Design and Fabrication of 3-DOF Dynamometer for Measuring Cutting Forces during Milling of Al Based Aerospace Alloy

Author

Aman Sharif

Regn Number

00000238662

Supervisor

Dr. Mushtaq Khan

DEPARTMENT

DESIGN AND MANUFACTURING ENGINEERING

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

ISLAMABAD

December, 2019

Design and Fabrication of 3-DOF Dynamometer for Measuring Cutting Forces during Milling of Al Based Aerospace Alloy

Author

Aman Sharif

Regn Number

00000238662

A thesis submitted in partial fulfillment of the requirements for the degree of

MS Design and Manufacturing Engineering

Thesis Supervisor:

Dr. Mushtaq Khan

Thesis Supervisor's Signature: ___________________________

DEPARTMENT

DESIGN AND MANUFACTURING ENGINEERING

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

ISLAMABAD

December, 2019

Declaration

I certify that this research work titled “**Design and Fabrication of 3-DOF Dynamometer for Measuring Cutting Forces during Milling of Al Based Aerospace Alloy”** is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged / referred.

Signature of Student
Aman Sharif
00000238662

Plagiarism Certificate (Turnitin Report)

This thesis has been checked for Plagiarism. Turnitin report endorsed by Supervisor is attached.

Signature of Student
Aman Sharif
00000238662

It is certified that MS Thesis Titled "**Design and Fabrication of 3-DOF Dynamometer for Measuring Cutting Forces during Milling of Al Based Aerospace Alloy"** by Aman Sharif has been examined by us. We undertake the following:

a. Thesis has significant new work/knowledge as compared already published or are under consideration to be published elsewhere. No sentence, equation, diagram, table, paragraph or section has been copied verbatim from previous work unless it is placed under quotation marks and duly referenced.
b. The work presented is original and own work of the author (i.e. there is no plagiarism). No ideas, processes, results or words of others have been presented as Author own work.
c. There is no fabrication of data or results which have been compiled/analyzed.
d. There is no falsification by manipulating research materials, equipment or processes, or changing or omitting data or results such that the research is not accurately represented in the research record.
e. The thesis has been checked using TURNITIN (copy of originality report attached) and found within limits as per HEC plagiarism Policy and instructions issued from time to time.

Name of Supervisor: Dr. Mushtaq Khan

Signature: ________________

Thesis Acceptance Certificate

Certified that final Copy of MS thesis written by Mr. Aman Sharif Registration No. 00000238662 of SMME has been vetted by undersigned, found complete in all aspects as per NUST Statues/Regulations/MS Policy, is free of plagiarism, errors and mistakes and is accepted in partial fulfillment for award of MS Degree. It is further certified that necessary amendments as pointed out by GEC members and foreign/local evaluators of the scholar have also been incorporated in the said thesis.

Signature with Stamp: ___________________________
Name of Supervisor: Dr. Mushtaq Khan
Date: ___________________________

Signature of HoD with Stamp**:** ___________________
Date: ___________________________

Countersign By

Signature (Dean/Principal): ___________________________

Date: ___________________________

“DULLY SIGNED FORM TH-4”

Copyright Statement

Acknowledgements

All praise is for Almighty Allah for bestowing me the courage and honor for successful completion of this project.

Understanding the emerging concept in my project would never be so easy for me without the immense support, able guidance and motivation from my respected advisor Dr Mushtaq Khan. He not only educated me from his intellect but also helped me in resolving the problems that I faced during the course of this project. I am greatly indebted to his efforts and precious time that he gave even after working hours for the successful completion of my project. I also want to extend my sincere thanks to him, as he was not only a source of motivation for me during my project phase but also helped me learn and explore my own capabilities. I am also thankful to Dr. Husain Imran Jaffery and CNC Lab Staff who were always ready to help and guide whenever the project demanded.

I express my utmost gratitude to my parents and family for their kind prayers, support, love and unconditional patience towards my extended working hours. Without their prayers and cooperation, the project could not be a success.

I dedicate this work to my parents, siblings and advisor who have always been a constant source of support and guidance to me.

ABSTRACT

In various engineering applications, need of miniature components is increasing manifolds with the continuous evolution of micro and nano technology. There are several techniques with in the subtractive and additive manufacturing methods/ techniques, however among all, micro milling shows great promise in manufacturing and fabrication of micro/ nano components required in aerospace, electronic/electrical, instrumentation and bio-medical applications. In aerospace applications alone, micro milling may be used for fabrication of moulds for micro gears, miniaturized components for rockets, micro gyroscope parts in missiles, micro servos and valves etc. Due to superior mechanical properties, aluminum and titanium based alloys are used in aircraft, armor plating, naval ships, spacecraft, missiles and biomedical applications. Measurement of cutting forces during micro machining is an important activity which helps in establishing the quality of both the machined product and the machining process. Therefore, in this study, strain gauge based 3-DOF dynamometer is designed and fabricated using commercial of the shelf load cells for calculating cutting forces in macro machining of Al based aerospace alloy. Subsequent to design and fabrication, experimentations were performed and the results were compared with those available in literature. This research is envisaged to act as stepping stone for utilizing the same approach for calculating micro forces during micro milling machining processes.

Keywords: Dynamometer, Cutting Forces, Milling Machining, Arduino Mega 2560, Strain Gauge Based Load Cells.

Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

Background

1. Detection and quantification of physical variables are undertaken by easuring the effects they cause, for example a force cannot be seen directly instead it is quantified by measuring its effect such as stress, displacement and/or deformation. These effects may also be referred to as signals. Generally, signals require pre-conditioning prior to their interpretation thus requiring amplifier and/or Analogue-to-Digital Convertor etc. Depending on importance of signals, the sensing systems may also require online/offline monitoring and data archival modules so that signals are preserved for further analysis by subject matter experts.

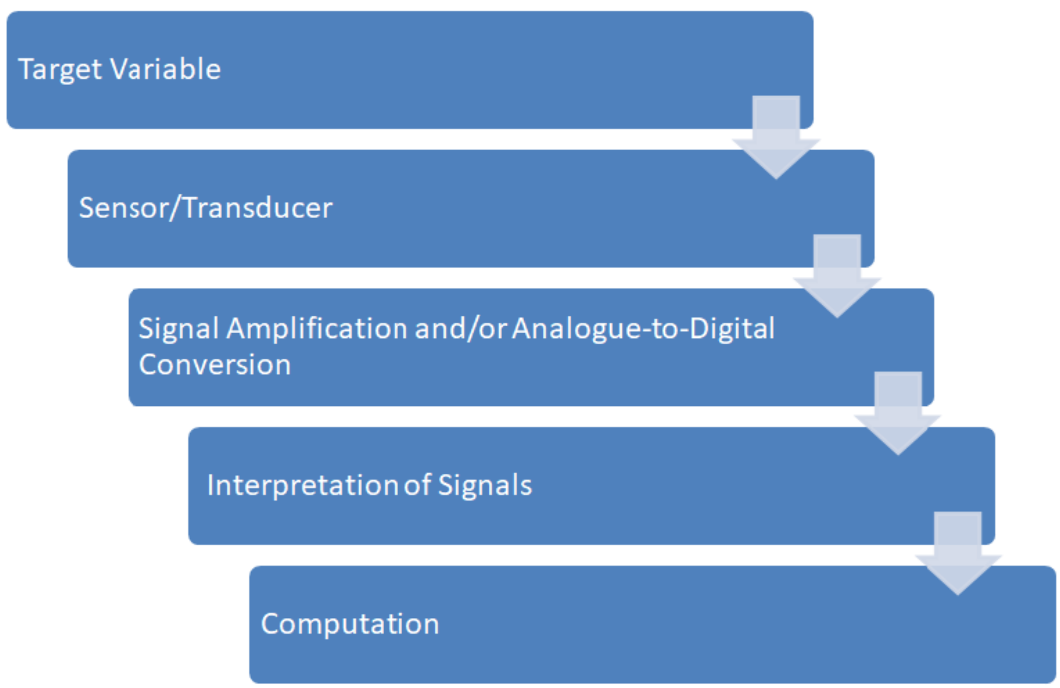


Figure 1 : Principle of Measurement

Scope of Research

2. The scope of this research is to develop strain gauge load cell based 3-DOF (axis) dynamometer able to sense cutting forces during Milling Machining processes.

