DEVELOPMENT OF DATA ACQUISITION SYSTEM AND CALIBRATION PROTOCOL FOR TIRE CORNERING FORCE AND MOMENT TESTING MACHINE

by

Amol Dwivedi

A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Mechanical Engineering

Charlotte

2018

Approved by:

____

Dr. P.Tkacik

____

Dr. Jerre Hill

____

Dr. R.Keanini

ABSTRACT

AMOL DWIVEDI. Development of Data Acquisition System and Calibration Protocol for Tire Cornering Force and Moment Testing Machine. (Under the direction of DR. P.TKACIK)

Tires provide the only point of contact between the car and the road. The safety of the driver, passenger depends on the contact patch between the tire and the road, a mere $8\frac{1}{2}$"x10" size of rubber is in contact with the road which lets us control the movement of the car on road. Now that we've understood the importance of the tire and contact patch, it is a necessity to determine the forces and moments generated on these tires at a different spectrum of speeds. This type of test data helps the tire manufacturers and vehicle manufacturers to decide which tires to select depending on the purpose of the car. For example:- A hatchback car, with a capacity of carrying five passengers is not supposed to go hard on corners, neither the tires on the car are supposed to give a high cornering stiffness, accordingly a tire which generates vast amounts of lateral force at low slip angles is not the best fit for the example car. The question now arises that how do we determine the magnitude of the forces which are generated in the tires (about the three axes and corresponding moments). The obvious answer to that question is, tire force and moment machine, there are basically two types of Tire Force and Moment testing machines available in the market namely:- Flat track machine and road wheel machines. The difference between the two type of machine are apparent from their names, flat track machine uses a flat belt to simulate road conditions and road wheel machine employs a huge road-wheel covered by safety walk for the same purpose. However, the two machines have shortcomings of their own, a flat track machine usually is accompanied by the problem of belt floating thereby affecting the data acquired, whereas the road wheel machine is suspected for not properly, creating a road because of curvature of the road wheel. At UNCC motorsports facility we've been working on the development of data

acquisition system for the calibration of the load cell of the machine present inside the hub. This was a specially challenging task because the load cells cannot be taken out from the hub also the number and locations of the load cell were unknown due to the absence of proper documentation. This restriction forced us to manufacture a calibration fixture which allowed us to apply know load on the hub and then uses it for calibration of load cell present inside the hub. A part of the calibration fixture was to attach a reference load cell which had to be calibrated to yield out readings in pounds as well.

ACKNOWLEDGEMENTS

I would like to thank my faculty advisor Dr.P.Tkacik under whose guidance and support, I was able to finish such a challenging and industry-level project. I appreciate my committee members, Dr. J.Hill, Dr. R.Keanini for their valuable time which they spent in going through my work and guidance for this research. I would also thank my research group partner, Dhiraj Muthyala who helped me many times during the data acquisition process also for the calibration fixture which he manufactured which was the basis of my research. I would also like to thank my fellow colleagues in graduate school: Shashank Ghodke, Nikhil Madhusdhana, Amol Sathe, Aditya Kanchibotla, Shreyas Joshi for giving their support during tough times. I would like to extend my thanks to all faculty and staff members of the Department of Mechanical Engineering and Faculty of Graduate Studies. At last, I would like to thank all the graduate students working at UNC Charlotte motorsports facilities without whom it would have been very difficult to work on my research project.

DEDICATION

To my parents Mr. Malay Dwivedi and Mrs. Sudha Dwivedi

My Sister Mrs. Anuradha Bajpai

&

Waheguru

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Tire testing is a complex task in many aspects. The tire data obtained from the tire testing machine is not only important from the sales perspective of the tire manufacturer but also for the tire consumer, they may be: a regular person looking for a new tire to replace the old one, race team or an auto manufacturer[1]. The data obtained from the tire testing machine is very complex and needs to be as precise as possible. The consequences of imprecise tire data can result in severe results, both cost-wise and safety-wise. For instance, consider a situation where, a Auto-Manufacturer asks for a tire category that generates 1000 pounds of lateral force at mere a degree of slip angle for their sports category sedan, considering the tire force and moment testing machine is not properly calibrated to give out accurate forces, then even percent of error in the force calculations would result in an error would lead to a change of 10 pounds at about 1000 pounds of load[2]. For auto-manufacturer participating in a particular race series, this sort of error can be disastrous. The reason being all the suspension calculations (related to suspension geometry, springs stiffness, alignment properties) is dependent on the tire data[3]. Consider, this case, the suspension setup of a race car would've been designed more aggressive considering the lateral force generation of tire (as per the tire data) and it is safe to assume that race cars are designed to push their limits, which means an inaccuracy of about a percents at 1000 pounds of load can result in the race car losing traction on road! This short case-study suggests that even though we are not dealing with precision manufacturing but it is of utmost importance to consider the various factors which can incorporate inaccuracies in the data acquisition system which is used to calibrate the load cells inside the hub[4]. There are three load cells inside the hub, which cannot be taken out from the hub for calibration purpose. Also, the data sheet and further details about the load cells present inside the hub were missing. Accordingly, the calibration of the load cells inside the hub namely: D51, D52 and E5 had to be calibrated very carefully meaning when the load cells are connected to the data acquisition device (SCXI-1600), the LabVIEW program dealing with the electrical details of the load cell had to be entered by lots of considerations i.e. calculations and advice from experts on forums and university who have previously worked on load cells[5]. For example: There were few values to be considered if the load cells are to be measured in LabVIEW as a strain gauge like: Gage Factor, Voltage Excitation, Initial Voltage. Now, if the voltage excitation value in the program was entered to be 10 volts and in reality, the load cell circuit is built for excitation of 5 volts then, in that case, the load cell is damaged and is not useful anymore[6].This situation can be harmful as the hub of the tire testing machine contains load cells which cannot be removed or changed and any damage to the load cells would've made the calibration of the hub impossible[7]. Apart from the technical details which had to be considered while calibrating the hub load cells another roadblock in the calibration was of the phenomenon known as, Load Cell Interactions, which means that when load is applied in one direction then unexpected measurements are seen in the load cells, ideally in which no deflections should have occurred[8]. But the challenges posed by the location of the load cells inside the hub didn't simply allow us to use dead-weights on the load cell and then create a scale for load vs strain[9]. These complexities involved forced to manufacture an Instronesque fixture which would mount on the carriage and can be used for pulling on one end through the use of airbags. The fixture allows us to connect the airbag to the calibration fixture which is mounted on the hub using lug nuts, this value will be used for data manipulation and figuring out if there exist load cell interaction.[10].Once, the fixture was manufactured, the details related to the data acquisition system still needed to be ironed out. For instance, there are many types of load cell available in the market and which one should be used for data acquisition system of the calibration fixture was one the things to be thought about[11]. A strain gauge load cell, pancake type load cell was used owing to the factors like cost, packaging, durability, robustness.

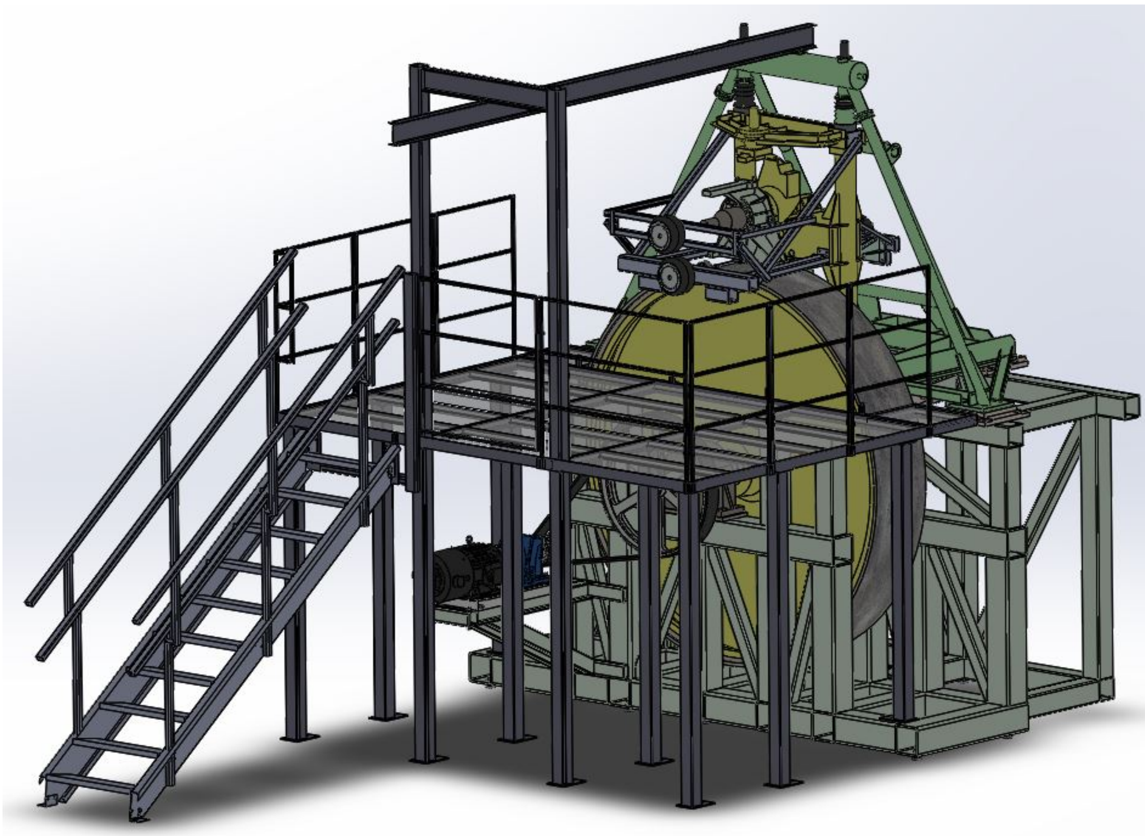

Figure 1.1: M15:Tire Force and Moment Testing Machine.

CHAPTER 2: DATA ACQUISITION SYSTEM SETUP

The very first step in making a data acquisition system for the calibration of M15 was to employ a load cell which translates the pull force applied by the airbag on one end of the fixture to the fixture mounted on the hub into pound-force. In order to do that a load cell had to be selected considering various factors like cost, durability, ease of use, ruggedness, packaging etc. There are a variety of load cells available in the market, depending on the principle of working load cells can be classified into hydraulic load cells, pneumatic load cells, Kistler load cells, strain gauge load cells. The Strain gauge load cell was selected for the use as a reference load cell, the reason being that strain gauge load cells are the most common form of load cells available which makes them cheapest possible option. Also the ease of use of strain gauge load cells was one of the factors why strain gauge was preferred over the other load cells. However, it can be argued that on what parameters were the strain gauges were considered to be easy to use load cells, the answer to that argument comes from the reason that these load cells work on the principle of detecting small change in resistance (as a function of strain) which was done by employing wheat stone bridge equations to calculate the amount of strain produced. Also, the equations so involved in calculations in strain gauge load cells made it easy to perform some hand calculations to check if something was going wrong. As for the reference load cell, further details can be specified, the load cell is a pancake and shear web, type load cell owing the name because of its' physical shape and shear web employed in the body to prevent any other forces from interacting with the strain gauge other than the axial loads, the shear web used in the load cell is made of alloy steel or stainless steel in order to make it durable to the environment and resistant to corrosion. Usually the strain gauge load cells are either tension or compression load cells, meanings the load cells are only supposed to measure strain in compression or in tension. But for the purpose of using it in a calibration fixture, the load cell so chosen was a tension-compression load cell meaning it was good enough to measure strain values in either direction.

Figure 2.1: Reference Load Cell.

The next step was to calibrate the reference load cell (strain gauge). The primary reason for doing so is because when the load cells are added on the LabVIEW program for data acquisition purpose, it doesn't show up the results in terms of force but rather it gives the results in strain or voltage. The results so obtained from the LabVIEW program have to be scaled to give us results in pound force. In order to do that certain dead weights were used to calibrate the load cell, the dead weights were in packages of (10lbs, 20lbs, 40lbs, 5lbs). Using the LabVIEW program, a sample rate of 100 samples and frequency of 1000 samples per second were set. Then strain values of the load cell were acquired from the LabVIEW program corresponding to zero loads, so there were 100 data points of strain at zero load then average of those 100 data

Figure 2.2: Dead Weights used for calibrating reference load cell.

points were taken and then this process was repeated 10 times for the same load (zero loads for this case) and average of those 10 averages was taken to improve accuracy of the calibrated scale. The accuracy is so important over here in the calibration of the reference load cell because all the measurements and data manipulation has to be done on the basis of the data acquired from this load cell and hence this load cell is needed to be super accurate. The same steps were repeated for the other dead weights of 10lbs, 20lbs, and 40lbs and then a scale was calculated from the graph of strain vs load.

The error or the difference of values between the one calculated from the reference load cell and the Instron load cell is shown in the above figure. However, these error values are due to the fact that the load cell in the Instron machine isn't linear in itself. Now, In order to check if the reference load cell is correct or not, we've used different scales and dead weights to check if the load cell yielded out proper values or not and fortunately, load cell gave out correct readings.

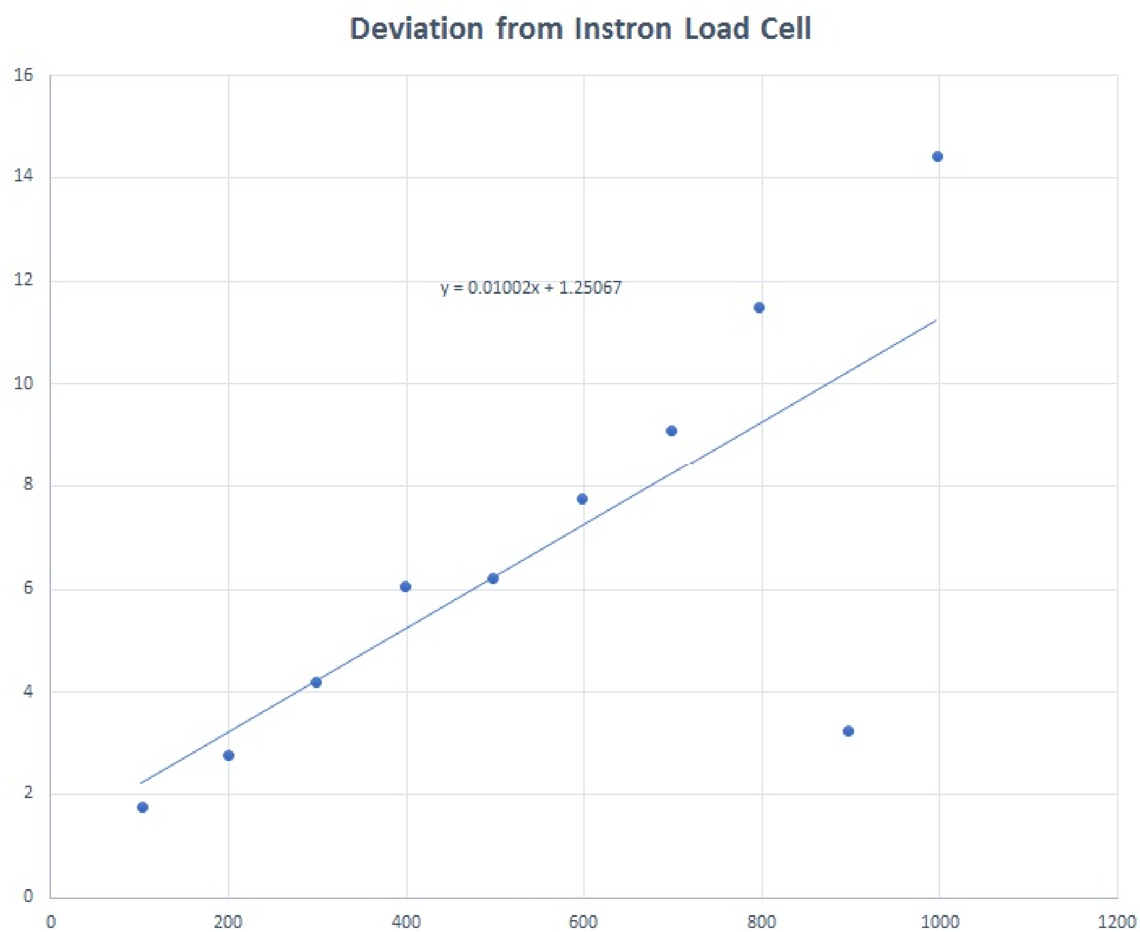

Figure 2.3: Deviation of Reference Load Cell scale from the Instron Scale owing to non-linear behavior of Instron Scale.

