DESIGN AND EXPERIMENTAL ANALYSIS OF HUB CALIBRATION OF TIRE FORCE AND MOMENT TESTING MACHINE

by

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ABSTRACT

DHIRAJ KUMAR MUTHYALA. DESIGN AND EXPERIMENTAL ANALYSIS OF HUB CALIBRATION OF TIRE FORCE AND MOMENT TESTING MACHINE. (Under the direction of DR. PETER T. TKACIK)

Tire cornering force and moment data from an indoor tire testing machine is very important to auto-makers and tire researchers with respect to the performance of vehicles. As such, the quality of the tire data is also crucial and it is dependent on the accuracy and repeatability of the tests for a given tire. One valuable parameter in the quality of the tire data for a given tire testing machine is precise calibration. This thesis presents the design of a force and moment calibration setup for Michelin's M-15 tire testing machine. Although 45 years old, this machine will later demonstrate quite good force and moment measurement capability.

Three calibration fixtures were designed to apply reference forces and moments on the hub of the tire testing machine as desired. By performing extensive calibration tests, the setup is fine-tuned to minimize the errors caused by load cell interaction and the geometrical inaccuracy of calibration setup itself. Furthermore, a standard calibration procedure has been developed to calibrate the Lateral Force (Fy), Aligning Moment (Mz) and Overturning Moment (Mx) for the M-15 tire testing machine. This comprehensive report will serve as a guide or hand-book for future calibrations. The calibration constants are determined for the M-15 machine that can be used for tire testing and the results of the calibration tests suggest that the error percentage in the tire data will be within 1% and which satisfies the SAE's recommended accuracy for force and moment testing.

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CHAPTER 1: INTRODUCTION

1.1 Organization of Thesis:

The thesis report is organized systematically, introducing the basic concepts of tire testing machines (TTM) and slowly narrowing it down to the development of the force and moment calibration setup. The progress of chapters follows a product development approach as shown below:

Chapter 1: Introduction - gives the outline of Force and Moment TTMs. Especially, the design features of the Michelin's (M15) drum-type tire testing machine.

Chapter 2: Testing and Calibration Protocols - the step by step procedures employed in tire testing and calibrating the TTMs are discussed in this chapter.

Chapter 3: Design of Calibration setup - the basic concept of calibrating the TTM is introduced in this chapter. By applying this concept, the design phase is presented systematically with the overview of all the components involved in the calibration setup. Additionally, the design and development of calibration fixtures has been discussed.

Chapter 4: Experimental Procedure - the experimental procedure involved in performing the calibration tests has been discussed in this chapter. A step by step procedure was also presented which can be helpful in standardizing the process. This chapter also provides insight on the data acquisition system (DAQ) and precautions to be taken while testing in order to obtain non-erroneous data.

Chapter 5: Analysis of Calibration Test Data - this chapter brings the design concepts and the test data together. It elaborates the mathematical model employed for calibrating the load cells involved in the force and moment measurements. Finally, the test data is processed using Matlab, generating important plots to check for the errors in the tests performed.

Chapter 6: Results and Conclusion - This chapter provides all the observations of the thesis by quantifying the results in terms of the maximum error expected in the tests, repeatability of the test, etc. Finally, the thesis is concluded, also providing future scope of the research work that is done.

1.2 Force and Moment Tire Testing Machine

The force and moment TTM dates back the to 1930s and It played an important role in the analysis of vehicle dynamics[1]. The idea behind the tire testing machines was to test the tires in a controlled environment in an indoor setting. This was particularly important for the growth of tire technology, as the tire behavior is not just a linear or a simple non-linear relation[2]. It is a complicated phenomenon that changes its behavior significantly, based on a large number of parameters such as rubber compound, tire cross section, temperature, pressure, inclination angle, steering angle, vertical load, tread pattern, contact area, tread wear, age, road surface properties, etc. Therefore, very few tire models exist till date that can predict a tire's behavior with confidence and be applied in the vehicle dynamic simulations or analysis[3].

