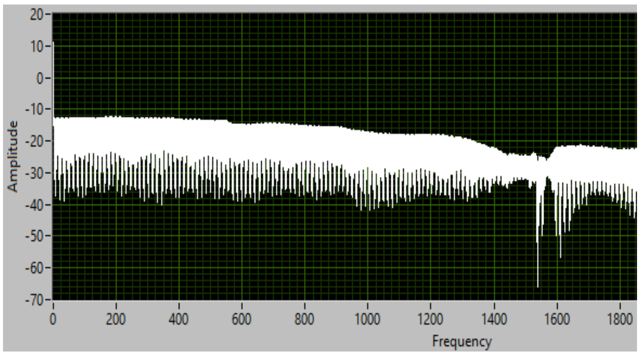

Fig. 9. The power spectrum of force dynamometer data

The power spectrum of impulse hammer and force dynamometer was taken. Fig. 9. Shows the power spectrum of data obtained at the output of force dynamometer. Power spectrum data was used to determine -3 dB bandwidth for both the sensors. Bandwidth for Force dynamometer was found to be 771 Hz and the bandwidth for impulse hammer was found to be 763 Hz. This shows that both the sensors had measurements having close bandwidths to each other.

Dynamic tests and the analysis of acquired data suggest that the force dynamometer is sufficiently accurate and responsive to the applied inputs. It can thus be said that dynamic tests and their results have been useful in sensor validation.

IV. CONCLUSIONS

The Kistler type 9257 B force dynamometer evaluated in this experimental investigation is found to be working satisfactorily. It can be concluded that the sensor has enough resolution, accuracy, precision and limited hysteresis as per requirement for further grinding research.

The sensor was found to be extremely responsive to inputs in dynamic state. The sensor showed excellent force measurement results in dynamic conditions for all its axes which proves that it is safe and reliable to be used for advanced level grinding research.

REFERENCES

[1] M. P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes and Systems. Wiley Global Education, 2012.