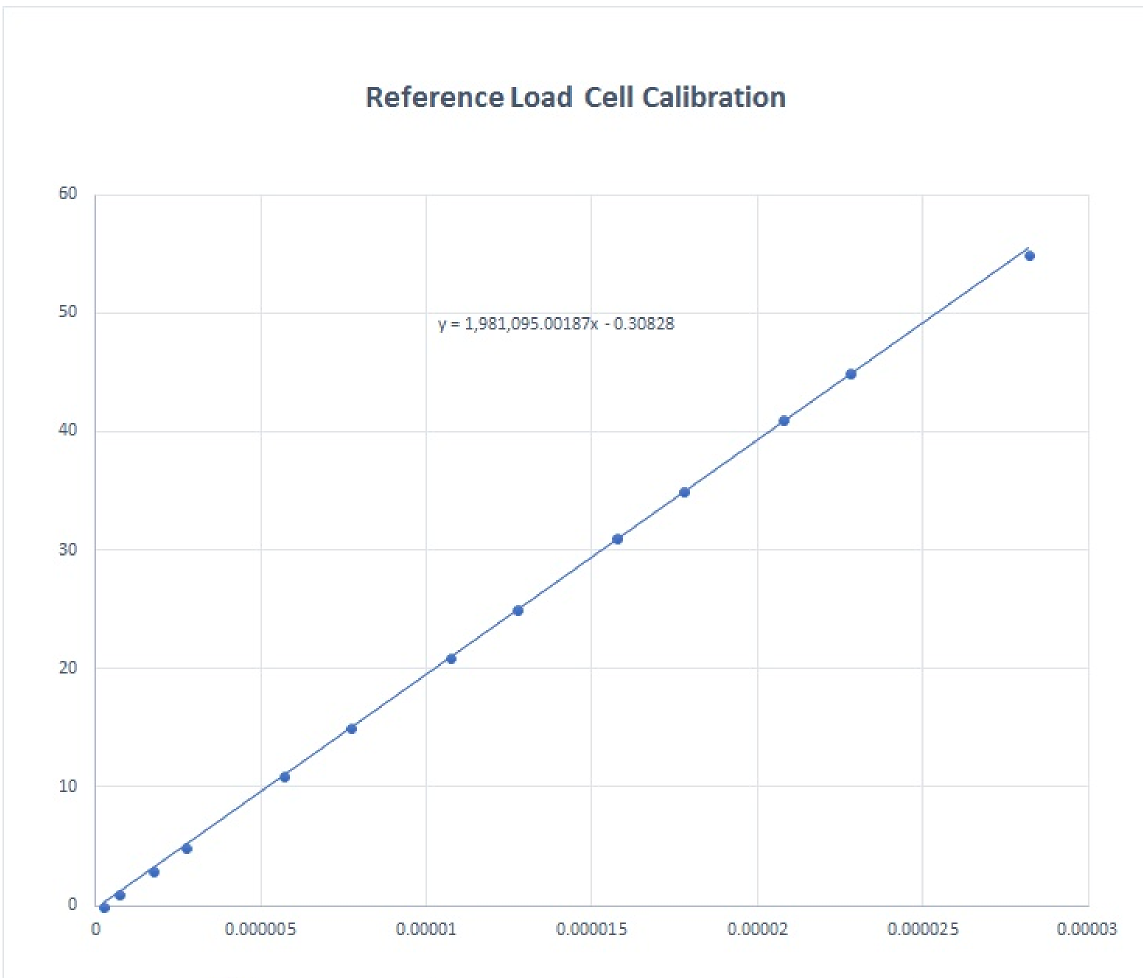

Figure 2.4: Reference Load Cell Calibration:Strain vs Pounds.

From the above graph it can be correlated that:-

$$Pounds = 1981095.00187 * Strain - 0.30828 \tag{2.1}$$

2.1 Working Principle

In mechanical testing and measurement, it is required to understand how the material or object reacts to various forces. The amount of deformation the material experiences due to an applied force is called strain. The Strain is defined as the change in dimension over the original dimension. In this case, the strain is positive in tension and negative in compression. When a material is compressed in one direction, the tendency to expand in the other two directions perpendicular to this force is known as the Poisson effect. Poissonś ratio (v), is the measure of this effect and is defined as the negative ratio of strain in the transverse direction to the strain in the axial direction[12] .

Now that we've discussed that what is the strain and it's sign conventions it is now important to understand how can the strain be measured. One of the most commonly used strain gage types are metallic bonded strain gages. The metallic bonded strain gages consist of a metallic wire wounded around in a grid pattern. The reason why the metallic wire is wounded in a grid pattern is that it subjects more amount of wire to the parallel direction of the strain applied. Accordingly, the strain experienced by the test specimen is transferred directly to the strain gage[13].
One of the basic parameters of a strain gage load cell is its sensitivity to strain, also commonly known as gage factor(GF). Gage factor can be defined ratio of fractional change in resistance to fraction change in strain.

$$GF = (\Delta R/R)/(\Delta L/L) \tag{2.2}$$

Gage factor for the majority of strain gage load cell is around 2. In reality, the strain measured values are of the order of milli-strains. Best possible way to accurately measure strain is to measure the change in resistance, accordingly with a gage factor of 2 and change in strain of about 1e-3 contributes for only 0.1 % change in resistance. In order to measure such a small change in resistance, a Wheatstone bridge is employed. The Wheatstone bridge consists of two parallel voltage divider circuits, where R_1 and R_2 comprise of one voltage divider circuit and R_3, R_4 of the other circuit. The output of a Wheatstone bridge, V_o, is measured in between the two nodes of voltage dividers.

$$V_o = [(R_3/(R_3 + R_4)) - (R_2/(R_1 + R_2)] * V_e x \tag{2.3}$$

By observing the above equation closely it can be said that if R_1 $/R_2$ = R_3/R_4 , the voltage output is zero and any change in any of the resistances will create an unbalance between the arms and a resulting output voltage V_o will be produced. Therefore, we'll use this phenomenon to our advantage the strain gage will be placed in the Wheatstone bridge circuit in place of resistance R_4 and consequent changes in strain of the strain gage will result in a measurable output voltage V_o.However, the method just suggested is only one of the types of configurations which can be set up in LabVIEW.

There are three types of configurations which can be used to configure the load cell connected with the SCXI 1600 data acquisition chassis: [14]

- Quarter Bridge Configuration
- Half Bridge Configuration
- Full Bridge Configuration

For our purpose we will be using full bridge strain gage type 3 configuration is employed for the following reasons:

- Measures axial strain.

- Two strain gages measure the Poissonś effect in compression(-ve).

- Two strain gages measure the tensile strain.

To summarize, the full bridge type 3 configuration allows us to have more accurate readings as it compensates for Poissonś effect and having two other strain gages taking the measurements instead of one, thereby neglecting the effect of temperature[15].

2.2 Apparatus Required

In order to acquire the data from the strain gage load cells, there are some necessary requirements:

- Strain gage load cell.

- Data acquisition chassis.

- Module compatible to acquire data from strain gage load cell.

- LabVIEW data acquisition program.

Following items were used for the purpose of this project:

- A strain gage load cell was ordered from load cell central with following properties, 2000lbs load capacity in either direction, tension-compression load cell, the internal resistance of 350 Ω and an excitation voltage of 10 volts. This load cell was used as a reference load cell.

- National Instruments SCXI 1600 chassis, the specifications of SCXI makes it an overkill for the project and the reason it was employed as it was available in our facilities and was not being used so for the purpose of cost cutting it was used.

- Module 1520 was used for acquiring data from the strain gage load cell, an SCXI-1314 front terminal mount block to use module 1520. Module 1520 has 8

Figure 2.5: Data Acquisition SCXI 1600 Chassis.

analog channels, which means that 8 load cells can be connected and data can be acquired from each of those load cells simultaneously.[16].

2.2.1 LabVIEW Custom Program Development

LabVIEW is a graphical designing environment developed by National Instruments[17]. The reason for opting for LabVIEW for data acquisition of M15 was, firstly, all the physical instruments used were from National Instruments, the chassis SCXI 1600, the module 1520 and secondly, the platform LabVIEW itself is known for its ease for data acquisition.

One thing to be understood over here is that as the development of the program started the main focus of the program has shifted from one aim to another rather more precise and accurate way of saying that is focus has grown narrower and narrower[18]. During the initial stages of program development, our main aim was to only display the measurements in the load cells inside the hub, in order to check the location of the different load cells inside the hub. This was done by simply applying loads on the hub by hand and seeking for the change and the type of change in the load cells,

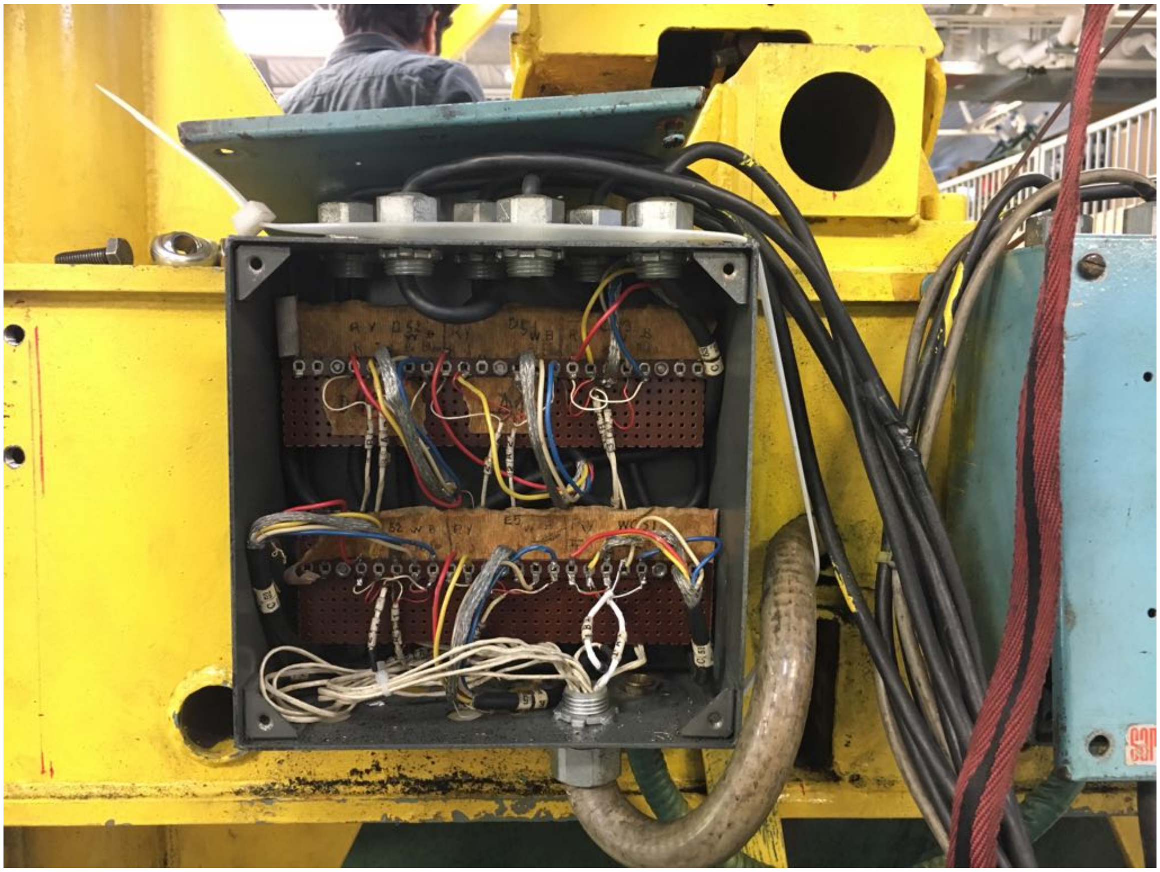

Figure 2.6: An S2 box which is connected to all the wire from the load cell inside the hub.

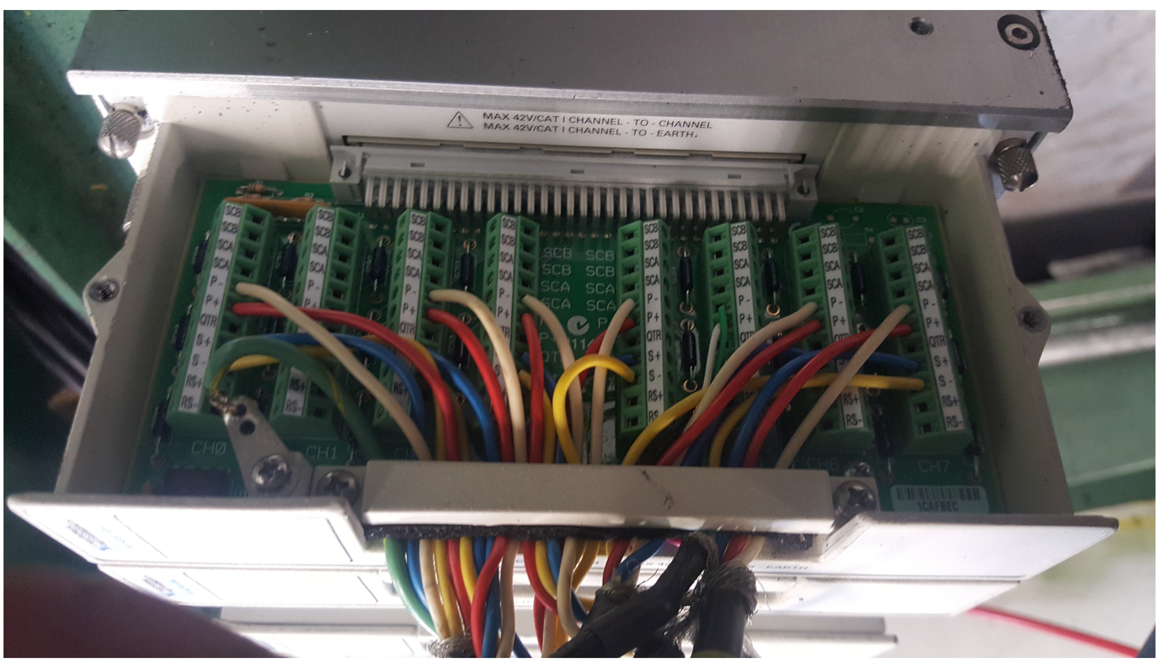

Figure 2.7: Module 1520 with 8 channels with 7 load cells from the hub connected.