The 'Tire Data' from a TTM contains a series of test conditions simulated in the lab. The data of number of relevant parameters are then collected at equal time increments. This data is then supplied to the tire companies, Automotive companies, Race teams, Researchers, etc[4][5]. to help them understand the tire behavior. The famous tire model given by Hans B. Pacejka known as the "Pacejka Model" or "Magic Formula"[6] helps to curve fit the tire data into a useful relation to work with. Thus, the tire data is helpful in quantifying and predicting the tire performance with a reasonable accuracy.

$$F_y(\alpha) = Dsin[CarctanB\alpha - E(B\alpha - arctan(B\alpha))] \tag{1.1}$$

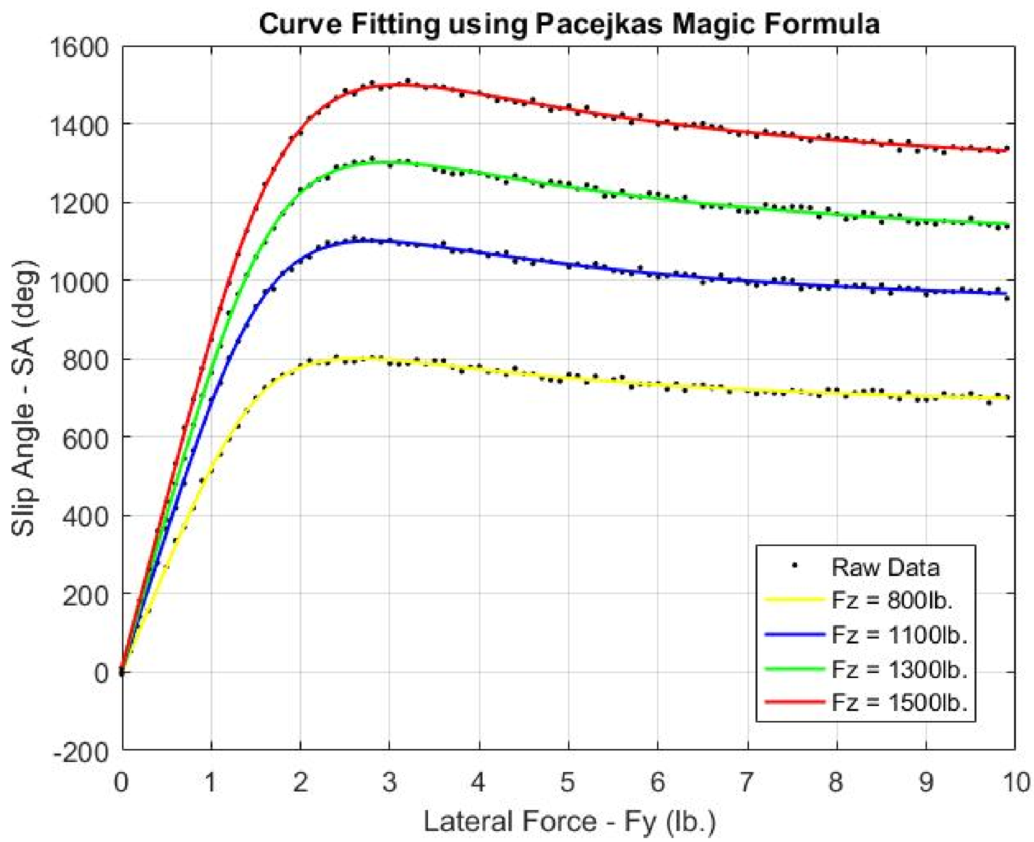

Figure 1.1: F_y vs α Curve fitting using Pacejka's Magic Formula

1.2.1 Forces and Moments on the tire

To allow a standardized way to understand the data, a widely accepted terminology is developed for all the parameters involved in the force and moment measurements. Two main platforms developed for this purpose are - SAE Tire Axis System and the ISO Wheel Axis System[7]. Throughout this research, the SAE tire axis system is followed. As shown below in the figure, the SAE Tire Axis System is defined at the contact patch. It follows a right-handed coordinate system and defines Forces and Moments as shown below.

- F_x = Longitudinal Force = X
- F_y = Lateral Force = Y
- F_z = Vertical Force = Z

- M_x = Over Turning Moment = L
- M_y = Rolling Resistance Moment = M
- M_z = Self-Aligning Moment = N