Research Objectives

3. Objectives of the research are appended as below:

   a. Determine most suitable and easily available strain gauge based load cell and establishing feasibility of interfacing load cell with Integrated Development Environment (IDE) of Arduino.

   b. Performing functional testing of Load Cell with Arduino Mega2560.

   c. Integrating multiple load cells with Mega2560 to develop a dynamometer.

   d. Design Validation through experimentation.

Outline of Thesis Report

4. Thesis report comprises of five chapters as listed below:

   a. Chapter 1 : Introduction

   b. Chapter 2 : Literature Review

   c. Chapter 3 : Methodology

   d. Chapter 4 : Results and Discussion

   e. Chapter 5 : Conclusions and Recommendations

CHAPTER 2: LITERATURE REVIEW

2.1. Machining process monitoring is considered as one of the most common and necessary requirement in the "Industry 4.0 era". It can also be compared with the concept of integrating precision sensors and equipment with the machine tools in such a way that machining process is efficiently and pro-actively monitored [1].

2.2. One among the most important and fundamental aspect in monitoring machining operations is to measure cutting forces [2]. It enables to identify following aspects of the machining processes:

a. Machinability of materials

b. Machining Malfunctions/ failures.

c. Monitoring tool usage/ wear.

d. QA/ QC of part being machined.

2.3. Most common method of measuring cutting forces during machining is by using a dynamometer [3]. A dynamometer can conceptually be classified into four basic types, appended as following [4]:

a. Indirect Measurement Dynamometers

- It may work on the principle of drive motor current monitoring and/or shaft displacement measurement using position sensors, etc.

b. Capacitance Based Dynamometers

- It is commonly spindle mounted apparatus which continuously measures the gap between rotating spindle shaft and spindle housing.

c. Strain Gauge Based Dynamometers

- Traditionally strain gauges mounted on four elastic octagonal rings.

d. Piezoelectric Based Dynamometers

- Most common and widely used, piezo sensor sensitive to changes in the applied load/ pressure.

2.4. Among the above listed type of dynamometers, the most commonly and widely used dynamometers are either of the following:

a. Strain gauge type and/or

- Inexpensive but less accurate and less consistent

b. Piezoelectric type

- Highly accurate, reliable, and repeatable but expensive for material cost and stringent construction.

2.5. Some of the contribution to body of knowledge in design and development of dynamometers is discussed as following:

a. Samir Makid. (2014)

- Title of the conducted research was "Design and Testing of a Micro-Dynamometer for Desktop Micro Milling Machine". In this research, author designed a piezo sensor based micro-dynamometer to measure cutting forces. It has been equipped with a data acquisition system comprising of hardware and software all developed for the purpose [4].

b. Yaldiz et al. (2007)

- The research by the authors pertains to design and development of four component dynamometer. A dynamometer design was presented using octagonal rings on which strain gauges were mounted to measure cutting forces during milling machining [5].

c. Bhargav et al.

- The designed Dynamometer was based on classical four octagonal ring members on which strain gauges were installed for measuring cutting forces during milling machining. The results of designed Dynamometer are compared with those on Kistler Dynamometer [6].

d. Yingxue et al. (2016)

- Authors have presented a strain gauge based three component fixed dynamometer. The authors utilized octagonal ring concept in their research [7].

e. Fenghe et al. (2018)

- Authors presented a force measuring tool holder system based on strain gauge sensors. It was designed and developed for measuring the axial force and torque [8].

f. Ming et al.

- Authors presented a novel instrumented working table with integrated polyvinylidene fluoride (PVDF) thin film sensors, thus enabling the dynamic miling force measurement [1].

g. Milfelner et al.

- Authors have presented LabView Software based cutting force measurement system for ball end-milling. The authors described that the efficient and successful measuring of cutting forces depends on two basic elements, firstly number of sensors used and secondly associated signal processing and simplification methods. Cutting force measuring system during cutting operation as shown in the research paper is illustrated as following [9]:

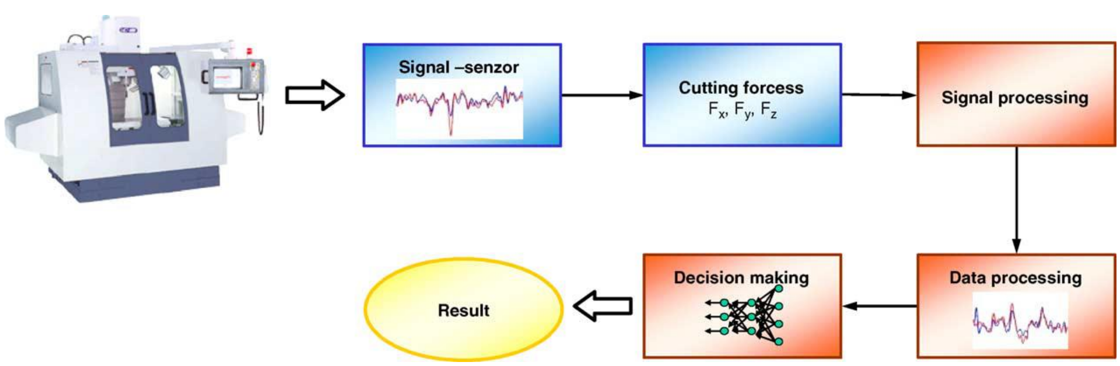


Figure 2 : Cutting Forces Monitoring System Schematic [9]

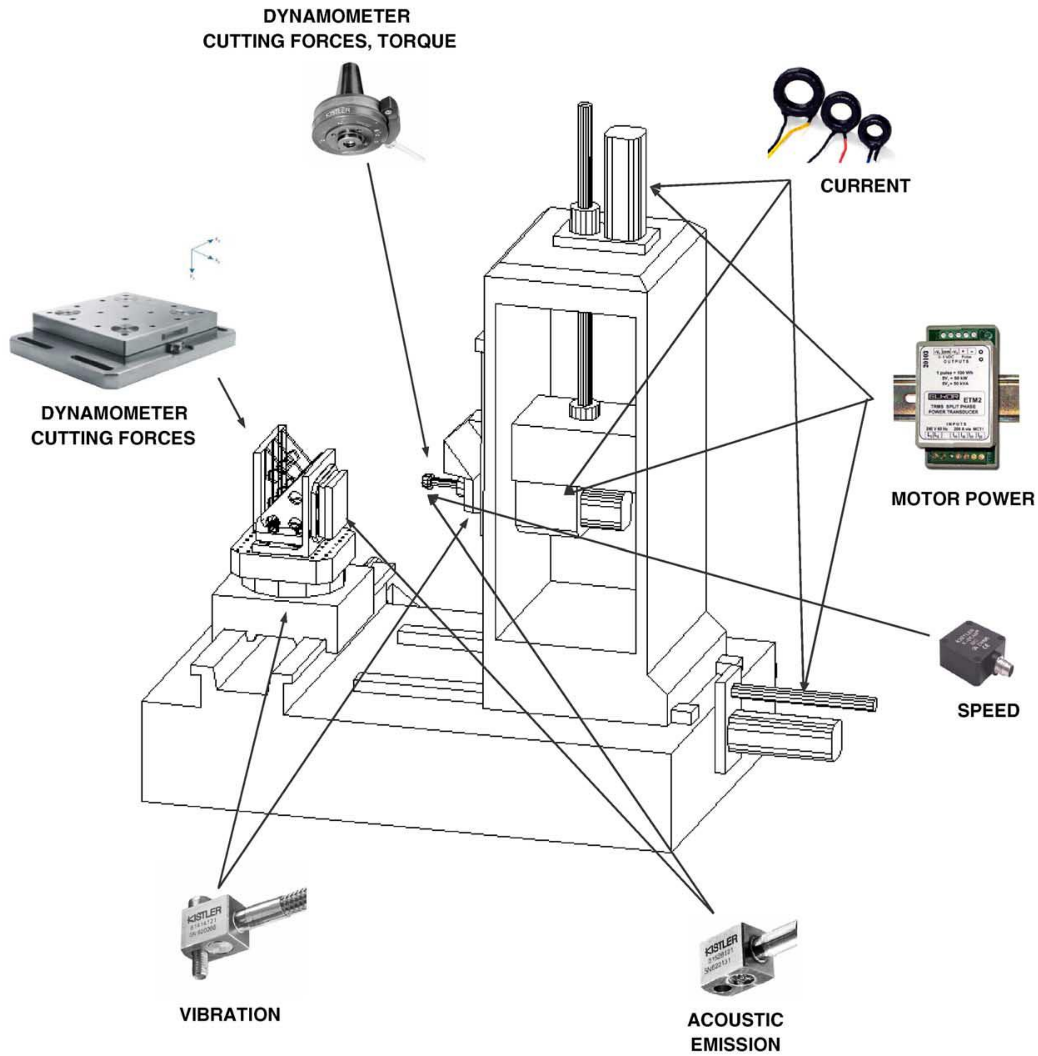


Figure 3 : Most Commonly Sensor Types Used in Cutting Process Monitoring Systems [9]