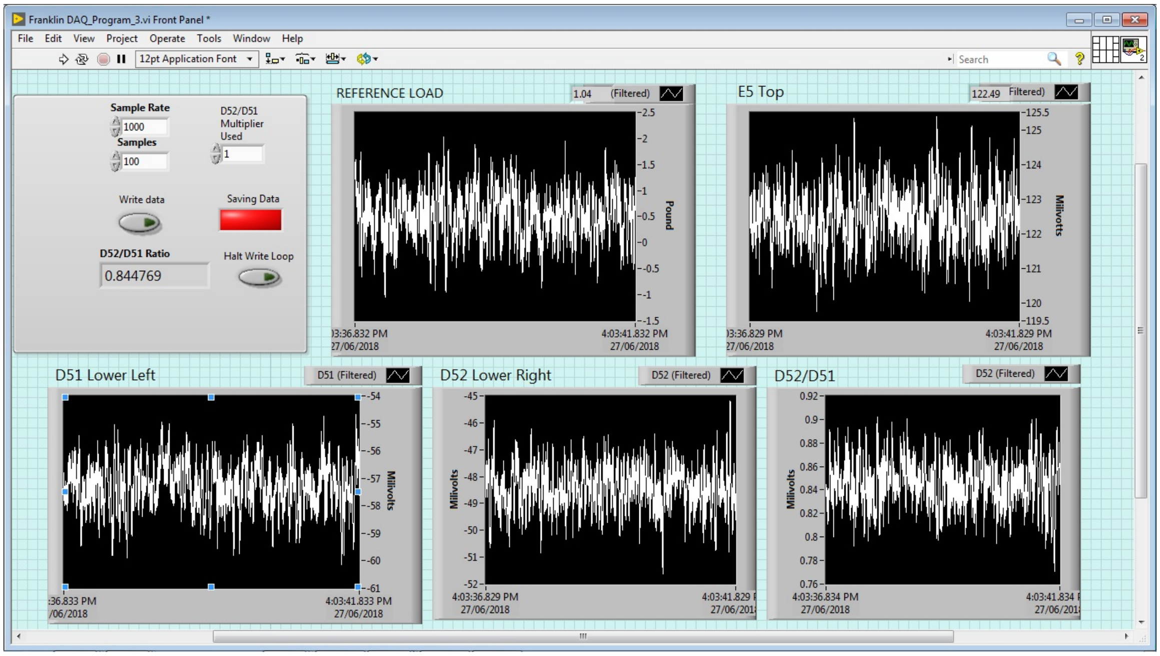

Figure 2.8: Front Panel of Custom LabVIEW program.

when only one type of load is applied, for example: when the hub is pushed towards left -hand side, then, in that case, two load cells should be in compression and two load cells should be in tension and the load cells on the top should have minimal readings. This was a logical explanation, as per our understanding of the locations of the load cells inside the hub and the deflection characteristics of the load cells,i.e. the load cells show positive deflection in compression and -ve deflection on tension, this characteristic of the load cell can be changed if the signal wires of the load cells connected to the module are interchanged, in that case, the load cell will read +ve in tension and -ve in compression[19].

Also, it is important to understand the components of a LabVIEW program. A simple LabVIEW program is called a VI acronym for virtual instrument and which itself has two sub-components:- front panel and block diagram. The front panel is the actual face of the program with which the operator of the machine will be interacting and the components on the front panel work according to the connections made with various components in the block diagram. Now, coming back to the first step, which dealt with just displaying the deflections in all of the six load cells connected to the data acquisition system[20]. For this purpose, the data acquisition assistant or commonly known as 'DAQ assistant' option was selected from the 'express' menu, of the type 'input', however, the next then was to configure the data acquisition assistant to read values from proper channels and label them accordingly. This was done by adding a channel by clicking on the '+' sign located on the data acquisition assistant and then choosing the proper channel type depending on our requirement, for example:- if 'strain' type measurements were to be chosen, then in that case the respective values have to be entered so as to properly configure the load cell and also to make the chassis compatible with the load cell. For instance, to configure the strain type measurements, the values to be entered are: Max. input range, Min. input range(which are dependent on the capability of the chassis to read the maximum or minimum amount of strain measurements from the load cell, the basic idea behind this input value is that in case of small deflection the widest range of measurements might not be good enough to see the small deflections and hence we can narrow the signal input range),gage factor(which the ratio of change in resistance to change in strain values of the load cell which differs depending on material of the load cell from which it is manufactured,gage resistance, is the value of resistance of the strain gage load cell at zero strain value, poissonś ratio is a material property and Vex voltage is basically the excitation voltage given to the load cell externally(from the chassis SCXI-1600) which 10 volts for reference load cells and the load cells inside the hub. Now, that the data acquisition assistant is configured to read the values of the load cells, another module was needed to display the values acquired from the data assistant module. For this purpose, a module called Waveform graph is incorporated, this module automatically displays the values acquired from the data acquisition assist module against time[21].

The aforementioned steps were enough for simply displaying the values acquired

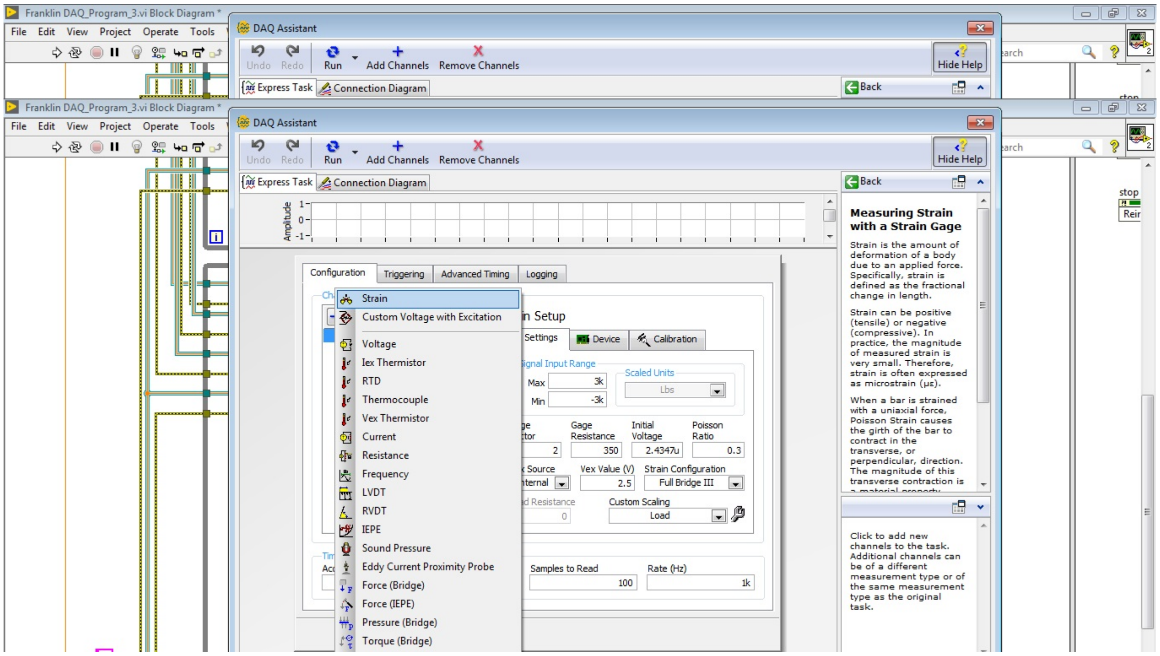

Figure 2.9: DAQ Assist channel selection.

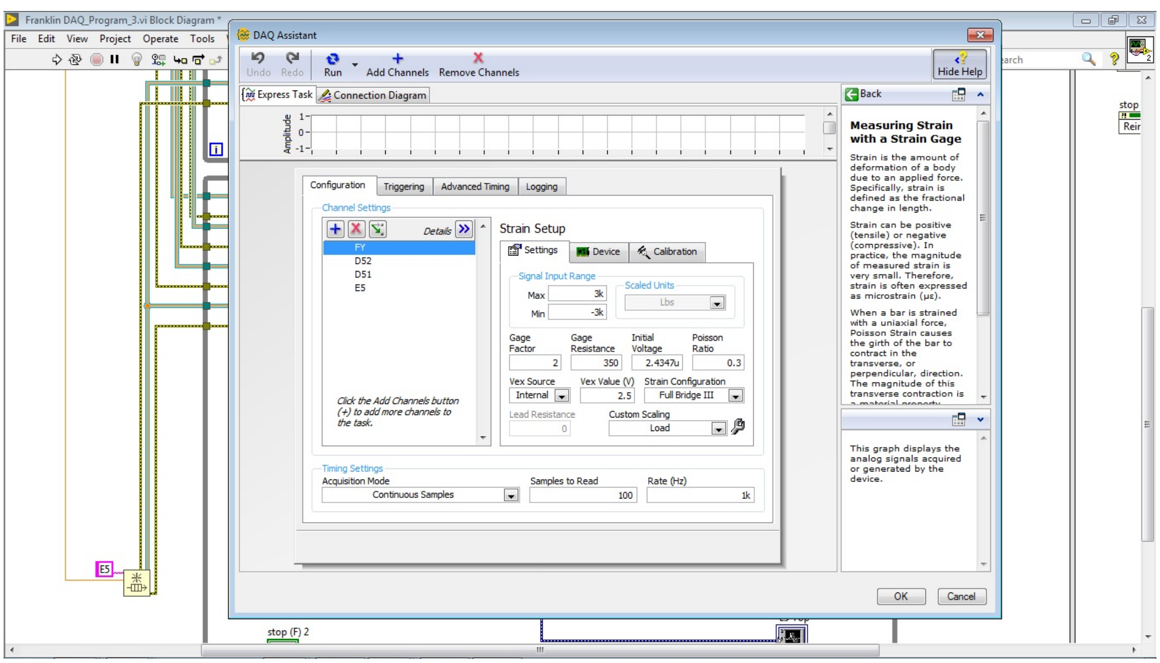

Figure 2.10: DAQ Assistant configure window.

from the load cells which was our initial aim to figure out the locations of the load cells. However, once the locations of the load cells were established, our next step was to acquire the data from the load cells when the load is applied using the fixture and the frame and air pressure to ramp up the load. In order, to do this not only acquiring data was important but also it is required to write the data into a file such that the file so obtained after an experiment can be post-processed in excel or MATLAB to generate results. Initially, for this purpose, a module was needed which can automatically write the data acquired into an excel file and this purpose was satisfied by using, Write to measurement file module. However, the write to measurement file also needs to be configured. To configure any, write to measurement file, the very first thing required is to set up an output path for the file so generated, which can be any path depending on the user and computer used. The next option to be chosen is, Save to one file, what this option does is that it saves all the data coming from one experiment only to one file, not multiple files, however, when required this option can also be chosen in the moment of need. The next option to be configured is 'If the file already exists', this option allows us to choose an action if the file of the filename mentioned already exists. The options available in this case are:- Rename existing file, Use next available filename, Append to file and Overwrite the file, since for this purpose the main aim was to create different files for each experiment, the first file was named by adding a number at the end of the filename allows the program to create iterations of new files with different filenames without any additional request from the operator.

Till this point, everything is set and we've got our program set up for data acquisition and generation of files from the LabVIEW code. However, initially, when the program was used for data acquisition purpose, the program used to crash and experiment data could not be written into a file. Therefore, a coding strategy needed to be employed in the LabVIEW program known as, Producer-Consumer loop, in this

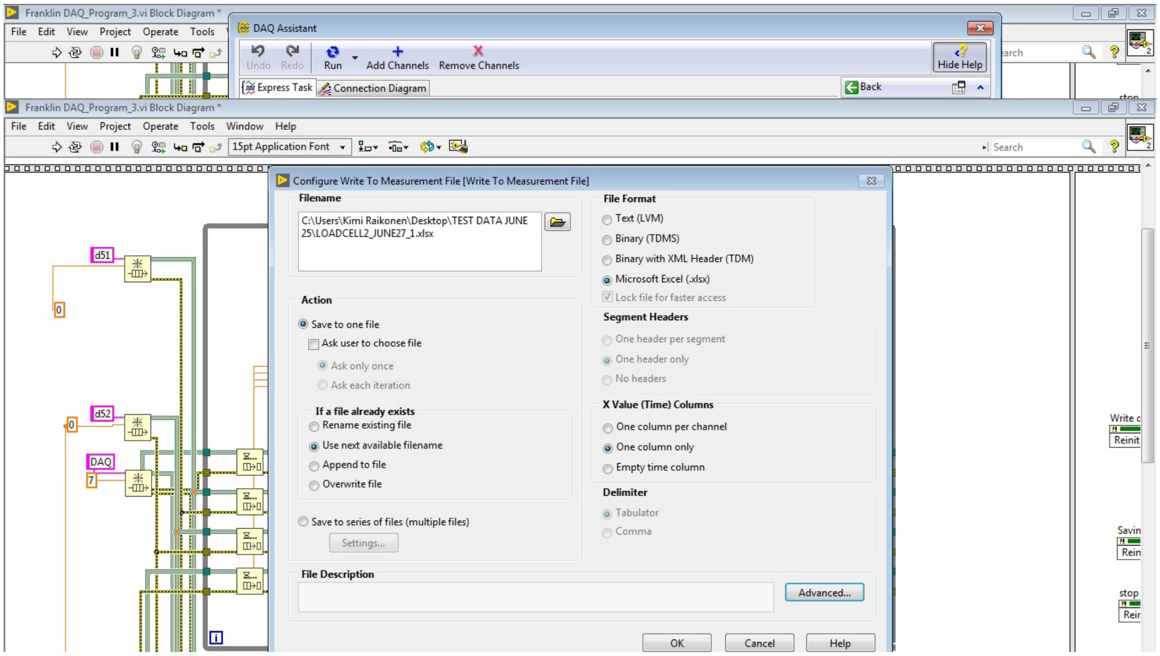

Figure 2.11: Write to measurement file configure window.

case, this strategy basically queues up the data acquired from the data assistant in the computer memory and then using a queue method it slowly gives out the data to the, Write to measurement file, module and thus by this method it saves the memory of the computer and prevents it from crashing. Therefore, a producer-consumer strategy was employed in our LabVIEW code[22].