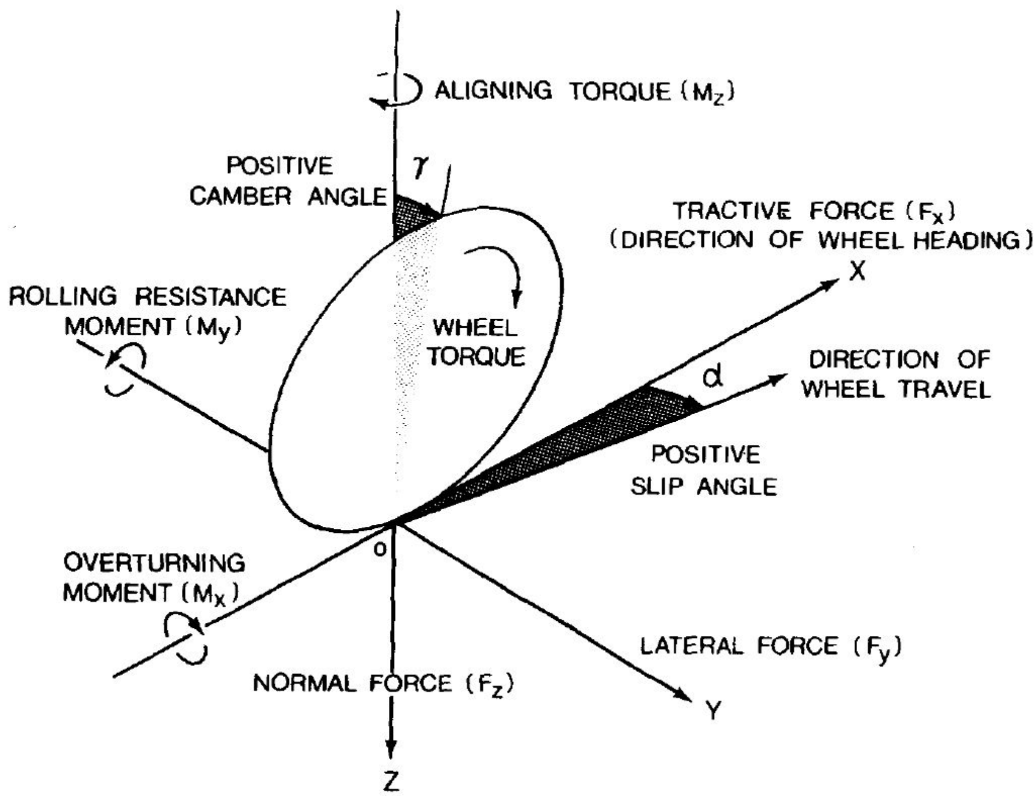

Figure 1.2: SAE Tire Axis

The center of the contact patch (center of the three axes), is defined as the point in the road plane where the line of intersection of wheel plane and road plane is cut by the projection of wheel spin axis. As a convention, the $+X$ direction is taken as the direction of travel of the wheel, $+Y$ direction is taken as right when the tire is viewed from the rear of the system and $+Z$ direction is into the road plane. The moments follow the right hand rule to determine the $+ve$ (positive) direction.

1.2.2 Indoor Tire Testing Machine

A thorough understanding of the cornering force and moment TTMs is needed for this research, to design a suitable calibration system for it. The three main parts involved in the machine are the roadway, tire manipulating system and sensors for collecting data. However, it is also important to note that not all TTMs are made equally. For instance, there are three different types of TTMs based on the type of roadway being used - concave drum, convex drum, flat track. They are used judicially depending on the purpose of tire tests being done. The TTMs with a drum type roadway have a simpler design and are cost effective compared to the flat roadway machines. However, they are regarded as producing less accurate tire data because of the complications due to the curvature of the roadway and tire contact patch. The ratio of tire diameter to the road-wheel diameter is an important parameter in this analysis. There exists no simple way to convert the data from a drum type TTM to a flat surface. Despite the inaccuracy of the drum type machines, they are still widely used in the industry to study tire endurance and performance at high-speeds[8].

On the contrary the flat-surface machine can generate data accurately matched to flat road conditions[9] but fails to maintain the simplicity of design. The construction of high-speed flat-surface machine is complicated and expensive to maintain. They are also not as durable as the drum type machines. They are essentially configured like a belt sander and typically consist of a steel belt for the roadway, that is running over two drums and a flat bearing in between. For example, the Calspan TIRF machine[10] shown in the figure below uses a special type of hydro-static air bearing to maintain the flat contact surface in between the two drums. Also, the steel belt needs a controller to maintain its lateral position throughout the test regardless of lateral force generation.