2.6 For basic understanding and measuring of response of the system, force sensors are used. The same can be elaborated that cutting forces generated during machining processes can be monitored and subsequently can be interpreted into tool failures & associated causes and surface finish, subsequently, relationship with process controlling parameters can be established. Force sensors may also enable to efficiently measure impact forces generated during manufacturing processes. They may also be useful in controlling of electro-mechanical systems.

2.7 Some type of force sensors measures the deflection/ displacement caused by the force as a result generates electrical signals (in mV) which can further be amplified and processed to correlate them to newtons. One example of forces versus deflection mechanical mechanism can be a helical spring. Hook’s law defines the relationship between force and the deflection in the spring while in the elastic region. Piezoelectric and strain gauge based force sensors are common while used with half and full bridge circuits. These force sensors can measure and monitor both impulsive as well as continuously varying forces.

2.8 Within the force measuring techniques, a general category can be defined as that of load cells. These load cells are generally constructed with an aim to withstand harsh test environment while equipped with the necessary elements to sense and relay impulsive and continuous forces of both compressive and tensile natures.

CHAPTER 3: METHODOLOGY

3.1 In this chapter, steps of the undertaken research are elaborated. Following block diagram illustrates the adopted methodology:

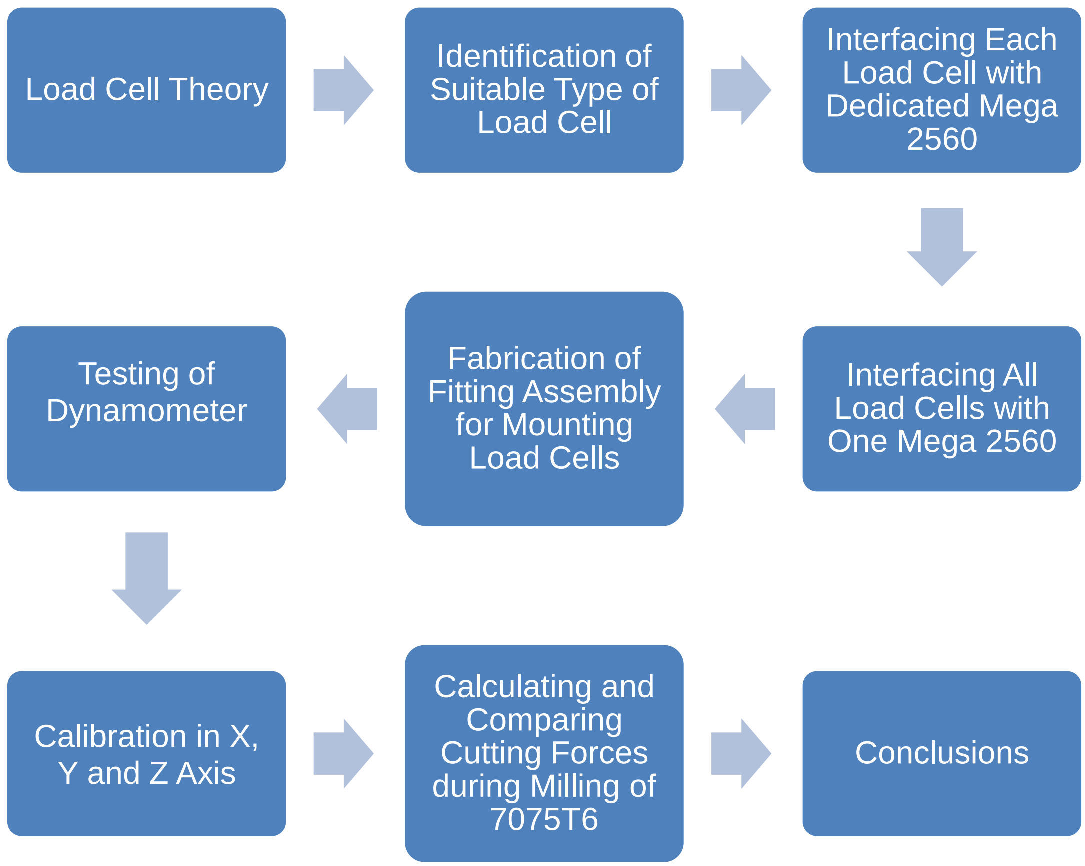


Figure 4 : Adopted Methodolgy

3.2 In the light of Aim and Objectives of research, dynamometer was anticipated as per the following conceptual design:

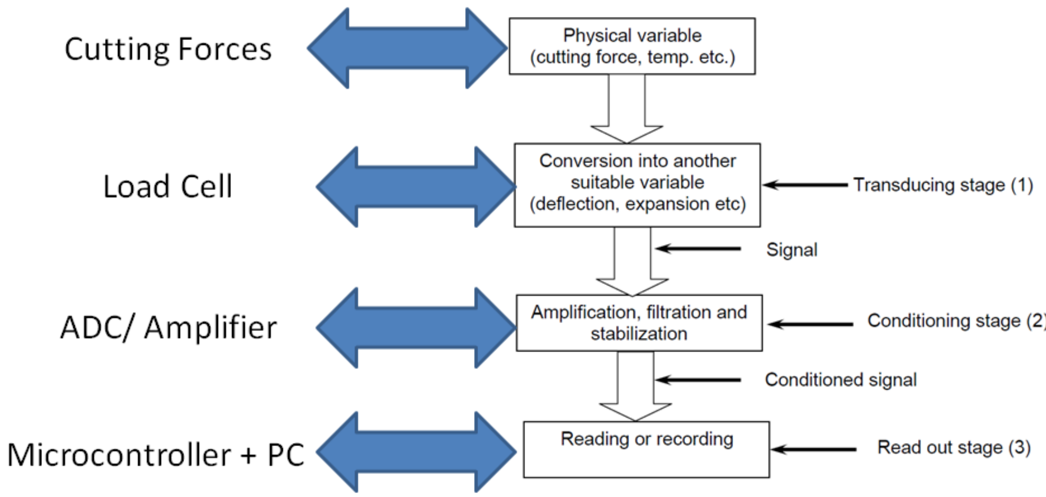


Figure 5 : Conceptual Design of Dynamometer

3.3 A strain gauge based load cell was selected. Specifications of the same are tabulated as following:

Table 1 : Load Cell Specifications

S.No	Variable	Specs
1.	Rated Load	20 Kg
2.	Output	2mv/v
3.	Temperature Zero Drift	0.1 % F.S
4.	Output Sensitivity	±0.15mv/v
5.	Temperature Sensitivity	0.05% F.S
6.	Insulation Resistance	2000MΩ ≤
7.	Excitation Voltage	5 – 10VDC