2.3 Calibrating Reference Load Cell using Data Acquisition System

For the purpose of this project, the device used was National Instruments SCXI 1600 chassis, the configuration of SCXI 1600 makes it an overkill for the project but it used because it was available in the lab and was not being used and in order to cut down the costs involved in the project SCXI 1600 was used. To acquire the data 1520 module for strain gage type load cell data acquisition. The next requirement in the data acquisition process was to develop a LabVIEW program using which the live plots of the data can be seen and later on changes were made in the program to create an excel file containing all the data from the experiment performed. Although the scale devised from the graph of strain vs load looked to be accurate enough and other weights were also used for testing the scale and it yielded out perfect results. However, this wasn't the most efficient way of devising the scale for the load cell. The main reason for that argument was that the full-scale load-bearing capacity for the strain gauge load cell is of 2000 lbs and the scale was calculated using only dead weights measuring up to 55lbs, which was basically too small of weight in comparison to the full-scale load capacity of the load cell. This forced us to calibrate the load cell to even higher loads and in order to do that Instron was used to apply loads. However, it isn't best of the practices to apply loads till full-scale load capacity of the load cell as it may damage the load cell. After careful considerations, it was decided that the load cell will be calibrated to 50% of its full-scale capacity i.e. 1000 lbs. In order to do that 1000 lbs of load was applied through Instron machine in the materials lab and the load scales of the reference load cell was compared with the scale of Instron machine. On comparing the data it was found out that at 1000lbs of load there was an error of about 14.43 lbs in the reference load cell, however, it was later found out that the Instron load cell wasn't accurate. On plotting, the data in excel it was found that the extension vs load graph of Instron wasn't linear rather it was somewhat curved and was a reason there was a difference of 14 lbs at maximum load. This short experiment confirmed that the reference load cell scale which was devised earlier was accurate enough.

The most evident solution to the scale calibration problem of the load cell was to calibrate the load cell to load capacity of 1000lbs. An effective and less time-consuming way of scale calibration was to check if the current scale calibrated for pound force was accurate or not and then moving on to calibration of the full-scale load, this was done because the load cell was new and was supposed to be linear and it should adhere to the scale which was devised using dead weights. So, the reference load cell was mounted on the Instron and it was loaded to 1000 lbs load and the values of pound force on the reference load cell matched at most points with the load values in the Instron machine. However, some points on the scale weren't matching with values on the Instron because of the reason that loads applied by the Instron weren't linear and followed a polynomial curve.

Later on, it was found that the load cell had included a calibration sheet which was given by the manufacturers themselves, however, the calibration sheet so attached with the load cell wasn't meant for the strain measurement setup but rather it was for voltage measurement.

Here are the data sheet specifications of the load cell:

Rated Capacity : 2000 lbs

Rated Output : 2.0215 mV/V (Tension) / 2.0432 mV/v (Compression)

Rated excitation voltage : 10 volts

Now, from the equations shown above, it is hard to come to some logic. The basic idea behind these equations is that on a Wheatstone bridge when an excitation voltage is applied it yields out a signal voltage of 2.0215 mV/V. Now the question arises that output voltage of 2.0215 voltage at what load? and how does the voltage change.

Looking at the datasheet of the load cell it specifies that the current rating for the load cell is 10 volts which implies that when 10 volts of current is applied to the circuit it will give an output of 20.215 mV in tension at full load i.e. 2000 lbs and accordingly for compression data point there will be an output excitation of 20.432 mV at a full load of -2000 lbs. Now, these, data points of tension and compression will be used to plot a graph of millivolts vs load and consequently, a load scale will be devised.

Now, the scale for millivolts to pound-force conversion as calculated from the load cell data sheet was linear and was given as:

$$y = 98.40825x + 10.67729 \tag{2.4}$$

where y, refers to the load in pounds and x, refers to millivolts.

Now, from observation, it could be seen that the two scales (i.e. the scale from strain vs load and the scale from millivolts vs load) are perfectly linear. However, there was no such way to quantify that the two load cells would conform with each other. In order to figure out that if the two scales are similar, a possible solution was to use same dead weights on the load cells and then measure the readings given by the load cell in the LabVIEW program through both strain calibration settings and millivolts calibration settings. On performing this simple experiment it was confirmed that both the scales were correct and yielded out similar results, therefore either of those two scales could've been used for calibration purpose. For this purpose, the strain calibration scale was used as it was calibrated using fifteen data points rather than two as in the case of millivolt calculation and hence can be considered to be more accurate.

CHAPTER 3: CALIBRATING LOAD CELLS INSIDE THE HUB

The hub of the M15 is the main part on which the test tire is mounted and then tested. Accordingly, there are a total of six load cells mounted inside the hub in three different positions, making that two load cells on each position[23]. However, the reason for the mounting of two load cells was to have a backup load cell in case one load cell gets damaged the other load cell inside the hub can be used. The six load cells are named as:- E5, D51,D52,C51,C52,D53.

Now the very first step in calibrating the load cells inside the hub was to first determine the location of the load cells inside the hub. From the drawings of the machine, it was figured out that the three load cells are mounted on a circle with PCD of 200 mm and 150deg and 30 deg offsets. In order to determine the location of the load cells wires from all the load cells were connected to NI 1500 module and the module was connected to the SCXI 1600 chassis and the computer connected to the chassis was installed with a labVIEW program for the data acquisition. Once, the setup was complete the hub was simply pushed by hand in either direction and consequent changes in graphs of all the load cells were observed it was observed that:

- D51- Lower Left Side.
- D52- Lower Right Side.
- E5- Upper Center.

Figure 3.1: Center Hub of M15.

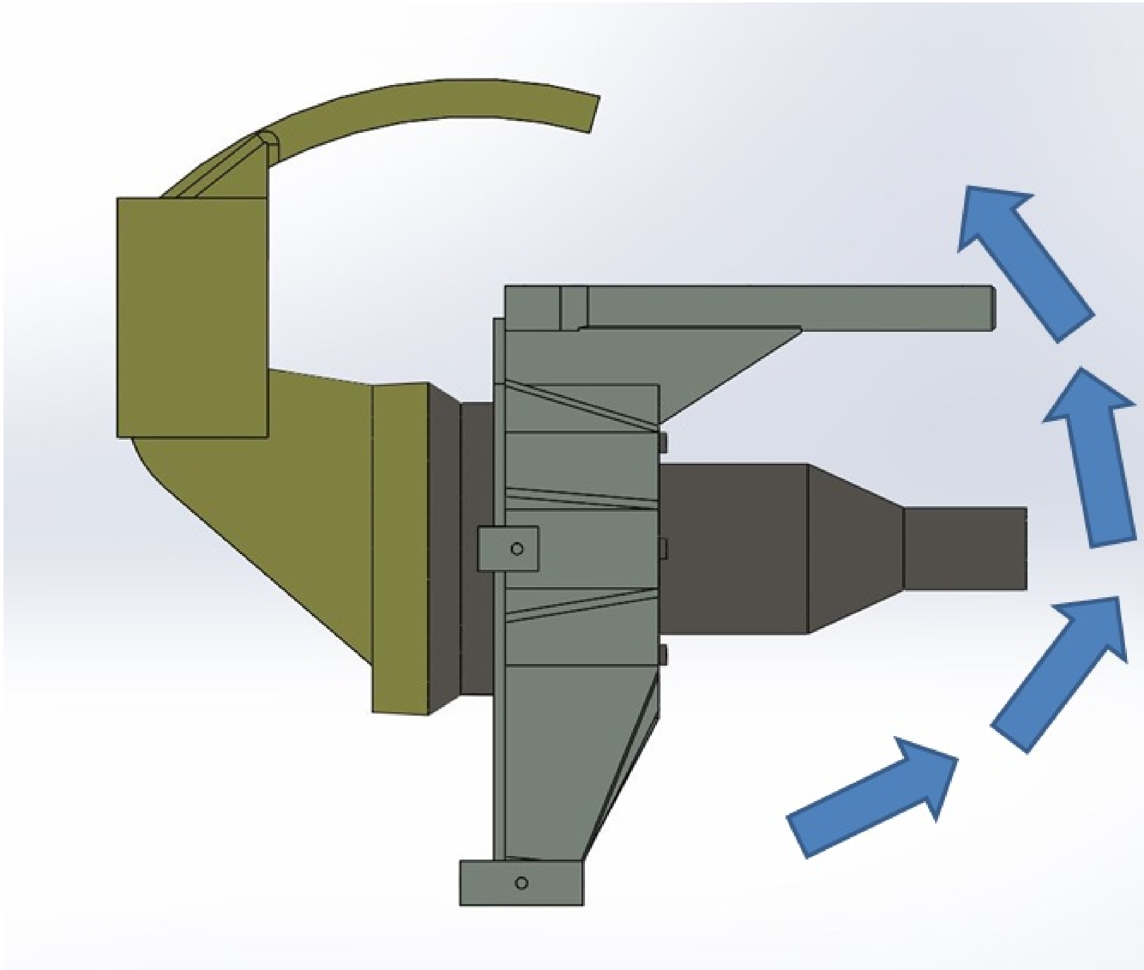

Figure 3.2: Overturning Moment (L).

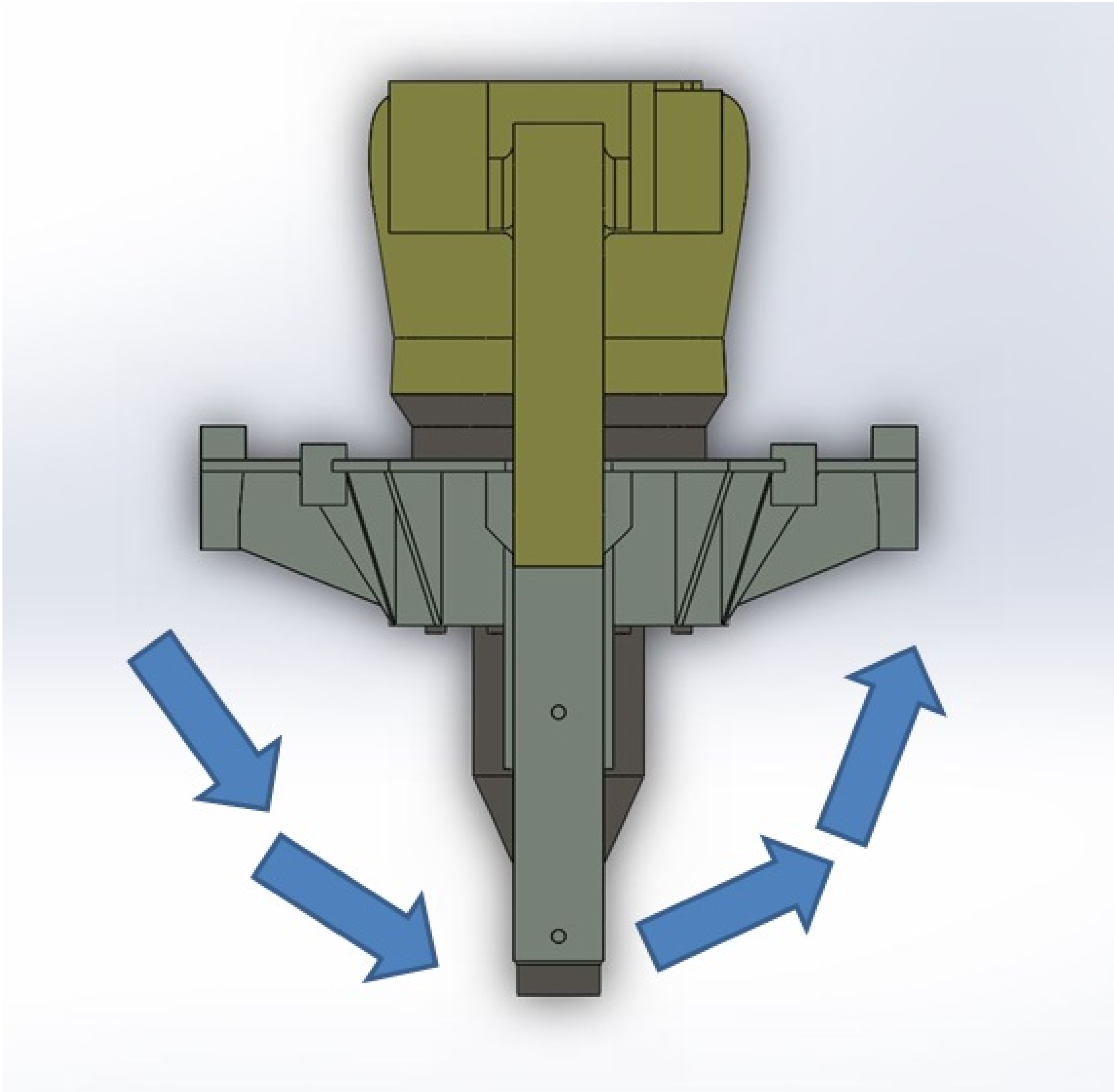

Figure 3.3: Align Moment(N) about Z axis.

Now, as it known that the load cells inside the hub are meant to read out the values of:

- Lateral Force Fy.
- Aligning Moment N.
- Overturning Moment L.

3.1 Aligning Moment Calibration(N)

In principle, for the load cells to be calibrated to read a value of the aligning moment, we need to derive a relation between load cell readings and a known aligning moment[24]. For acquiring the load cell readings the data acquisition system has already been set up as discussed in previous topics but in order to apply a known aligning torque, some additional fixtures are required. At first, a green calibration fixture is mounted on the hub which was previously used for calibration purposes as well an advantage of using this fixture is that it already has various mounting points which allow us to apply load on different locations of the fixture[25]. For the purpose of calibrating aligning moment the two rod end locations on lower left and lower right on the green fixture will be used but to apply known dead weights on these two locations it was determined that another fixture was required which in addition to the calibration fixture will be used to apply aligning moment via pulleys and has an airbag mechanism which uses air pressure to pull the calibration fixture from the lower center part.

When the fixture for airbags and pulleys was manufactured it was fixed on the M15 carriage using fasteners and lateral force Fy was applied using air pressure through the air bags mounted on the fixture. However, for deriving the scale between the load cells D51, D52 and aligning moment, the dead weights were mounted on the shackles which were connected to the rod ends on the calibration fixture through a pulley mechanism on the fixture mounted to the carriage. The dead weights used for calibrating aligning moment were 10lbs, 20lbs, 40lbs.