Figure 1.3: Calspan Flat Belt Tire Testing Machine

Most TTMs employ various types of hydraulically actuated tire manipulators for increased loading speed. This consists of a carriage, on to which the tire is mounted, and hydraulic pistons used to manipulate the tire's vertical position, inclination angle, steering angle, etc, with respect to the roadway. The M-15 used hydraulic loading at MARC but because of the simplicity of the UNCC test protocol is being converted to electric load. The M-15 currently has no automated steer or camber angle control.

In addition, a Force and Moment Measurement System is used in conjunction with a Data Acquisition System. Typically, the load cell sensors are placed in the carriage to generate the force and moment measurements. These load cells can measure single or multiple forces and moments. A typical measurement head is shown in the figure (the shiny part on the red frame behind the tire). The tire is mounted on to the spindle, which is a rotating part on the carriage. These measurement systems not only measure forces in the direction intended, but also gives readings in the unintended direction by a fraction. The elimination of these unnecessary forces is done through calibration of the system. The calibration procedure involves computation of a load cell interaction matrix that can be used for accurate force and moment measurements while testing.

1.3 Michelin's M-15 Tire Testing Machine

The Michelin's M-15 Tire Testing Machine was made in-house by Michelin in Clermont Ferrand, France about 1973 and originally used by Michelin Americas Research and Development Corporation (MARC) in their Greenville, SC facility for testing tires. It was donated to the Motorsports Research Laboratory at the University of North Carolina - Charlotte (UNCC) in 2015. At MARC, it was in a two story concrete test cell but is being rebuilt on a steel frame with modern electronics to carry out tire research under the supervision of Dr. Peter T. Tkacik, Professor at Mechanical Engineering and Engineering Sciences at UNCC.

An in-depth understanding of the design of Michelin's M-15 TTM is very important for designing a calibration system. This chapter discusses the design layout of the TTM, with a special focus on the Force and Moment Measurement System.

1.3.1 M-15 Machine Design Overview

The M-15 machine is a convex-drum type TTM machine with the tire mounted above and rolling on top of the 8.5m circumference road wheel. The main components of the machine are the Carriage, Tire manipulator, Force and Moment Measurement System, Main Drive and Road Wheel. The specifications and features of each of these components is described below.

Carriage: The Carriage is mounted on a heavy frame standing about 27m(9ft) tall. The heavy steel frame is then mounted on a heavier steel frame that has a working platform about 2.2m (7ft) high, which is where the tire operator works. The carriage acts as a connection between force and measurement system and the actuators. It is the most important part of the machine as the tires are mounted on the carriage while testing. The carriage controls the load an also the Inclination angle and Steering angle via a rack and pinion geared connection with 0.5 deg increments.