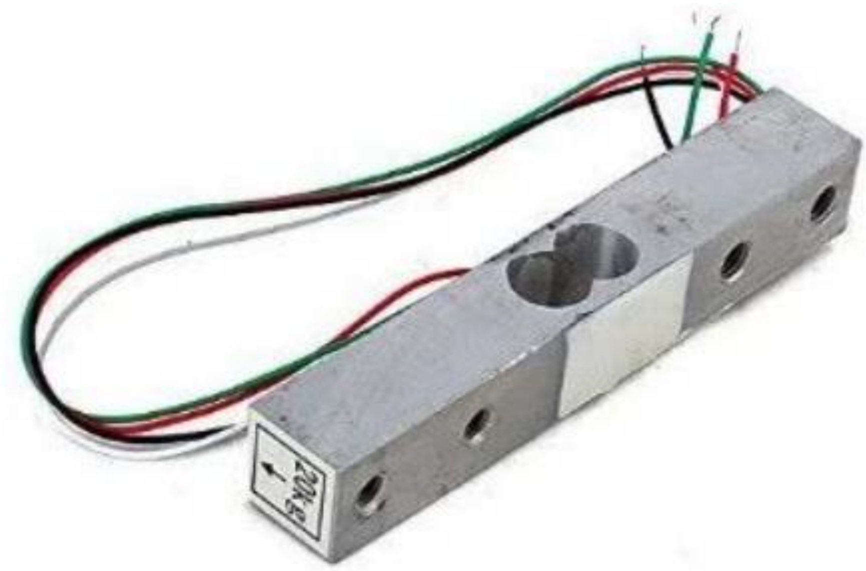


Figure 6 : Load Cell (Strain Gauge Based – 20Kg)

3.4 The above shown load cell bears strain gauges in a full bridge circuit. Colour coding of wires and circuit diagram are illustrated as following:

Table 2 : Colour Coding of Load Cell Wires

S.No	Wire	Color Code
1.	Vcc	Red
2.	GND	Black
3.	Signal + (A+)	Green
4.	Signal – (A-)	White

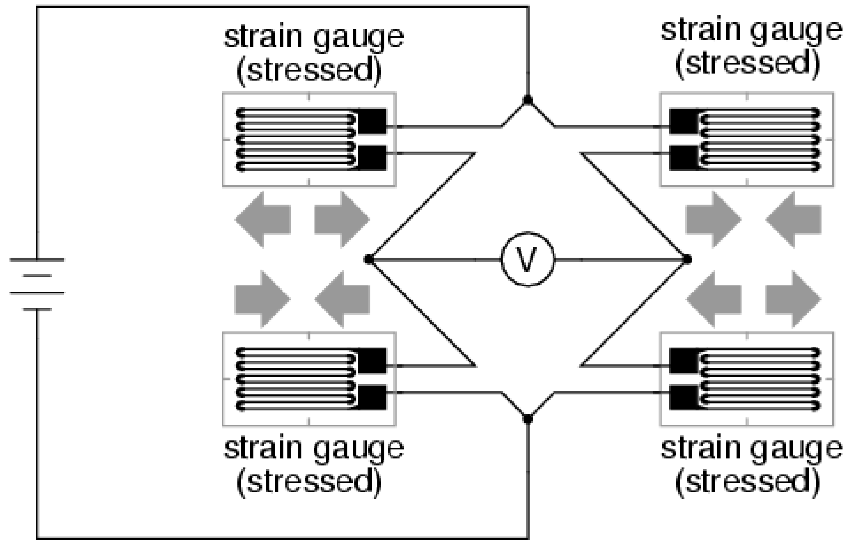


Figure 7 : Circuit Diagram of Load Cell

3.5 **HX-711 (ADC)**

3.5.1 Interfacing of a load cell with a microcontroller requires signal amplifier as well as Analogue-to-Digital Converter. It was deduced from literature that HX-711 is best suited for interfacing full brodge circuits with microcontrollers. It is a semi-conductor based board which amplifies load cell signals as well as enables interfacing for subsequent signal interpretation. Figures below illustrate HX-711 board and its circuit diagram:

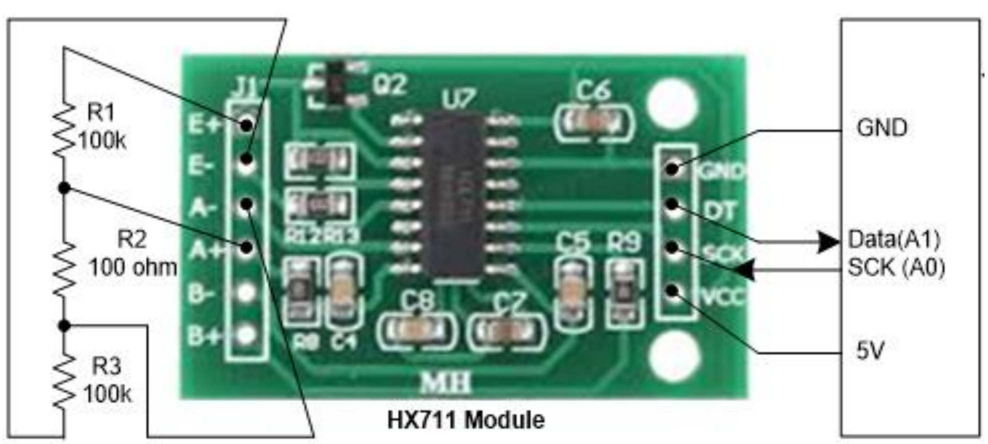


Figure 8 : HX-711

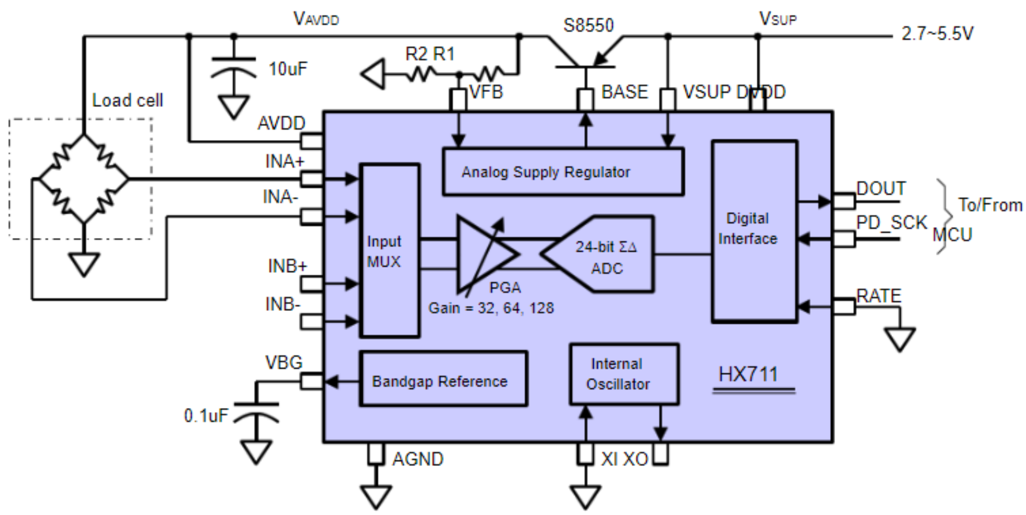


Figure 9 :Circuit Diagram of HX-711

3.6 Arduino Mega2560

3.6.1 Arduino Mega2560 is a micro-controller board. It is based on ATMega2560 microcontroller processor. It possesses a number of digital and analogue pins which can be used as Input/ Output ports. Mega2560 board can communicate serially with PC through USB port. Arduino Mega2560 can be pre-programmed in Integrated Development Environment (IDE) of Arduino. Figure below illustrates the Mega2560 board and its pins:

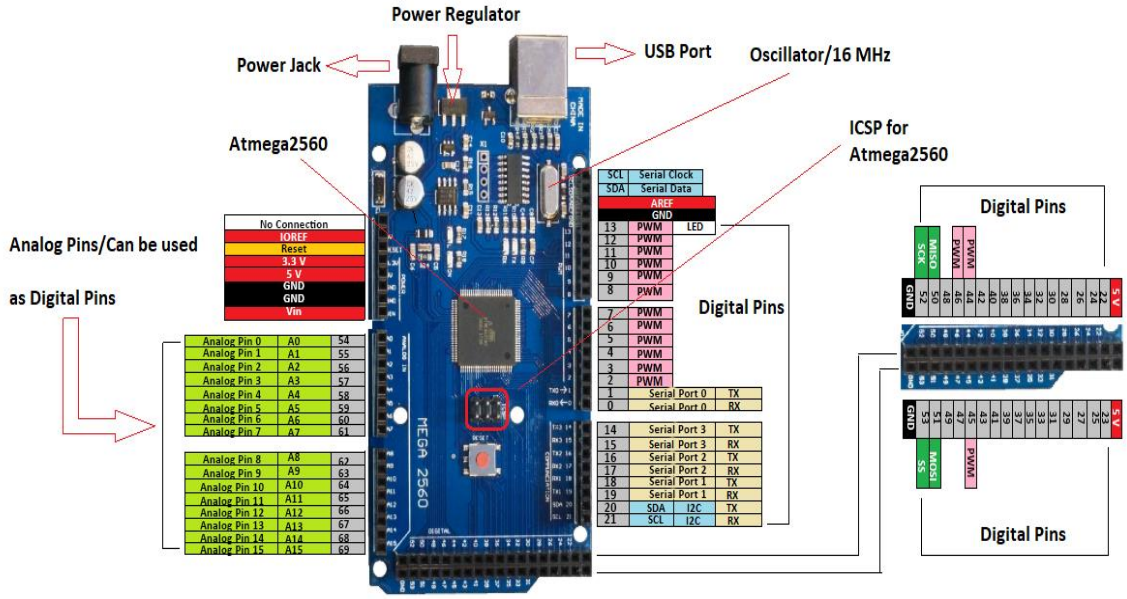


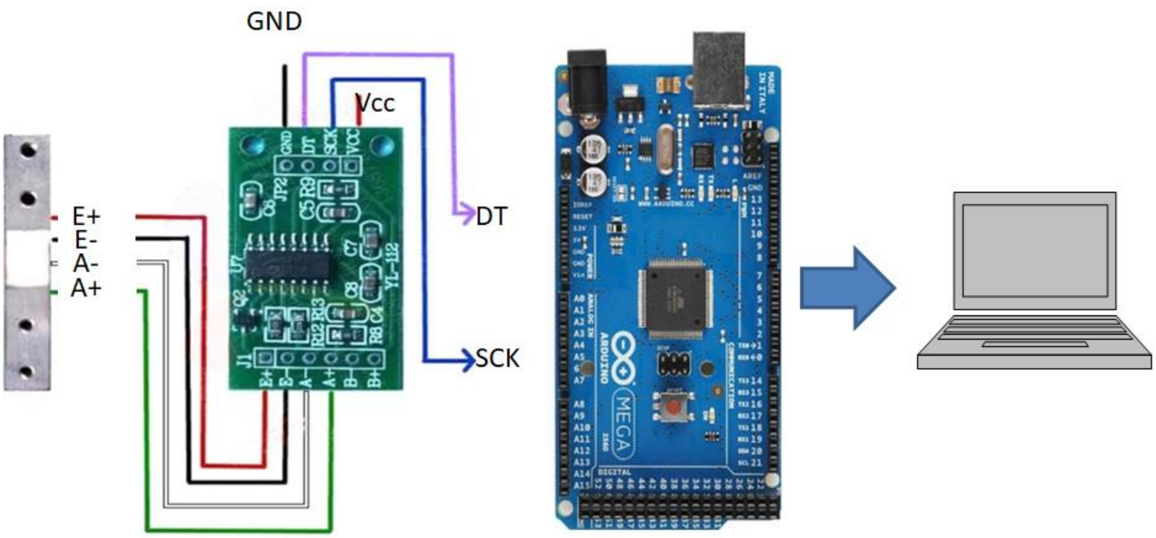
Figure 10 : Arduino Mega2560

3.6.2 **Interfacing Load Cells with Mega2560**

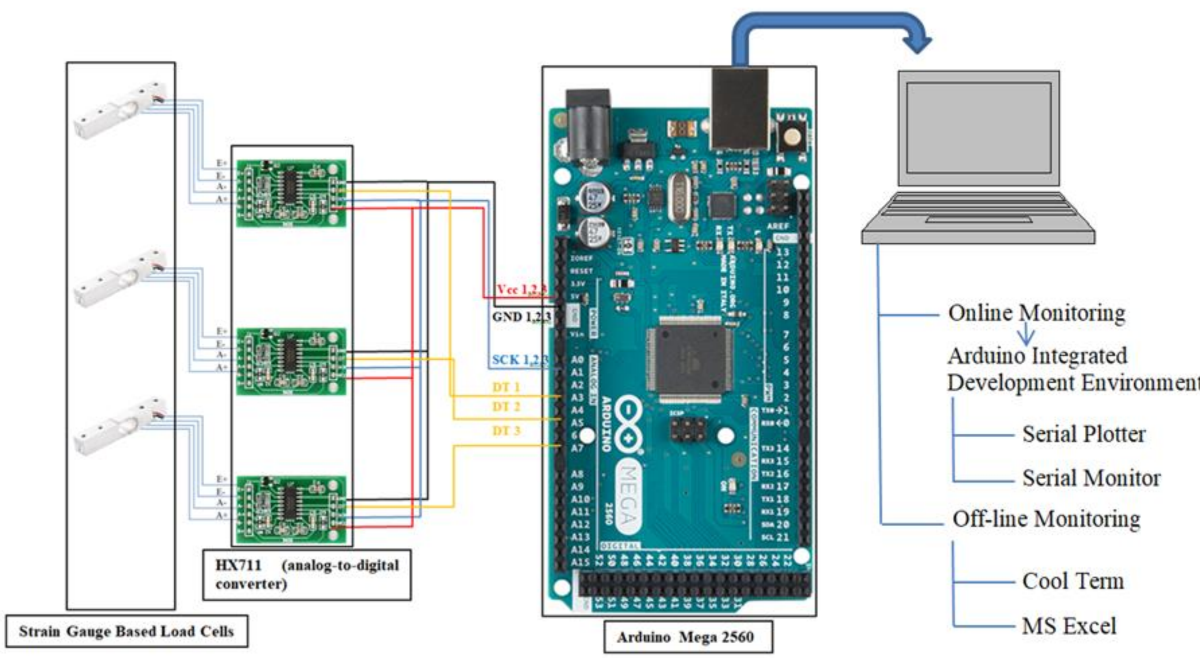
Load cells were interfaced with Mega2560, initially each load cell with a dedicated Mega2560 boards. Subsequently, 03 x load cells were interfaced with one Mega2560 by combining following wires in output wires of HX-711 with each other thus enabling them to share similar ports on Arduino Mega2560:

a. PWR wires
b. GND wires
c. SCK Wires

Following circuit diagram illustrates interfacing of 01 x Load cell and 03 x Load Cells with Arduino Mega2560 respectively:



(a) Interfacing 01 x Load Cell with Arduino Mega2560

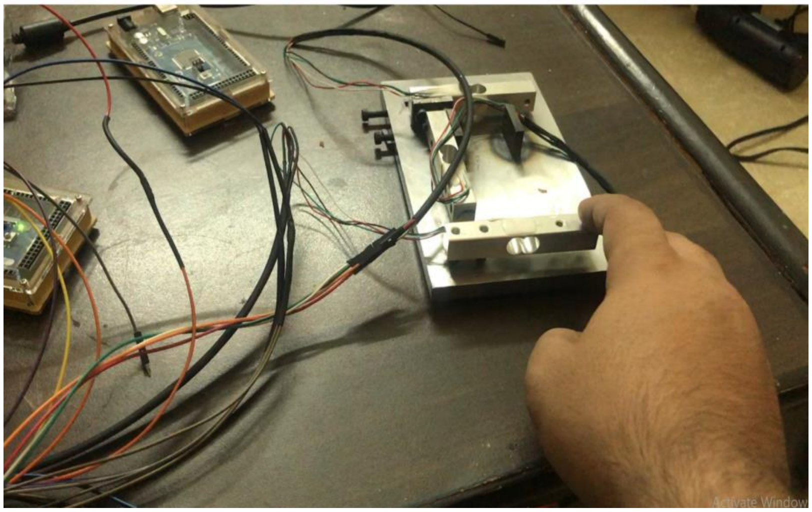


(b) Interfacing 03 x Load Cells with Arduino Mega2560

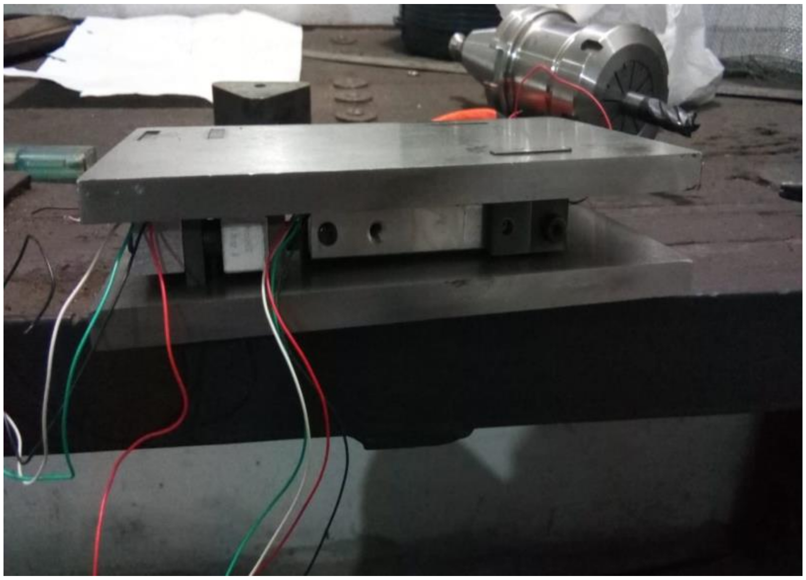
Figure 11 :Interfacing Load Cells with Arduino Mega2560

3.7 Fabricating Fitting Assembly and Functional Testing Dynamometer

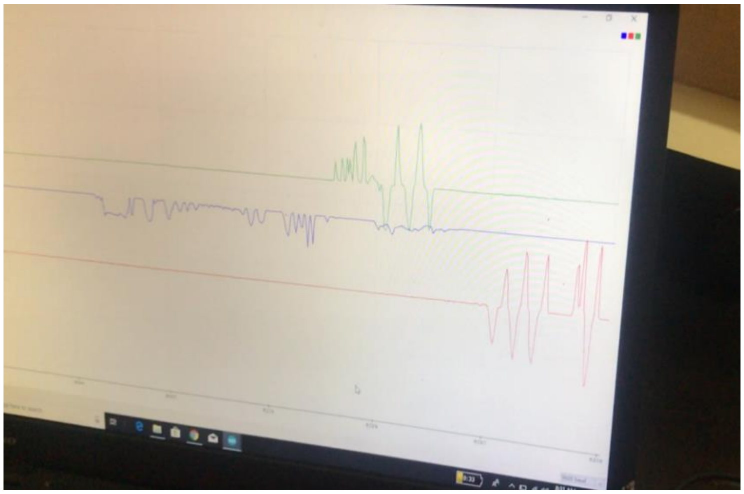
3.7.1 Fitting assembly was fabricated and 03 x Load cells in three axis (x, y, z) were installed to sense forces in X, Y and Z axis. Initial testing was performed to check for working and proper functioning. Figures below illustrate fabrication and testing of dynamometer:



(a) Load Cells Installation



(b) Assembling Fitting Assembly



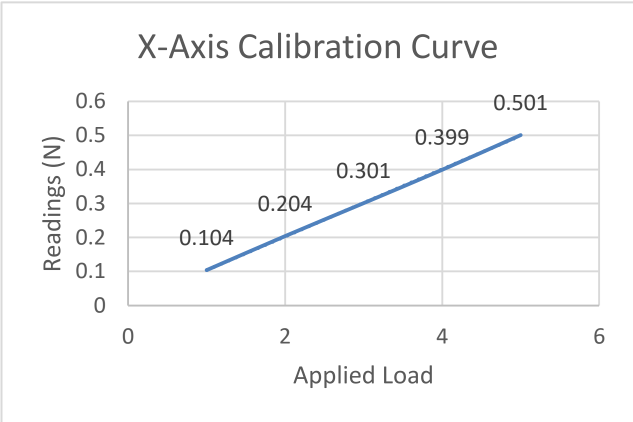
(c) Functional Testing of Dynamometer (forces in x, y and z axis in serial plotter of IDE 1.8.9)

Figure 12 : Fabrication and Testing of Dynamometer

3.8 Calibration of Dynamometer

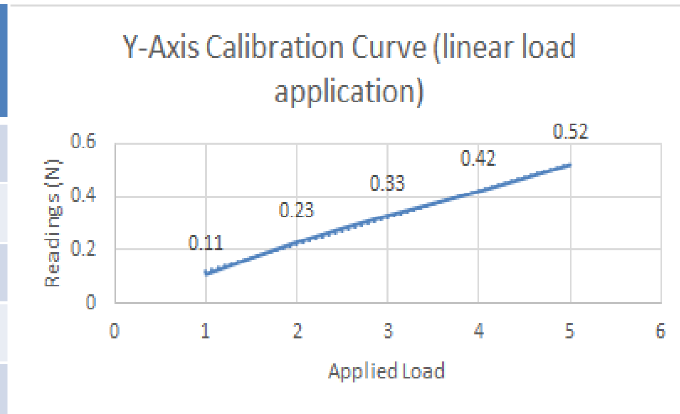
3.8.1 Dynamometer was calibrated in X, Y and Z axis by calibrating load cells in IDE 1.8.9. Calibration curves were plotted, and illustrated below, as relation between applied load and subsequent readings in newtons.

Load No	Weight (g)	Readings (N)
1.	10g	0.104
2.	20g	0.204
3.	30g	0.301
4.	40g	0.399
5.	50g	0.501



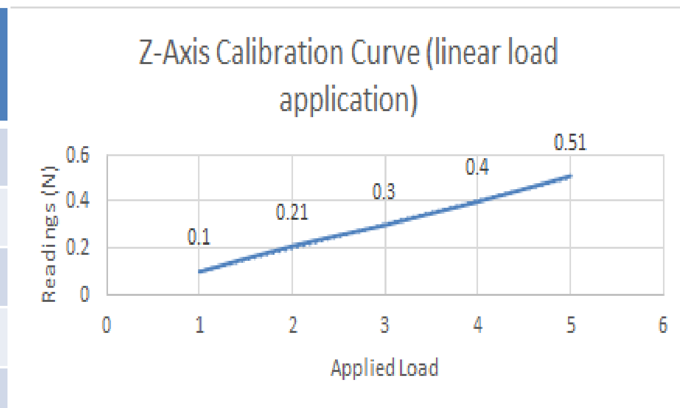
(a). X-Axis Calibration

Load No	Weight (g)	Readings (N)
1.	10g	0.11
2.	20g	0.23
3.	30g	0.33
4.	40g	0.42
5.	50g	0.52



(b). Y-Axis Calibration

Load No	Weight (g)	Readings (N)
1.	10g	0.1
2.	20g	0.21
3.	30g	0.3
4.	40g	0.4
5.	50g	0.51



(c). Z-Axis Calibration

Figure 13 : Calibration Plots of Dynamometer in X, Y and Z-Axis

Chapter 4: RESULTS AND DISCUSSION

4.1 Experiments were performed based on the concept that dynamometer is installed below the workpiece. It is worth mentioning that lower plate of the dynamometer was secured with machining vise whereas the top plate carries workpiece in a way that cutting force is sensed by load cells, installed in Z position (each end secured with either top or bottom plate of dynamometer). Following figure depicts the schematic of dynamometer:

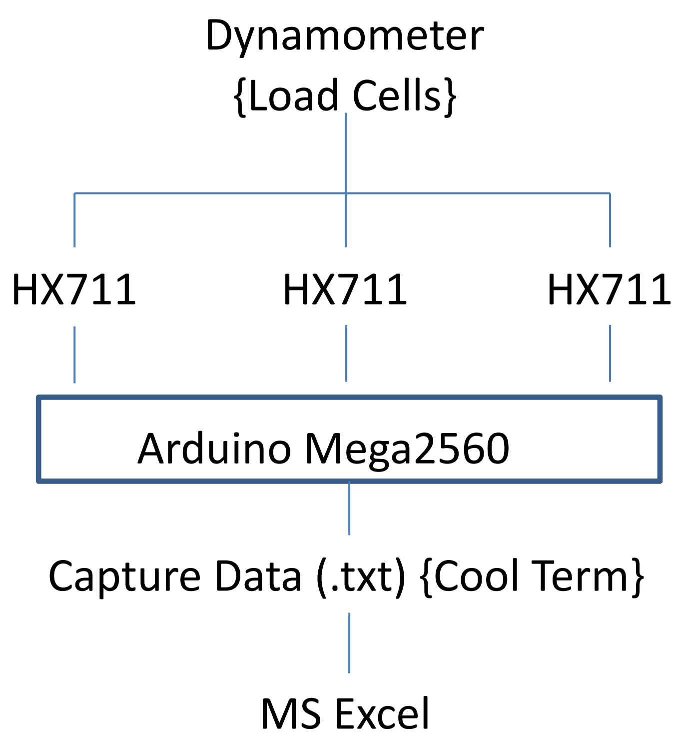


Figure 14 : Dynamometer Schematic

4.2 Experimental/ process conditions for the experiments are tabulated as following. It is noteworthy that these conditions were borrowed from literature as cutting forces at these conditions are known [10]. Furthermore, capabilities of the existing machine (MV-1060, slow rpm machining center) at CNC Lab of SMME are also in favour of the aforementioned publication. Process conditions and process parameters are tabulated as following:

Table 3 : Process Conditions

Process Conditions		
1.	Machine Tool	CNC Machining Center MV-1060, Controller: FANUC Series 0i-MC
2.	Work piece Material	Aluminum Alloy 7075 T6
3.	Cutting Tool 	No of Flutes : 2 Diameter : 10mm Material : Flat End Carbide End Mill Helix Angle : 30 deg
4.	Machining Type	Dry Cutting, Full Immersion

Table 4 : Process Parameters

Process Parameters (for design validation)				
	Process Parameter	**Level 1**	**Level 2**	**Level 3**
1.	Cutting Speed (m/min)	60	120	180
2.	Feed Rate (mm/min)	100	200	300
3.	Depth of Cut (mm)	0.5		
4.	Width of Cut (mm)	10		
5.	Type of Cutting	Orthogonal Cutting		

4.3 Following figures illustrate the experimental setup. Dynamometer and associated hardware's were installed as discussed earlier and shown as below:

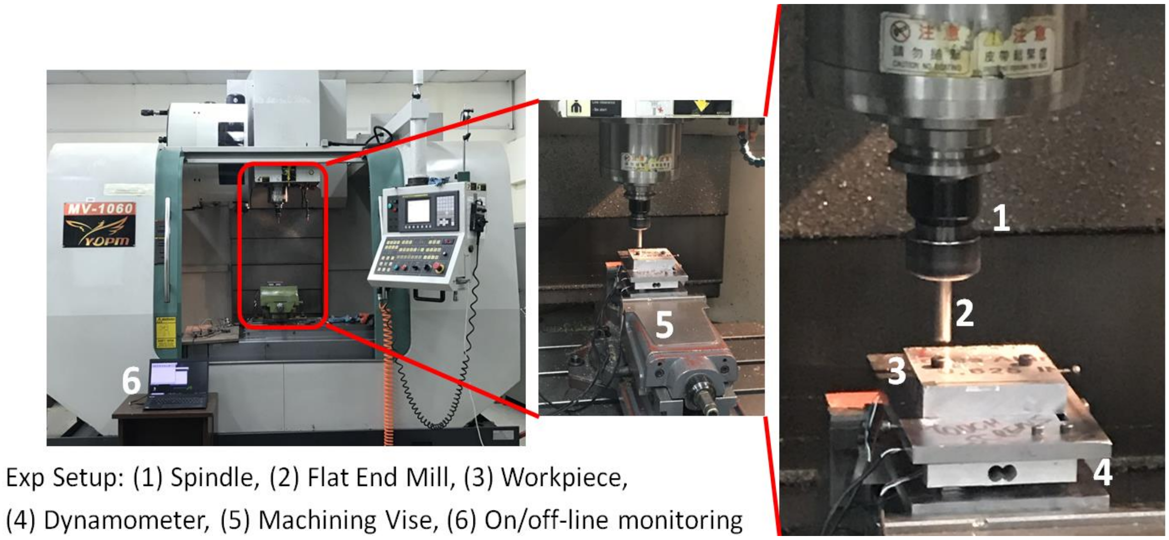


Figure 15 : Experimental Setup

4.4 Experimental Results

4.4.1 09 x Experiments were performed as already been performed and published in literature. Cutting forces observed during these experiments were noted. Following table shows the spindle speed, feed rate and observed forces in X and Y axis:

Table 5 : Experiments and Observed Forces

S.No	Spindle Speed (RPM)	Feed Rate (mm/min)	Fx avg (N)	Fy avg (N)
1.	1911	100	28.43	30.22
2.	1911	200	41.93	43.30
3.	1911	300	49.39	51.04
4.	3822	100	20.82	22.49

5.	3822	200	30.86	32.52
6.	3822	300	39.32	40.85
7.	5733	100	19.68	17.75
8.	5733	200	28.48	21.64
9.	5733	300	32.1	31.63

4.4.2 Results were ploted in MS Excel and compared to those already pubished. Forces observed during the above experiments were found to be in agreement to already published cutting forces on milling of 7075T6 on the given conditions [10]. Plots below shows the comparison between sensed forces on kistler as undertaken vide [10]:

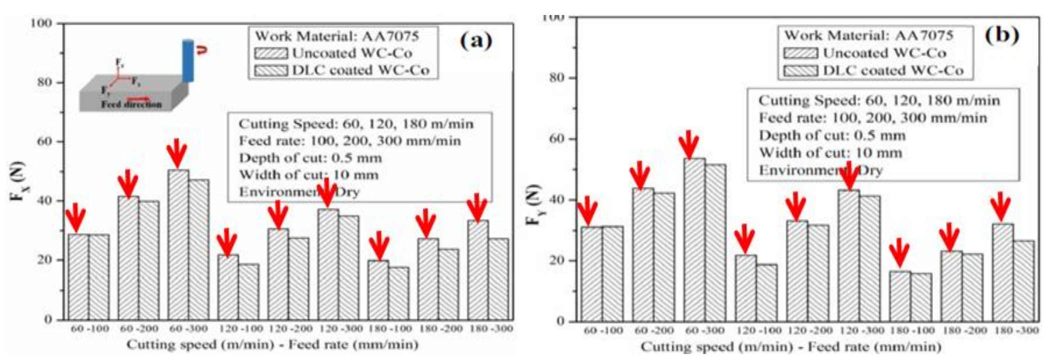


Figure 16 – Cutting Forces during Milling of 7075T6 [10]

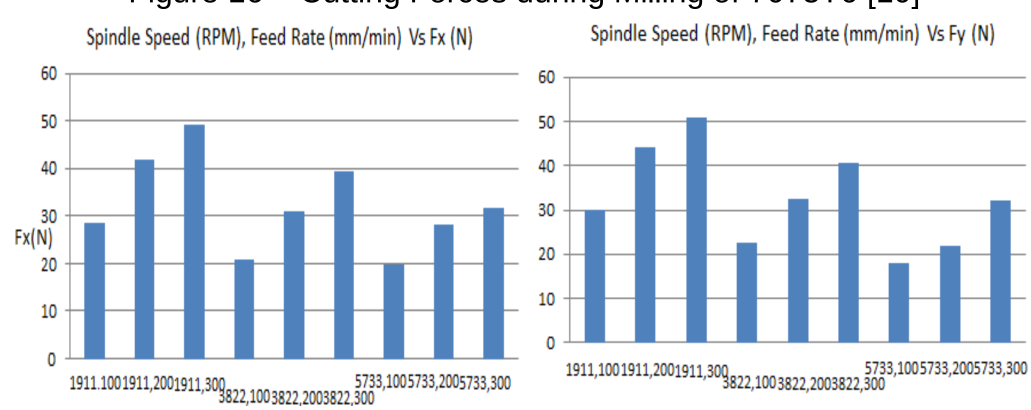


Figure 17 – Cutting Forces Observed on New Dynamometer during Milling of 7075T6

CHAPTER 6: CONCLUSION & RECOMMENDATIONS

6.1 Subsequent to design, development and testing of load cells based dynamometer, following is concluded:

a. Strain Gauge Based Load Cells can be used effectively for measuring cutting forces during Milling Machining

b. Interpretation of multiple load cells signals can be undertaken by an Arduino Mega2560 board.

c. Cutting forces can be monitored online through Serial Monitor/Plotter in IDE.

d. Cutting forces data can be captured using third party softwares (eg. Cool Term) for data archival and offline monitoring.

e. Concept followed by Design validated from experimentation and results are in agreement to that published in literature as per given conditions.