Following equation was used to calculate the aligning moment applied on the green calibration fixture mounted on the hub.

$$N = deadweight(lbs) * 4.45 * 0.6(Nm) \qquad (3.1)$$

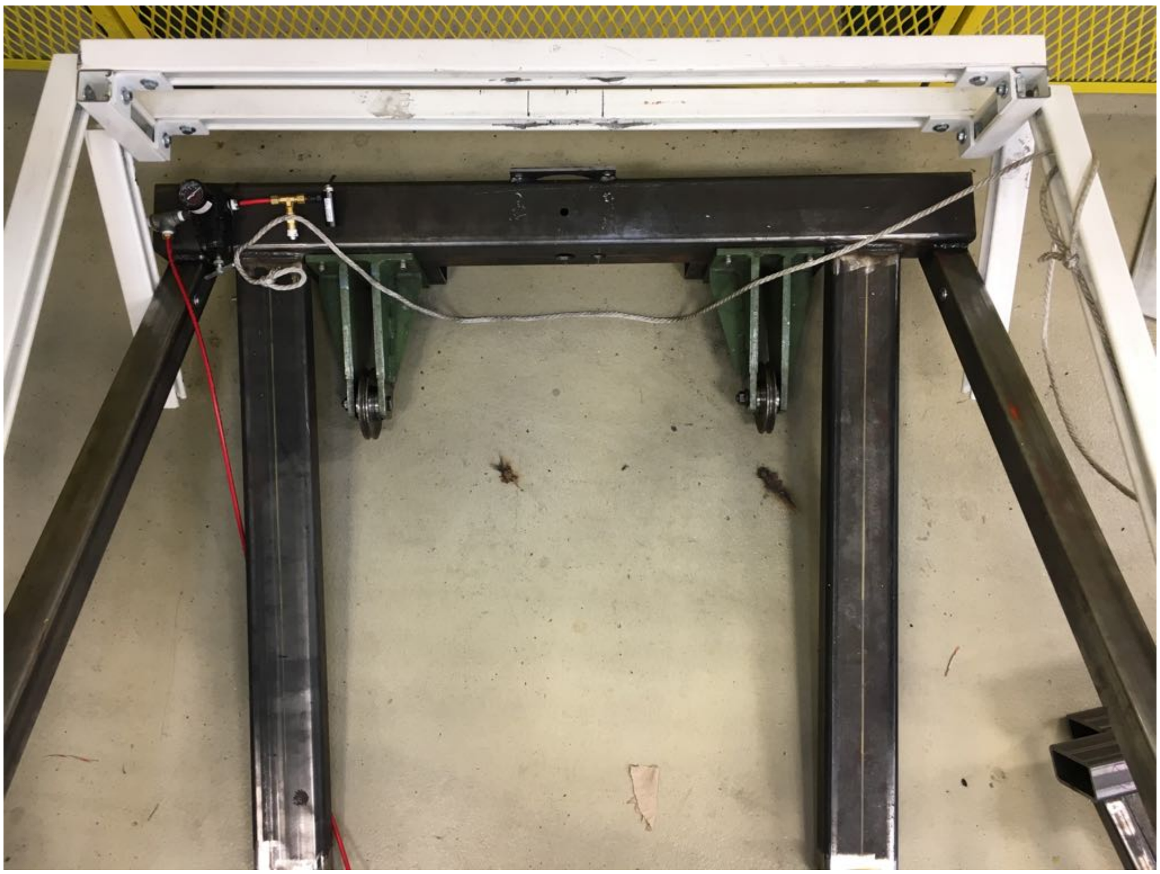

Figure 3.4: Fixture frame for front carriage mounting.

Figure 3.5: Fixture Frame for rear carriage mounting.

As per the above equation if the dead weights are mounted on diagonally opposite sides, which depends on what type of aligning moment the operator wants to apply. For example, if clockwise(+ve) aligning moment is required then the dead weights are mounted on the front right and rear left corner of the calibration fixture as seen from the operators perspective[24]. Also, the 0.6 m in the above-mentioned equation refers to the distance between the two loading points.Accordingly, the torque applied is as follows:-

- 10 lbs = 26.7 Nm
- 20 lbs = 53.4 Nm
- 30 lbs = 80.1 Nm
- 40 lbs = 106.8 Nm

The signs for the above-mentioned torques could be positive or negative depending on where the dead weights are applied. Now with no lateral force(Fy) and only dead weights applied using the data acquisition system, the strain measurements values from the hub load cells are plotted against the corresponding torque values, as calculated from the equation mentioned above and the linear equation obtained from the graph gives us the relation between the strain values of D51 and D52 against torque applied.

$$Torque = K1 * (D51 - D52) \tag{3.2}$$

The first problem in this step was that the two load cell reading for D51 and D52 weren't same i.e. the strain measurement readings from D51 and D52 readings were different even at zero loads. So there were two possible solutions to this problem either changes could've been made in the labVIEW code so that it automatically adjusts the readings of the two load cells to read the same value or acquiring the data as it was and then manipulating it to read the same values. In this case, the latter option was chosen, using excel the readings from D51 and D52 were plotted against each other on a graph and resulting equation of the line as obtained was used to calculate a new D51 value, such that it is closer to the D52 values. Once the calculated and D51 values and D52 strain values are acquired, the values are tared off, the same procedure is repeated for D51 and D52 strain values acquired from the data acquisition system corresponding to all dead weight values which are used to apply aligning torque. And then the constant K1 value is acquired from the resulting graph between Torque v/S D51-D52. A scale is derived from the excel graph between torque and difference between D51 and D52, the labVIEW code is altered so that we directly acquire the value of D51-D52 and the scale obtained from the torque v/s D51-D52 graph is inserted into the 'DAQ Assistant' module of the labVIEW program which will now automatically convert the data acquired into calculated torque values.

3.2 Load Cell Interaction

Till this point the load cells D51 and D52 had been calibrated to read out the torque values applied on the hub and the data acquisition system was tested by applying known dead weight values again to check if the torque values as calibrated on the LabVIEW program read the exact same value as they are applied or not, the calibrated scale passed this test as the values shown on the labVIEW program through the calibrated scale were same as the calculated values. However, there was one problem which had to be resolved. Since, the calibrated scale read out the exact same values as the torque applied through the dead weights, we checked if the scale read the same value even when the lateral force is applied or not. When the lateral force was ramped up with known dead weights stacked to generate a definite aligning moment there was a change in aligning moment even with the applied dead weights remaining the same, this phenomenon is known as load cell interaction. Which means that when in a system load is applied on one or multiple load cell in one axis there is a measurement value in one or more load cells in the same system aligned in a different axis. We tried to study our system again using which we were applying loads on the hub, so that we can figure out the reason and how to counteract the load cell interaction. After some research, it was found out that if there is a change in aligning moment reading when the lateral force is applied then it is because of the reason that somehow the lateral force is generating aligning moment itself. It was easy to understand that the only way the lateral force (Fy) can contribute to the aligning moment(N) applied on the hub is if the line of action of the lateral force (Fy) is not exactly in line with the rod end located in the center of the green fixture attached on the hub. In order to make the airbag lined up exactly with the center of the green fixture, the holes in the manufactured fixture which is used to mount the airbag were widened using a drill machine, so that we've enough clearance to adjust the airbag to align it to the central rod end mounted on the green fixture. Another visual method of figuring out if the load acting through the central stud mounted to the airbag is acting on a straight line is that the fixture which is mounted on the hub rotates about the axis of the hub. Also, it was significantly important to get rid of the misalignment between the stud connecting the airbag and the rod end located at the center of the hub as some preliminary calculations reveal that at a lateral force (Fy) load of some 1200 lbs, the misalignment would contribute to an aligning moment of. In order to reach that value of aligning torque contribution by the lateral force (Fy), we need to figure out the amount by which the green fixture rotates, in order to do that an inclinometer is placed on the top hat of the green fixture and at the current position the lateral force through the stud connecting the airbag. As the load is ramped up the green fixture rotates consequently a reading can be seen on the inclinometer. For our case on full ramped up load the inclinometer showed a reading of 2 degrees and since our fixture is 900 mm tall this converts into about 7mm deflection laterally. This means that when a lateral force(Fy) is applied the green fixture tilts to an angle such that the stud is applying lateral force (Fy) at an offset of 7mm and thus contributing to aligning torque in the clockwise direction. After some hit and trials, the airbag so mounted was placed in a location which aligns perfectly straight with the rod end present on the green fixture.

3.2.1 Matlab Post Processing

As the required changes were made to the calibration setup which included the green fixture mounted on the hub, making more clearance in the holes on the manufactured fixture mounted on the carriage. And the airbag was mounted in direct line of action with the lower central rod end of the fixture. After a few, hit and trials the calibration fixture was aligned with the airbag. Consequently, the data was acquired with the changes made, with and without lateral force (Fy), applied on front and backloading and also with all the weights mounted in clockwise and anti-clockwise direction. The data so acquired was then processed using MATLAB[26], the code generated was used to analyse if the data acquired after the changes were made to the fixture and the carriage was good enough to devise a new scale or the problem still persists and if it is then some other questions need to be answered such as, are the load within the permissible range? is the error in the load readings varying linearly or the error is of second or third order? In short, the data acquired after the changes installed on the fixture were analyzed by the MATLAB code so that the errors in load measurements readings with the changes installed. However, apart from the changes in the apparatus, one change was made in the calculations as well. Perviously, the overturning moment(L), aligning moment(N) and lateral Force(Fy) were calculated from the moment calculations and that the applied forces result in zero moments about the center axis of the hub, accordingly using the distances between the load cells(E5, D51, D52) and the center of axis of rotation were located. Now, this time onwards the calculated values of Lateral Force (Fy), Overturning Moment(L), Aligning Moment(N) are now to be calculated by considering the contribution from all the three load cells E5, D51, and D52, i.e. a third-dimensional curve fit equation of first order was considered[27]. For this purpose, the MATLAB code was so generated such that it calculates the coefficient values for all the load cells. The equation was initially defined as:

$$Fy = K1 * D51 + K2 * D52 + K3 * E5 + K4 \tag{3.3}$$

$$L = K5 * D51 + K6 * D52 + K7 * E5 + K8 \tag{3.4}$$

$$N = K9 * D51 + K10 * D52 + K11 * E5 + K12 \tag{3.5}$$

Now, by using the MATLAB code the values of the aforementioned coefficients were calculated against the acquired data. One advantage of using this technique was that unlike calculating the aligning moment and overturning moments from the simple mechanics and then calibrating individual load cells to yield out required parameters, we were now considering the contribution from all the load cells irrespective of their location inside the hub to calculate all the parameters we were concerned with, those being namely:- Lateral Force (Fy), Overturning Moment(L), Aligning Moment(N). By calculating the parameters this way means that we are actually considering the contributions or to be specific, the measurements in other load cells as well while calculating either of the aforementioned parameters. This way, we are able to tell that the results so obtained are more accurate, as the contribution from all the load cells is considered. Also, using this method meant that we are actually considering the load cell which is not meant for calibration of a particular parameter and how it changes as the forces are applied corresponding to that parameter.

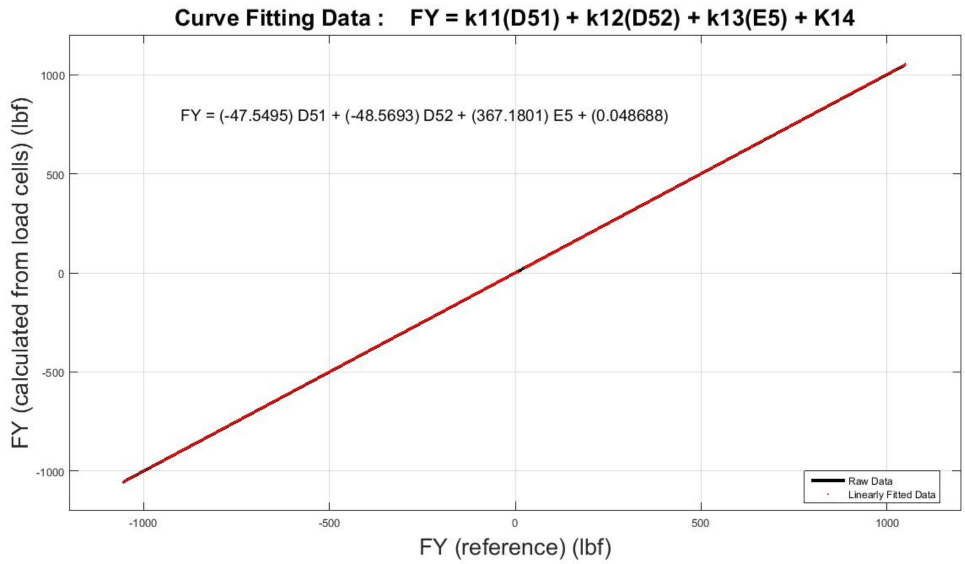

Figure 3.6: Fy vs Fy(calculated from three dimensional curve fit, the errors are small in comparison to the graph scale and therefore the two lines look coincident.)

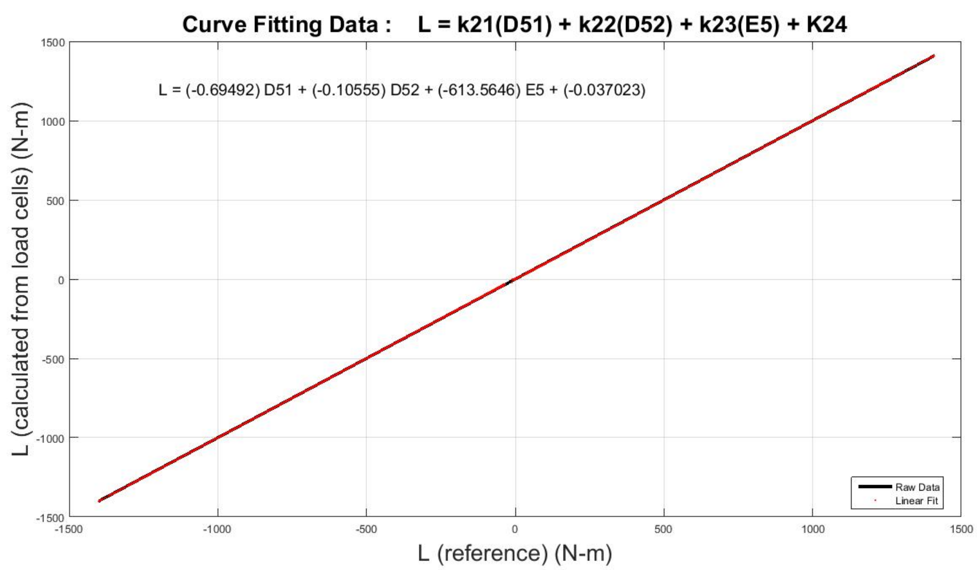

Figure 3.7: Overturning Moment(L) vs Overturning Moment calc.(L), the errors are small in comparison to the graph scale and therefore the two lines look coincident.