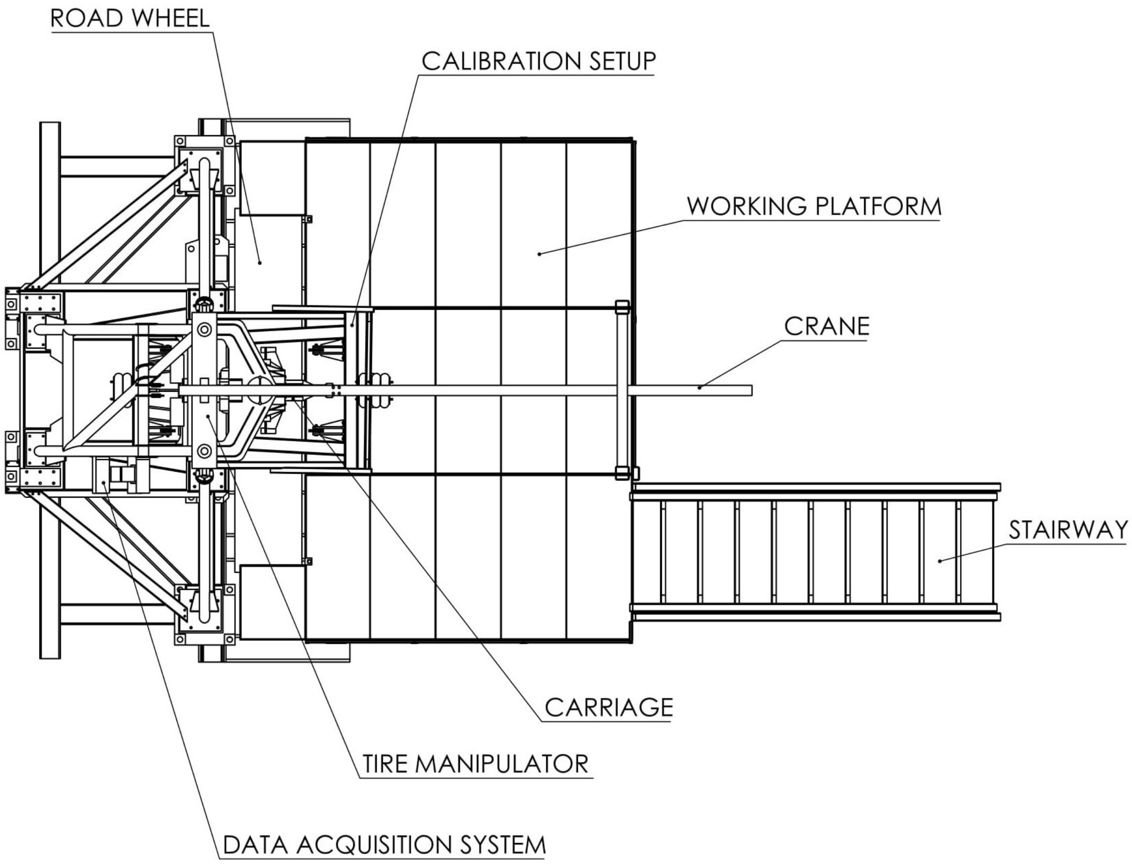

Figure 1.4: M-15 TTM Top View Layout

Tire Manipulator: The M-15 machine is originally designed such that only the vertical load can be applied by motion in the Z-axis. It was hydraulically actuated through piston mechanism placed below the carriage.At UNCC, it is being converted to load via an electronic "Linear Actuator". A DL-06 Programmable Logic Controller (PLC) system is used to operate and control the linear actuator loading mechanism in the machine.

Force and Moment Measurement System: The tire is mounted on a very special wheel which is then attached to a hub with six lug nuts. Inside this hub is the main system used for Force and Moment Measurements in the M-15 machine is made up of six Custom made Full-Bridge Strain Gauge Load cells that are strategically placed two each at three vertices of an equilateral triangle and are located in the hub just behind the rotating wheel attach. More on the Force and Measurement system is given in the next section.

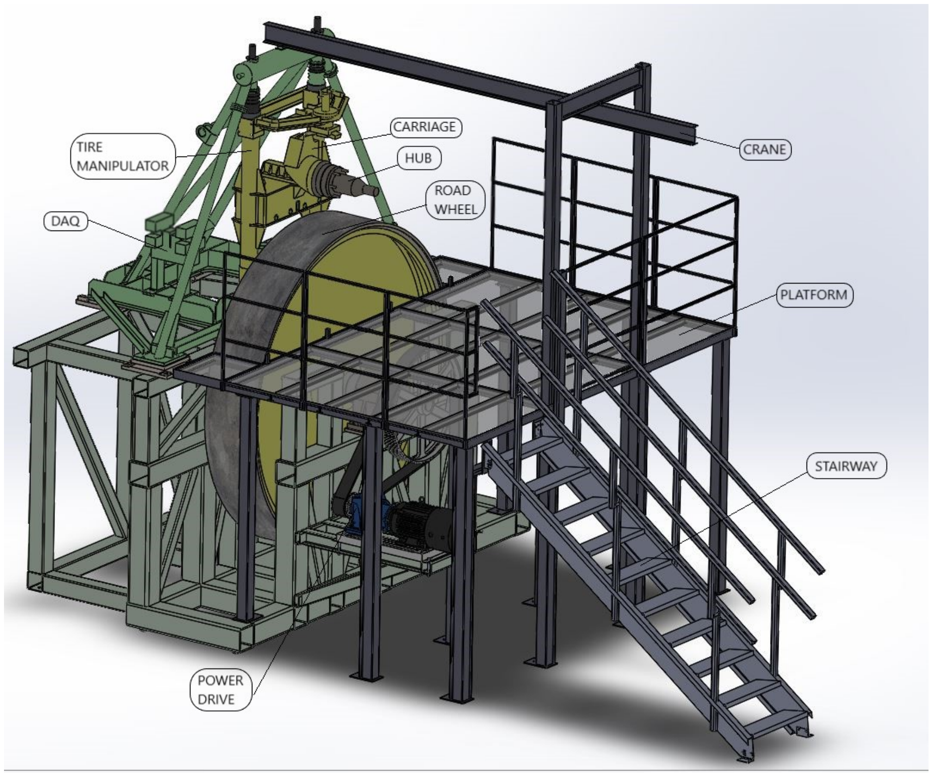

Figure 1.5: M-15 TTM Overview

Power Drive: The M-15 machine uses a 20hp vector motor powered by a 430VAC three phase frequency drive. The motor and a five to one gear reducer are mounted on the main frame and uses a four to one HTD timing belt and pulley system for driving the Road wheel. The combination of gear reducer and timing belt allows the road wheel to operate at the low 3.5kph standard test speed. The road-wheel motor drive, like the tire manipulator is controlled by the DL-06 PLC.