6.2 Based on the undertaken research following is recommended as future work:

a. Design may also be validated by replacement of load cells with piezo sensors

(1). Load Cells based on piezoelectric sensors may be used in place of strain gauge based load cells

b. Special vises with high strength to weight ratio may be designed for holding workpieces of different sizes and shapes

c. Printed Circuit Board (PCB) may be fabricated for circuitry of the dynamometer to reduce wiring requirements and eliminate loose connectors/ soldering.

REFERENCES

1. M. Luo, Z. Chong and D. Liu, "Cutting Forces Measurement for Milling Process by Using Working Tables with Integrated PVDF Thin-Film Sensors", *Sensors*, vol. 18, no. 11, p. 4031, 2018. Available: 10.3390/s18114031.
2. *Egr.msu.edu*, 2019. [Online]. Available: http://www.egr.msu.edu/~pkwon/me478/cuttingtool.pdf. [Accessed: 24- Dec- 2019].
3. M. Fujishima, K. Ohno, S. Nishikawa, K. Nishimura, M. Sakamoto and K. Kawai, "Study of sensing technologies for machine tools", *CIRP Journal of Manufacturing Science and Technology*, vol. 14, pp. 71-75, 2016. Available: 10.1016/j.cirpj.2016.05.005.
4. S. Mekid, "Design and Testing of a Micro-Dynamometer for Desktop Micro-Milling Machine", *Advanced Materials Research*, vol. 902, pp. 267-273, 2014. Available: 10.4028/www.scientific.net/amr.902.267.
5. S. Yaldız, F. Ünsaçar, H. Sağlam and H. Işık, "Design, development and testing of a four-component milling dynamometer for the measurement of cutting force and torque", *Mechanical Systems and Signal Processing*, vol. 21, no. 3, pp. 1499-1511, 2007. Available: 10.1016/j.ymssp.2006.06.005.
6. B. Pathri, A. Garg, D. Unune, H. Mali, S. Dhami and R. Nagar, "Design and Fabrication of a Strain Gauge Type 3-axis Milling Tool Dynamometer", *International Journal of Materials Forming and Machining Processes*, vol. 3, no. 2, pp. 1-15, 2016. Available: 10.4018/ijmfmp.2016070101.

7. Y. Li, Y. Zhao, J. Fei, Y. Zhao, X. Li and Y. Gao, "Development of a Tri-Axial Cutting Force Sensor for the Milling Process", *Sensors*, vol. 16, no. 3, p. 405, 2016. Available: 10.3390/s16030405.8.

8. F. Wu, Y. Li, B. Guo and P. Zhang, "The Design of Force Measuring Tool Holder System Based on Wireless Transmission", *IEEE Access*, vol. 6, pp. 38556-38566, 2018. Available: 10.1109/access.2018.2853735.

9. M. Milfelner, F. Cus and J. Balic, "An overview of data acquisition system for cutting force measuring and optimization in milling", *Journal of Materials Processing Technology*, vol. 164-165, pp. 1281-1288, 2005. Available: 10.1016/j.jmatprotec.2005.02.146.

10. I. Suresh Kannan and A. Ghosh, "Dry Machining of AA7075 by H-DLC Coated Carbide End Mill", *Procedia Materials Science*, vol. 5, pp. 2615-2621, 2014. Available: 10.1016/j.mspro.2014.07.522.

11. K. Murthy and I. Rajendran, "Design and development of strain gauge based milling tool dynamometer", *International Journal of Machining and Machinability of Materials*, vol. 7, no. 34, p. 304, 2010. Available: 10.1504/ijmmm.2010.033072.

12. S. V. Dhanal, "Finite element analysis of octagonal ring for a three component milling tool dynamometer", *IOSR Journal of Engineering*, vol. 3, no. 01, pp. 16-19, 2013. Available: 10.9790/3021-03141619.

13. H. SAGLAM, "Optimization in design, construction and testing of a milling dynamometer", *Materials & Design*, 2004. Available: 10.1016/j.matdes.2004.10.007.

14. İ. Korkut, "A dynamometer design and its construction for milling operation", *Materials & Design*, vol. 24, no. 8, pp. 631-637, 2003. Available: 10.1016/s0261-3069(03)00122-5.

15. G. Qu, M. Qian, J. Zhang and Q. Xing, "Investigation on Unitary Piezoelectric Four-Component Cutting Dynamometer", *Materials*

Science Forum, vol. 626-627, pp. 93-98, 2009. Available: 10.4028/www.scientific.net/msf.626-627.93.

Operational Code

```
#include "HX711.h"
#define calibration_factor (-2000.0)
#define n_Sensor 3

#define CLK  A1
#define DOUT0  A3
#define DOUT1  A5
#define DOUT2  A7


HX711 scale0(DOUT0, CLK); //Fx
HX711 scale1(DOUT1, CLK); //Fy
HX711 scale2(DOUT2, CLK); //Fz


HX711 scale[n_Sensor];

float raw_data[n_Sensor],  prev[n_Sensor];
int initialize = 0;
//unsigned long t_cur,   t_prev,   t_loop;

void setup() {
  Serial.begin(9600);
  Serial.println("Micro Forces During Micro Milling");

  scale[0] = scale0;
  scale[1] = scale1;
  scale[2] = scale2;


  for (int i = 0; i < n_Sensor; i++)
    scale[i].set_scale(calibration_factor);
}

void loop() {

 /* t_prev = t_cur;
  t_cur = millis();
  t_loop = t_cur - t_prev;

 */
```

```
 Serial.print("Fx,y,z:     ");
 if (initialize == 0)
  {
    for (int i = 0; i < n_Sensor; i++)
    {
      raw_data[i] = scale[i].get_units();
      prev[i] = raw_data[i];
      Serial.print(raw_data[i], 0);

      Serial.print("     ");

    }
    initialize = 1;
  }
  else
  {
    for (int i = 0; i < n_Sensor; i++)
    {
      raw_data[i] = scale[i].get_units();


     Serial.print(raw_data[i], 3);
      Serial.print("     ");
    }
  }
  Serial.println();
if(Serial.available())
  {
    char temp = Serial.read();
    if(temp == 't' || temp == 'T')
      scale0.tare();  //Reset the scale to zero
      scale1.tare();
      scale2.tare();
  }
}
```

Appendix B

Calibration Code

```
#include "HX711.h"
#define DOUT  A7
#define CLK  A1
HX711 scale(DOUT, CLK);
float calibration_factor = -2145; //
void setup() {
  Serial.begin(9600);
  Serial.println("HX711 calibration sketch");
  Serial.println("Remove all weight from scale");
  Serial.println("After readings begin, place known weight/force on scale");
  Serial.println("Press + or a to increase calibration factor");
  Serial.println("Press - or z to decrease calibration factor");
  scale.set_scale();
  scale.tare();  //Reset the scale to 0
  long zero_factor = scale.read_average(); //Get a baseline reading
  Serial.print("Zero factor: ");
  Serial.println(zero_factor);
}
void loop() {
  scale.set_scale(calibration_factor); //Adjust to this calibration factor
  Serial.print("Reading: ");
  Serial.print(scale.get_units(), 3);
  Serial.print(" calibration_factor: ");
  Serial.print(calibration_factor);
  Serial.println();
pai  if(Serial.available())
  {
    char temp = Serial.read();
    if(temp == '+' || temp == 'a')
      calibration_factor += 10;
    else if(temp == '-' || temp == 'z')
      calibration_factor -= 10;
  }
}
```