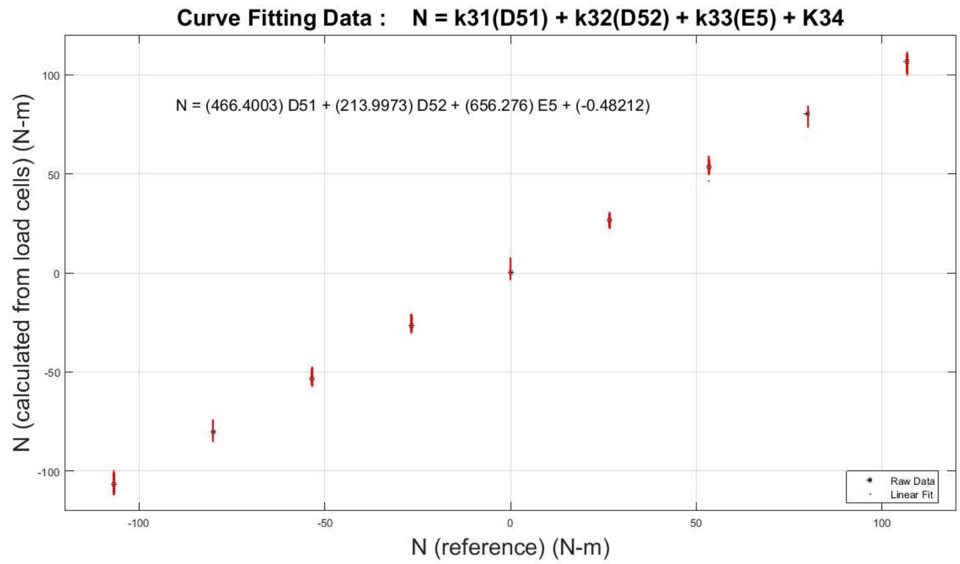

Figure 3.8: Align Moment (N) vs Align Moment calc.(N), the errors are small in comparison to the graph scale and therefore the two lines look coincident

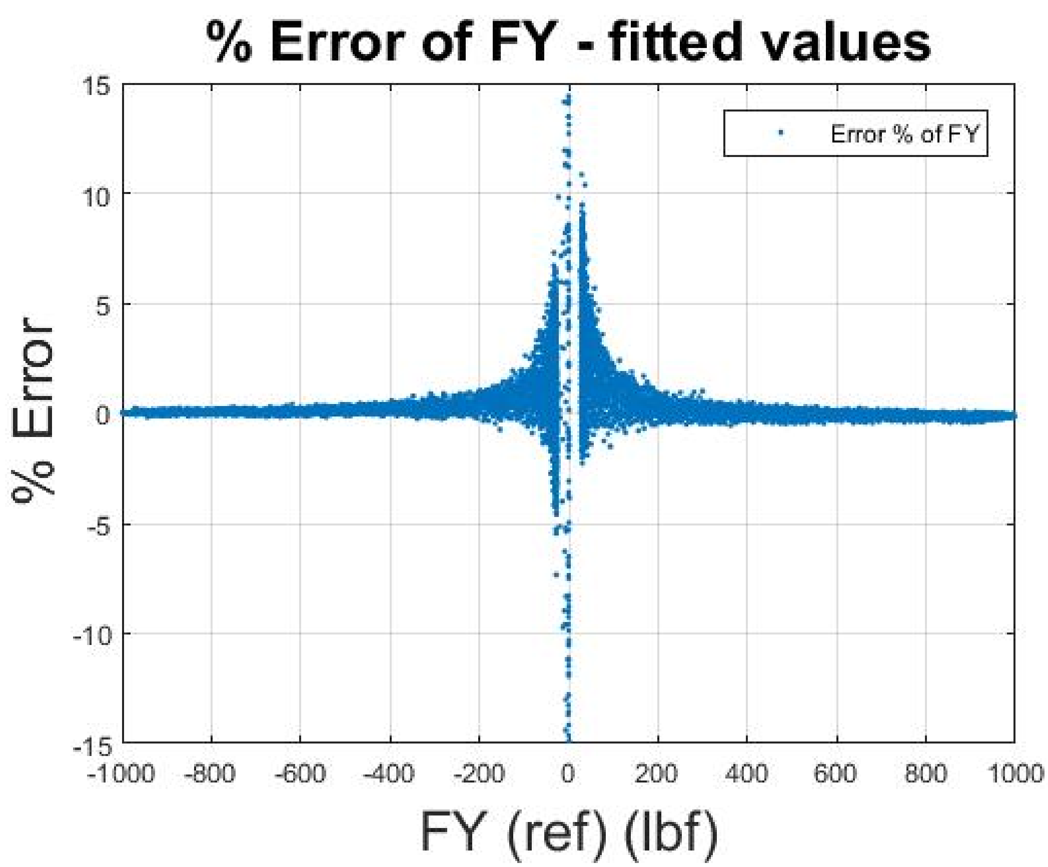

Figure 3.9: Initial Error values in Fy in terms of percentage these error values were significantly improved after individual load cell weight calibration.

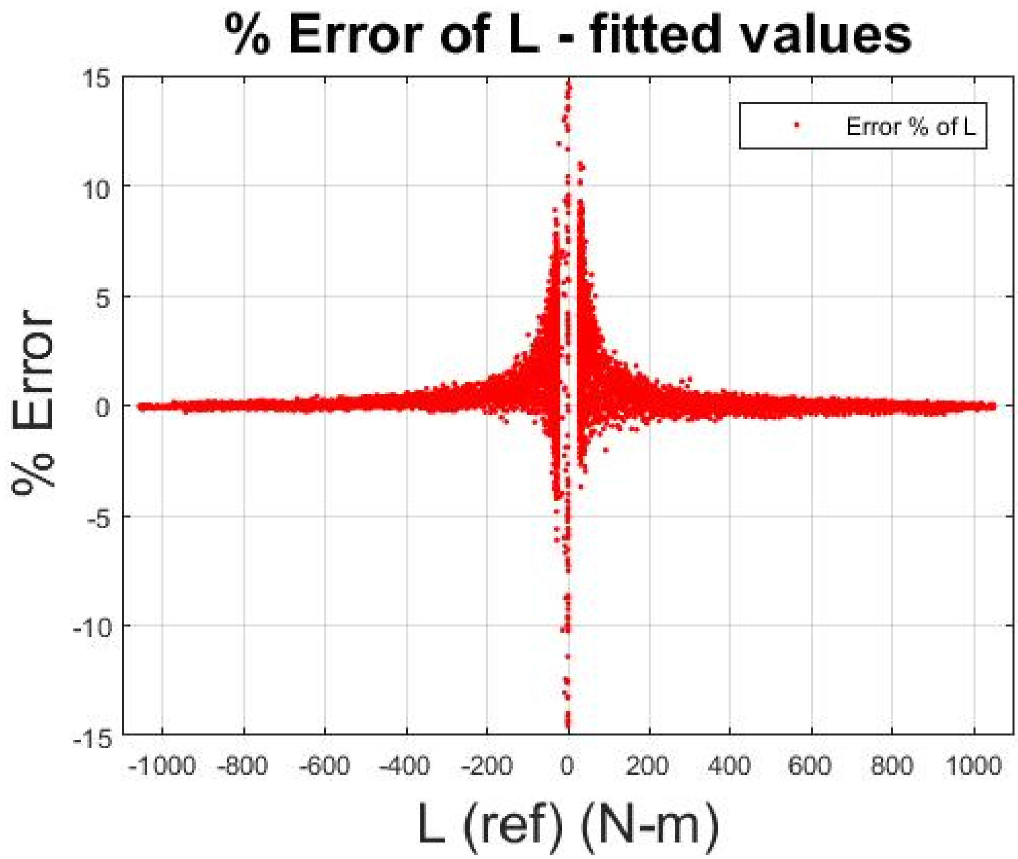

Figure 3.10: Initial Error values in L in terms of percentage these error values were significantly improved after individual load cell weight calibration.

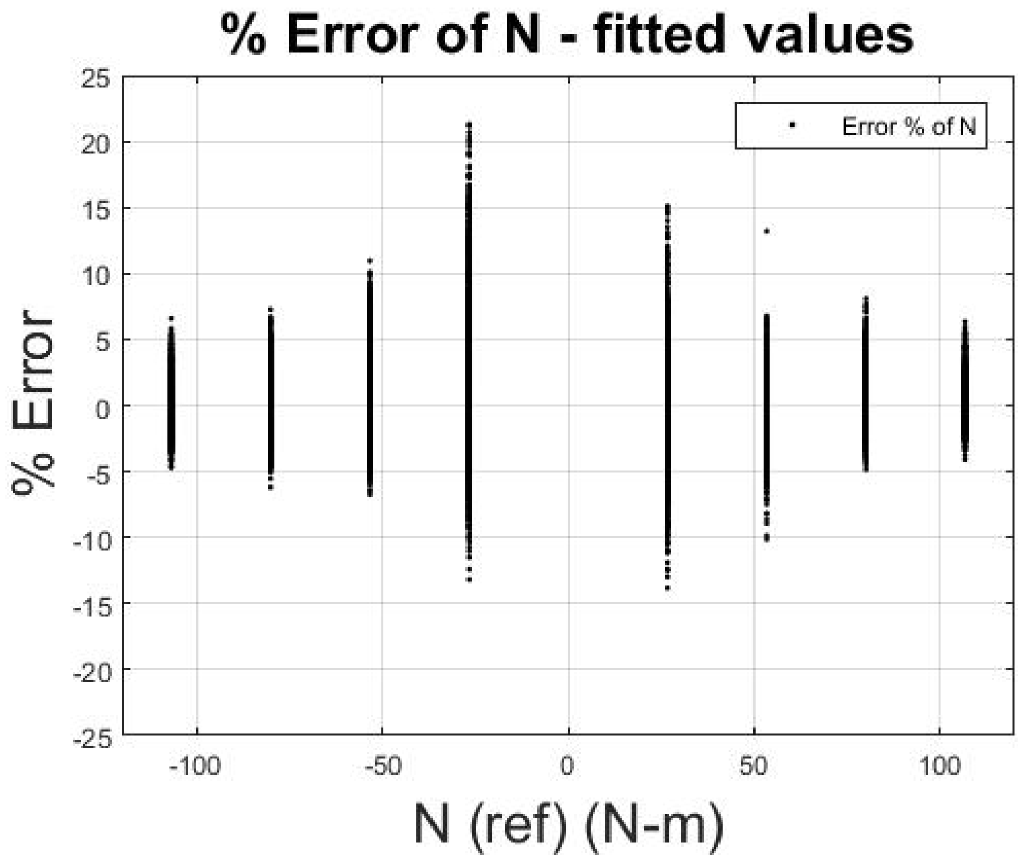

Figure 3.11: Initial Error values of N in terms of percentage these error values were significantly improved after individual load cell weight calibration.

3.3 Load Cell Pull

The results obtained from the bottom pulling of the green fixture with adjustments as well as changes employed in the calculations using the third dimensional and first order curve fit equations for calculating the different parameters gave some proper results and were consistent and had small error values.However, in order to offset the error values from the final result, another physical change was introduced.

This physical change was to pull the hub at the exact location of the load cells inside the hub, as per the drawing of the machine, the load cells D51, D52 and E5 were located at a PCD of 200mm and the load cell being located on the top of the circle as when seen from the front. And the other two load cells D51 and D52 lie on left and right side of the circle centerline, with both the load cells having an angle of 60 degrees between them.Also, in order to do this experiment, the hub could be exactly rotated so the the holes line up with the exact location of the load cell,whether it be D51,D52 or E5. This was done with ease as the holes present on the rotating part of the hub enabled us to see the location of the load cells, as the load cells were named as Y1,Y2 and Y3 respectively.Now, another physical change that had to be incorporated was, a method by which we can exactly align the reference load cell and the airbag hardware with the location of the load cell.At this point we've figured out the location of the load cells Y1,Y2 and Y3 but the problem lying here was that the holes through which the exact location of the load cells were determined weren't exactly aligned with the load cells, because the holes were located on a circle of PCD of 205 mm, whereas the load cells as previously discussed were mounted on a circle of 200mm PCD, so the two entities were not exactly aligned.Now, it was required to employ a mechanism that allows us to mount the airbag hardware on the exact location of the sensors, in order to do this, a simple mechanism was devised, in this mechanism, a small nut as compared to the nut which mounts on the hub is welded on to it. However, the nut, so welded is offset from the center of the nut which screws on the hub. This way by rotating the 'base' nut after a few iterations the nut was placed such that it aligned exactly with the load cell position inside the hub. After, all the physical adjustments were made and the airbag hardware and the reference load cell was connected to the load cell position the load was applied.

Now by using the data acquisition system(SCXI 1600, Module 1520 and the computer with customized labVIEW program) the load cell is calibrated to read out values in pound-force rather than millivolts.In order to do that, the hardware has to be first aligned with the load cell position, as discussed in previous topics. Now, with the hardware aligned, we increase the air pressure in the air bags and read the amount of pound force it translates into through the labVIEW program on the computer, the front panel of the program consists of some graphs,one of those graphs read 'reference load cell' which automatically translates the airbag pressure value to load applied on the hub in units of pound-force.Now, as per the load applied, the data was acquired for the respective load cell, for example:- if load is applied at the load cell D51, then in that case the load seen in the LabVIEW program's reference load cell graph, which increases as the air pressure is increased in the airbag, this implies that if the airbag hardware is located exactly in line of the axis of the load cell then the load cell will experience the same amount of load as seen on the reference load cell graph.If that is the case then there should be minimum or no readings on the graphs of other two load cells in the LabVIEW program.It turned out that even after some physical iterations to try and get the load cell aligned with hardware, there was somewhat a small amount of misalignment present, which can be eradicated by using the custom LabVIEW program.When applying the load from the airbag to one particular load cell, it should be also taken care of that the measurements in the other two load cells are close to negligible at least, if that's not the case then the airbag and load cell are not perfectly aligned, after some iterations and using the LabVIEW program the load cells and the airbag was aligned.After this step, the next step was to calibrate the aligned load cell to read out values in pound force.This was done using a similar procedure, which was used to calibrate the reference load cell the only difference was that this time instead of strain values, millivolts readings from the load cells were used to calibrate.In this case, the load was ramped up using air pressure and the data so acquired from the data acquisition system, was used to devise a scale for calibration.A graph was plotted between the reference load cell values against the millivolts readings from the hub load cell and accordingly a equation describing the relation between the two entities was devised.