Road Wheel: M-15 machine uses an 8.5m road wheel (it has an 8.5m circumference). It is one of the largest road-wheels used on a tire testing machine in the industry. The reason for using a large road-wheel is to simulate almost flat road conditions locally near the tire contact area. Therefore, truck tires can also be tested with reasonable accuracy on the M-15 machine. The road-wheel is again mounted on the heavy steel frame and uses large spherical roller bearings on either side. It is vertically mounted such that the tire rolling surface is about waist high on the working platform.

1.3.2 Force and Moment Measurement System

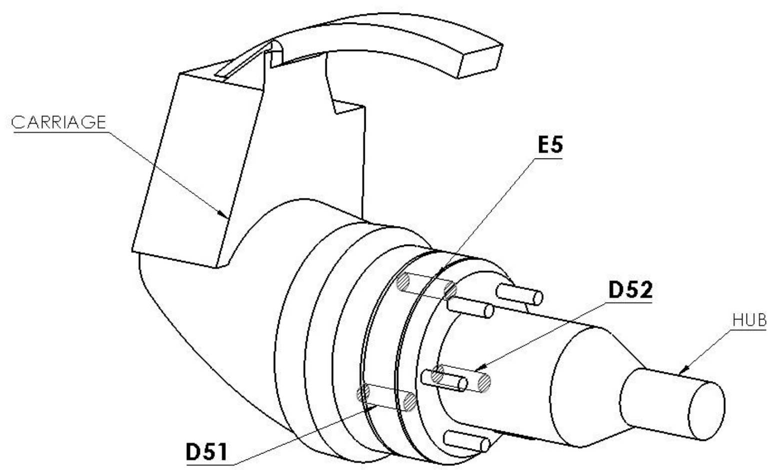

Figure 1.6: Calibration bracket and the location of load cells in the hub

As mentioned in the section above, the Force and Moment Measurement System uses 6 load cells placed at three vertices of an equilateral triangle, with 2 load cells at each vertex. The pitch diameter of the triangle is accurately 200mm and two load cells are used at each vertex, as one load cell serves as a backup for the other in case of a damaged load cell situation.

The load cells in the carriage are not easily visible externally and are manufactured in-house by Michelin in France. They proved to be highly sensitive and linear within the working range of the tire testing machine. The idea behind using three load cells is to calculate forces and moments about in multiple axis. Although, the machine is not capable of calculating Longitudinal Force (F_x) and Rolling Resistance moment

(M_y), it is capable of calculating the Lateral Force (F_y), Overturning Moment (M_x) and Aligning Moment (M_z) from the interaction between the three load cells. Also, the Vertical Force (F_z) is calculated using an isolated load cell located below the carriage and mounted on the vertical motion actuator itself.

All the load cells are connected to the National Instruments SCXI Data Acquisition System (DAQ). The DAQ system is used with the LabVIEW software to view the real time data and also log the data into usable formats such as .xlsx, .dat, .lvm, etc to further process the data.

1.4 Problem Statement

The Calibration of any measurement device is a basic criterion for obtaining measurements. The development of highly precise sensor technology in the recent years has necessitated the development of highly precise calibration equipment. For the same purpose, the aim of this research is to calibrate of the three load cells located in the hub of the M-15 Tire Testing Machine's Force and Moment Measurement System.

The calibration of M-15 machine helps to maintain the quality of the measurements. The results of the calibration procedure give the 'Calibration Constants' as the output. However, these constants may vary by a fraction over the time because of the hysteresis and noise of the sensors. In our case, we are calibration a system of load cells, which also gives rise to errors due to interaction of load cells in the setup. This calls for a re-calibration of the system regularly over time.

Therefore, the design criteria of calibration setup must include the feasibility of simple and quick calibration procedure to perform regular calibration of the Force and Moment Measurement System of the M-15 Machine. Consequently, the research also covers the steps involved in the calibration experiments by systematically documenting it.