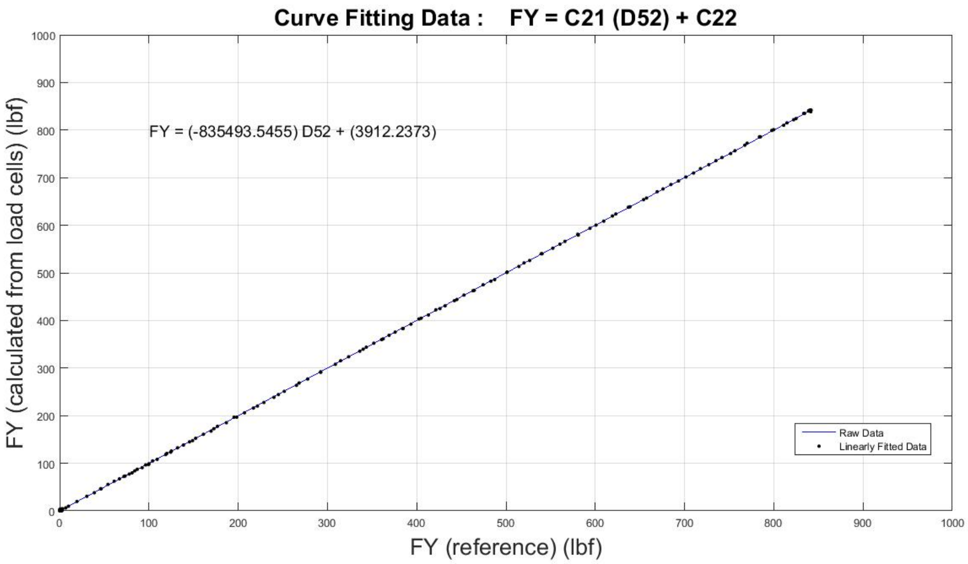

Figure 3.13: Graph of D52 vs Force with scale equation.

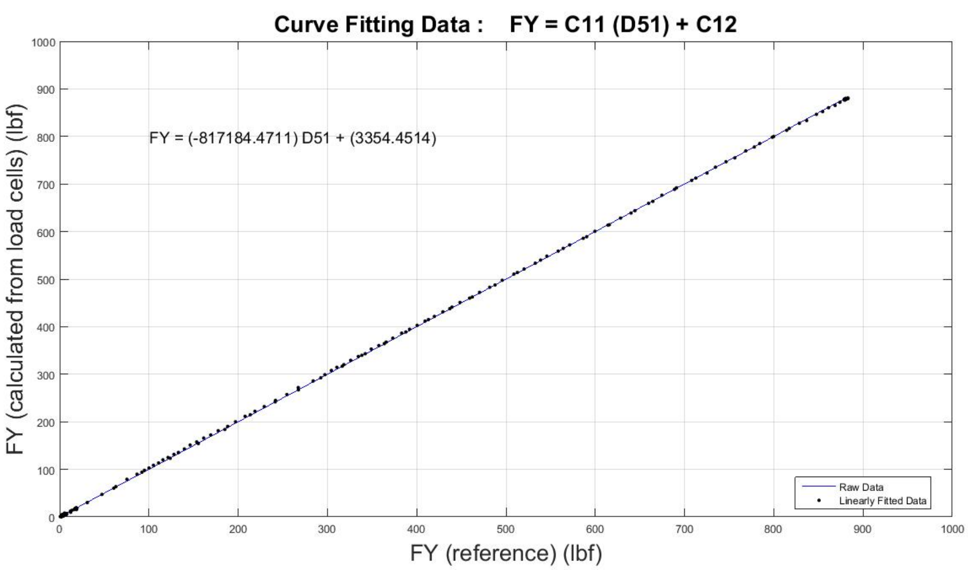

Figure 3.12: Graph of D51 vs Force with scale equation.

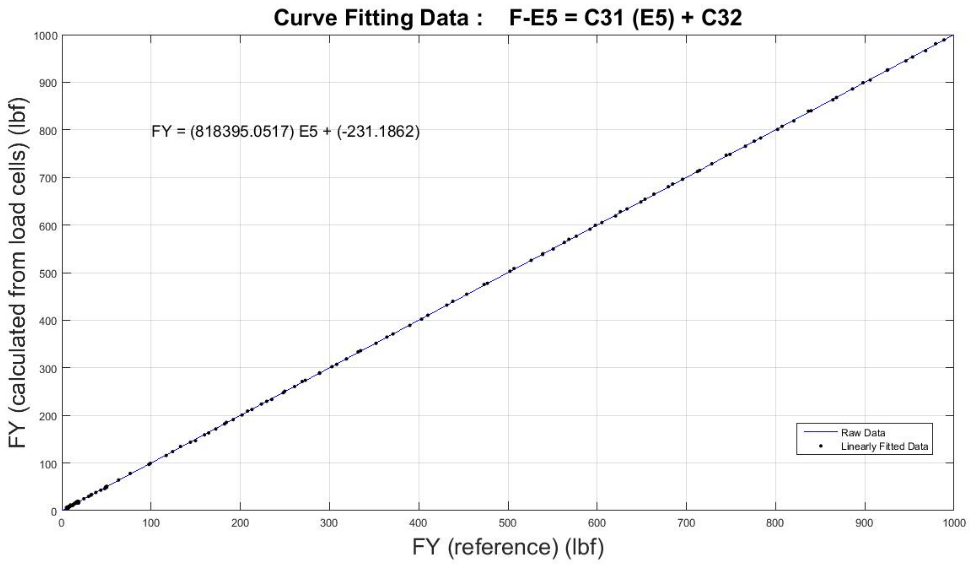

Figure 3.14: Graph of E5 vs Force with scale equation.

The following graphs were obtained by following the above procedure:

The same process was repeated for the other two load cells as well. the step by step method for load cell calibration can be written as follows:-

- Arrange the nut weldments such that they align with the location of load cells inside the hub(Y1, Y2, Y3).
- Ramp up the load to a mid-range load.
- Iterate using LabVIEW program to fine tune to the exact location of the load cell.
- Ramp up the load to a maximum value and back to minimum load.
- Acquire the data through the LabVIEW program.
- Devise an equation for the relation between the millivolts and pound-force of the reference load cell.

The same steps can be repeated for E5 except for a small change. The load cell E5 is located on the centerline and topmost part of the circle with PCD 200mm. In order to make physical adjustments such that the line of action of the airbag aligns with the centerline of E5, some changes related to manufacturing had to be made in the fixture. So, instead of, for calibrating E5 by directly aligning it with the airbag, the lower fixture is used where the airbag can be mounted in the lowest position with respect to the carriage. With the airbag connected to the lowermost part of the green fixture (center rod end), basically considering the axis about D51 and D52 to be the pivot point for the loads acting on E5 a factor is calculated and the load applied at central lower rod end is translated to load acting on the topmost load cell E5 in terms of pound-force.

CHAPTER 4: RESULTS AND DISCUSSION

At this point, so far we've made changes in the physical setup of the calibration fixture, made changes to the calculations to calibrate the hub load cells to read out the values in terms of pound force and that too by different methods for D51, D52, and E5.

After all these changes were made, whether it be physical or mathematical. Now, at this point, we needed to acquire the data to validate all the changes that we've made. The data was acquired and can be classified in following classes:-

- Lateral Force (Fy) at Center Hub pull.
- Zero Lateral Force (Fy), Dead Weights in the clockwise direction.
- Zero Lateral Force (Fy), Dead Weights in the anti-clockwise direction.
- +ve Lateral Force (Fy), Dead Weights in the clockwise direction.
- +ve Lateral Force (Fy), Dead Weights in the anti-clockwise direction.
- -ve Lateral Force (Fy), Dead Weights in the clockwise direction.
- -ve Lateral Force (Fy), Dead Weights in the anti-clockwise direction.

Next step was to post-process the data we've acquired for the validation of our steps so performed. In order, to do that we developed a MATLAB code which uses the data as mentioned above and gives us the value of coefficients associated with D51, D52, and E5 for all the three parameters. Also, for further validation of our results, we also plot the error values, i.e. the difference between our calculated parameter

D51, D52, and E5 from our coefficients value to the actual experimental values of those parameters.

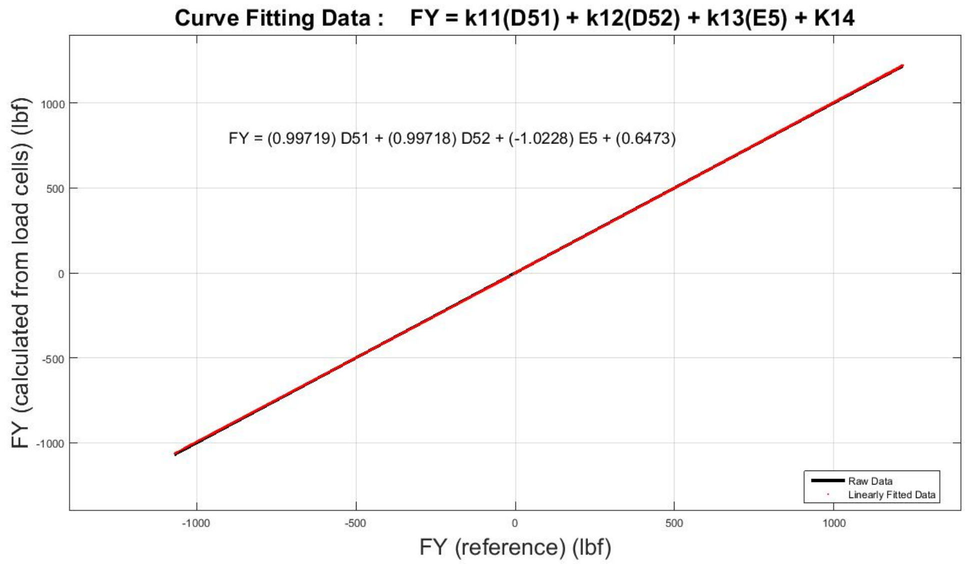

Figure 4.1: Fy vs Fy calculated values after tests were performed by calibrating individual load cells inside the hub. The deviation of calculated (Fy) from applied Fy is small as compared to the graph scale, therefore the two line seems coincident.

From the graph shown above, it can be inferred that by using the three dimensional, first order curve fit the accuracy of the curve fit equation has improved quite significantly. The reason for this is that now, the data from all the three load cells are considered for developing the curve fit equation and not only the load cell which seemed most appropriate.

A similar improvement can be seen in the graph of Overturning Moment(L) vs Overturning Moment Calculated. In this case, too, a similar curve fit equation was developed and significant improvements were seen here. Also, an important point to be noticed is that the coefficients so obtained are independent of the radius of the tire, which means that irrespective of the size of the tire, the parameters calculated will be correct.

Curve fit values remained consistent with the actual applied value of Aligning Moment(N) as well, with more accuracy and not being radius bound makes the equation

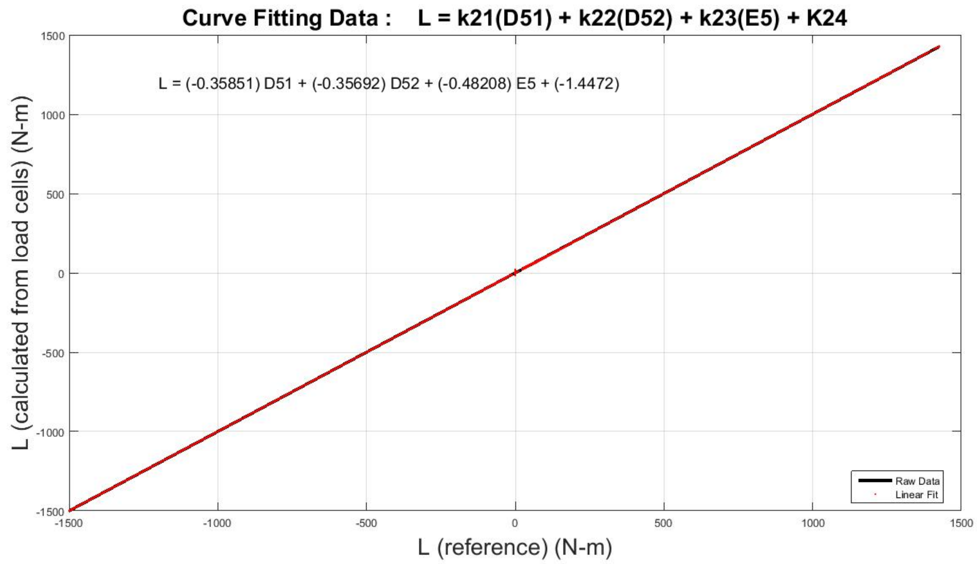

Figure 4.2: Overturning Moment(L) vs Overturning Moment calculated after tests were performed by calibrating individual load cells inside the hub. The deviation of calculated (L) from applied (L) is small as compared to the graph scale, therefore the two line seems coincident.

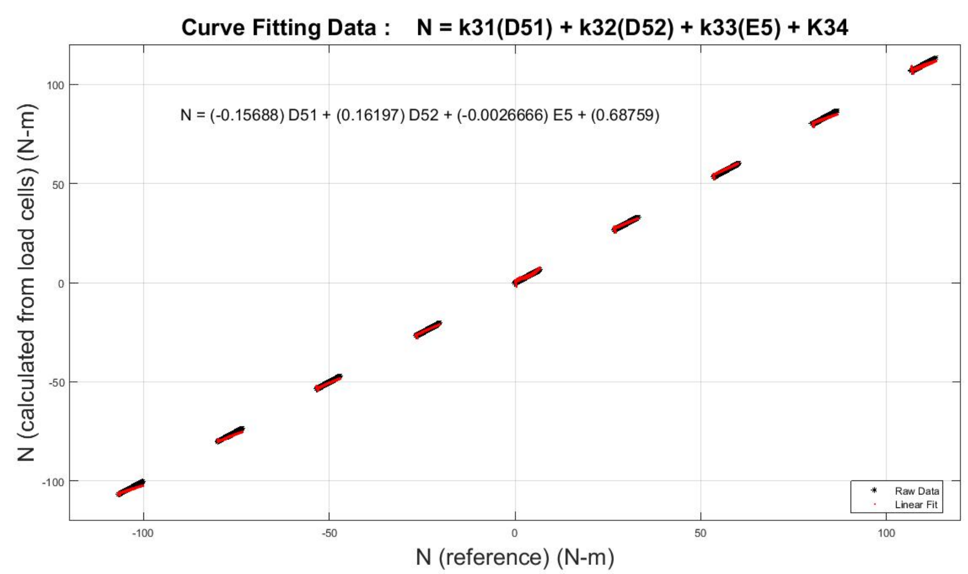

Figure 4.3: Aligning Moment(N) vs Aligning Moment Calculated after tests were performed by calibrating individual load cells inside the hub. The deviation of calculated (N) from applied (N) is small as compared to the graph scale, therefore the two line seems coincident.

perfect for real-life testing.

Also, from the MATLAB code so developed the final coefficient values for parameters: Lateral Force (Fy), Overturning Moment(L), Aligning Moment(N) are as follows:-

- The constants for Fy are:-
  - K11 = 0.99791
  - K12 = 0.99718
  - K13 = -1.0228
  - K14 = 0.6473
- The constants for L are:-
  - K21 = -0.35851
  - K22 = -0.35692
  - K23 = -0.48208
  - K24 = -1.4472
- The constants for N are :-
  - K31 = -0.15688
  - K32 = 0.16197
  - K33 = -0.0026666
  - K34 = 0.68759

From the above graphs, it can be understood that the values obtained for each of the parameters are within the permissible range i.e. the deviation from the expected values or the error values are not significantly high and are within the permissible limit. Also, these error values are validation point for all the changes that have been

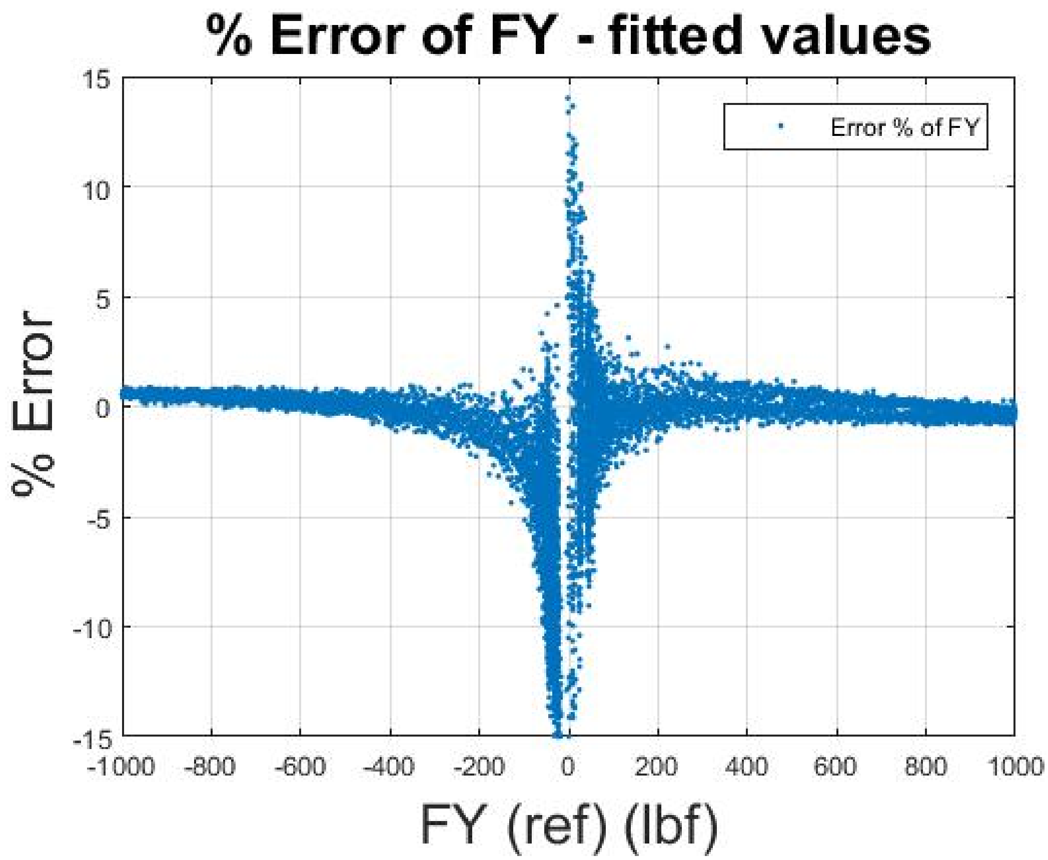

Figure 4.4: Lateral Force(FY) error values in terms of percentage when the individual load cells are calibrated and the results represent error values for (Fy) which is radius independent, which represents significant improvement over previous results

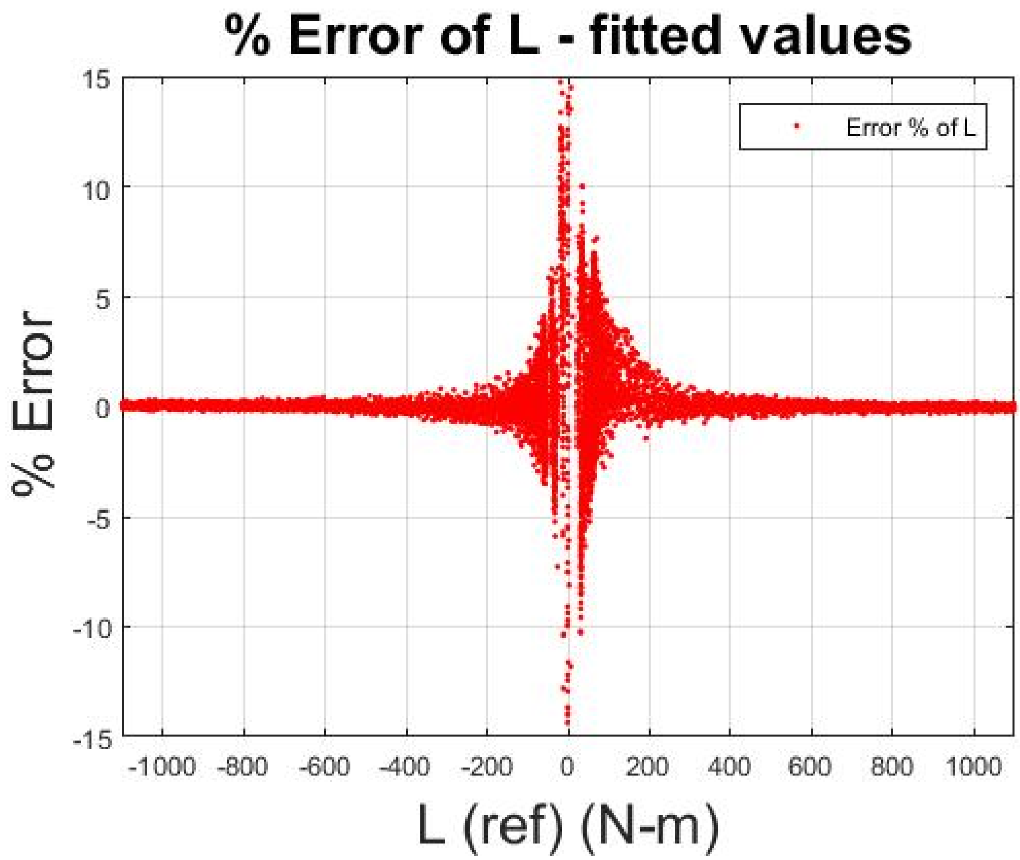

Figure 4.5: Overturning Moment(L) error values in terms of percentage when the individual load cells are calibrated and the results represent error values for (L) which is radius independent, which represents significant improvement over previous results.

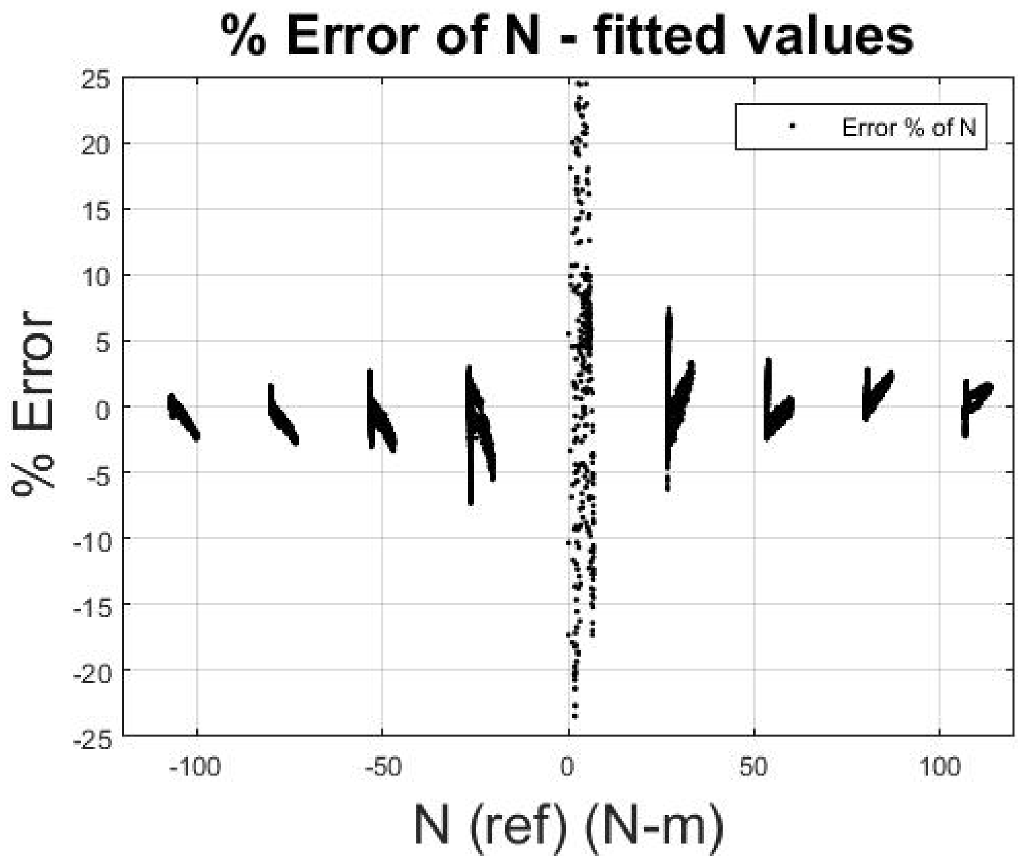

Figure 4.6: Aligning Moment(N) error values in terms of percentage when the individual load cells are calibrated and the results represent error values for (N) which is radius independent, which represents significant improvement over previous results.

made to the apparatus implying that all the necessary precautions and experimental changes were crucial to getting the current curve fit values and coefficients which happen to yield out values which are very much consistent with the expected or original values of all of the parameters, whether it be aligning moment, overturning moment or lateral force.

Also, from the curve fit data graphs it can be understood that when the three-dimensional curve fit equation of first order is employed. The accuracy of the results is improved significantly. The curve fits graphs of all the test data acquired i.e. with and without dead weights,(+)ve and (-ve) Lateral Force(Fy), the curve fit equation properly followed the trend of the raw data. The reason for that is because now while the equation is generated the data from the measurement readings from all the three load cells is considered for generating equation. And the reason why in first place, all the three load cells were considered for this purpose is because of the understanding that whenever a Lateral Force (Fy) is applied some component of that force is translated to the two other load cells as well and thus their contribution is also vital for generating accurate curve fit equations.

Another advantage of using the new curve fit equations which employs a three-dimensional curve fit of the first order is that the accuracy of the data acquired. This accurate data can be later used for generating 'Pacejka Coefficients' using MATLAB code, which is a very vital aspect of tire modeling. For instance:- When testing tires for a tire manufacturer or a race team, usually the main information they need from the test data is the Pacejka Coefficients. Accordingly, it'll be of great advantage if, in future, a MATLAB code can be written to generate Pacejka Coefficients, which will contribute to the growth of the machine, as more and more race teams and tire manufacturers will be tempted to test with the M15 machine.

REFERENCES

[1] E. M. Kasprzak and D. Gentz, "The formula sae tire test consortium-tire testing and data handling," tech. rep., SAE Technical Paper, 2006.

[2] J. Van Oosten, C. Savi, M. Augustin, O. Bouhet, J. Sommer, and J. Colinot, "Time, tire measurements forces and moments: a new standard for steady state cornering tyre testing," 1999.

[3] D. L. Nordeen, "Analysis of tire lateral forces and interpretation of experimental tire data," *SAE Transactions*, pp. 969–980, 1968.

[4] A. Yorgiadis, "Strain gage load cell," May 20 1980. US Patent 4,203,318.

[5] J. E. E. Simmons, "Explosion pressure gauge," Aug. 24 1943. US Patent 2,327,935.

[6] A. U. Kutsay, "Double shear beam strain gage load cell," Dec. 21 1982. US Patent 4,364,280.

[7] J. W. Dally, W. F. Riley, and K. G. McConnell, "Instrumentation for engineering measurements," 1993.

[8] F. A. Brunot, J. V. Motsinger, and M. P. Coppo, "Full bridge strain gage deflection sensor," Feb. 21 1995. US Patent 5,392,027.

[9] A. Hollinger and M. M. Wanderley, "Evaluation of commercial force-sensing resistors," in *Proceedings of the International Conference on New Interfaces for Musical Expression, Paris, France*, pp. 4–8, 2006.

[10] L. R. Ray, "Nonlinear tire force estimation and road friction identification: Simulation and experiments1, 2," *Automatica*, vol. 33, no. 10, pp. 1819–1833, 1997.

[11] A. U. Kutsay, "Strain detecting load cell," Oct. 3 1972. US Patent 3,695,096.

[12] K. Hoffmann, *An introduction to measurements using strain gages*. Hottinger Baldwin Messtechnik Darmstadt, 1989.

[13] www.Omega.com, "How load cell works." https://www.omega.com/prodinfo/loadcells.html, May 25 2018.

[14] N. Instruments, "Measuring strain with strain gages." http://www.ni.com/white-paper/3642/en/, May 25 2016.

[15] www.transducertechniques.com, "Wheatstone bridge." https://www.transducertechniques.com/wheatstone-bridge.aspx.

[16] N. Instruments, "Module 1520 for strain gage measurements." http://www.ni.com/en-us/shop/select/strain-bridge-input-module-for-scxi?modelId=124186.

[17] J. Travis and J. Kring, *LabVIEW for everyone: graphical programming made easy and fun.* Prentice-Hall, 2007.

[18] J. Y. Beyon, *LabVIEW programming, data acquisition and analysis.* Prentice Hall PTR, 2000.

[19] C. J. Kalkman, "Labview: a software system for data acquisition, data analysis, and instrument control," *Journal of clinical monitoring*, vol. 11, no. 1, pp. 51–58, 1995.

[20] D. Magin and S. Kanapathipillai, "Engineering students' understanding of the role of experimentation," *European journal of engineering education*, vol. 25, no. 4, pp. 351–358, 2000.

[21] B. Mihura, *LabVIEW for data acquisition.* Pearson Education, 2001.

[22] C. V. Knight and G. H. McDonald, "Modernization of a mechanical engineering laboratory using data acquisition with labview," in *Proceedings of the 1998 ASEE Annual Conference & Exposition*, pp. 1–13, 1998.

[23] J. W. Karsai, "Tire testing machine," Nov. 30 1954. US Patent 2,695,520.

[24] R. W. Topping, "Tire induced steering pull," tech. rep., SAE Technical Paper, 1975.

[25] M. G. Pottinger and A. M. Fairlie, "Characteristics of tire force and moment data," *Tire Science and Technology*, vol. 17, no. 1, pp. 15–51, 1989.

[26] Mathworks, "Curve fitting toolbox." https://www.mathworks.com/help/curvefit/curve-fitting.html.

[27] IDBS, "Three dimensional curve fit techniques." https://www.idbs.com/excelcurvefitting/best-practice/global-and-three-dimensional-fitting/.