CHAPTER 2: TESTING AND CALIBRATION PROTOCOL

2.1 Tire Testing Protocol

There are many tire testing and calibration protocols developed by standards organizations like SAE, ASME, ISO, the Tire Society, etc. Each of these protocols are developed to help standardize the experiments and tests being performed by various organizations. This not only improves the quality of tire testing data, it also quantifies the quality to compare and compete among organizations. The tire testing protocol is important for this research as it establishes limits for the testing needs such as minimum and maximum - Vertical Force (F_z), Lateral Force (F_y), Pressure (P), Inclination Angle , Slip Angle , Speed (V), etc. Therefore, establishing the limits for calibration of the M-15 machine.

The M-15 TTM follows the SAE's 'Force and Moment Test Method' protocol (SAE J-1987) for testing. It is the SAE recommended practice for all passenger car and light truck tires and is widely used in the tire industry. This method is suitable for accurate determination of Lateral Force (F_y), Longitudinal Force (F_x), Normal Force (F_z), Overturning Moment (M_x) and Aligning Moment (M_z) in steady state under free-rolling conditions with varying slip angle and normal forces. The table below shows the recommended working ranges and accuracy for the load cells used in the TTM.

Table 2.1: SAE J1987 Measurement Ranges and Accuracy

Measurement	Full Scale Range	Accuracy
Longitudinal Force (F_x)	0 to $\pm 1kN$	$\pm 10N$
Lateral Force (F_y)	0 to $\pm 15kN$	$\pm 150N$
Normal Force (F_z)	0 to $-24kN$	$\pm 240N$
Overturning Moment (M_x)	0 to $\pm 10kNm$	$\pm 100Nm$
Rolling Moment (M_y)	Not Measured	-
Aligning Moment (M_z)	0 to $\pm 1kNm$	$\pm 10Nm$

Additionally, the full-scale range recommended for the slip angle is $\pm 15°$ with an accuracy of $\pm 0.05°$. The test itself is carried out using two test formats - Full-Range Slip Angle Procedure and Low-Slip Angle Procedure. Both tests are carried out by varying slip angles incrementally while loading and unloading the vertical force also incrementally. While the Full-Range procedure is performed under the full range of slip angles, the Low-Slip Angle procedure is performed with limited slip-angle range to facilitate the calculation of Cornering Stiffness and Aligning Stiffness. The detailed test procedure is not described as it is out of the scope of this thesis report. Finally, it is important to note that the data may not be tampered in any form other than load cell taring, interactions, and transformation of coordinates to SAE system. Therefore, the calibration setup must be designed accordingly

2.2 Calibration Protocol

The calibration practices recommended by SAE refers to the National Institute of Standards and Technology for usage of Calibration Fixtures, Standard Reference Load Cells, Standard Dead Weights, and angle references. The above must be incorporated into the design of the calibration setup and procedures. The calibration protocol also recommends the usage of Class F dead weights for the initial calibration of the Reference Load Cells that are being used for calibration of the Force and Moment

Measurement System of the M-15 machine. Finally, the calibration may be done using the reference load cells or the designated standard dead weights by loading and recording the data in the individual load cells. This data is used to generate a load cell interaction matrix that removes the load cell interaction from the measurements.

Additionally, it is mandated that daily checks for calibration are done such as 'Shunt Calibration' and 'Control Tire check'. The control Tire Check may be performed by a recommended procedure like that of the actual test with less range of slip angles. The control tires are selected from the available standardized properties of the tires. They shall be smooth tread radial tires and needs to be properly stored to limit aging of the tire.

CHAPTER 3: DESIGN OF CALIBRATION SETUP

3.1 Calibration of Force and Moment Measurements

The M-15 machine can measure Lateral Force (F_y), Vertical Force (F_z), Overturning Moment (M_x) and Aligning Moment (M_z). However, the three load cells in the hub are used to measure F_y, M_x and M_z as the force F_z is measured using an external isolated load cell located below the carriage. Therefore, the focus of this research is on the calibration of the forces and moments calculated by the hub of TTM (i.e. F_y , M_x and M_z).

The concept of calibration for a load cell is applying known (reference) loads on the load cell and interpolating the voltage/strain output to that known load values. This concept remains unchanged with the calibration of any sensor in general. However, while dealing with a system of load cells present inside a mechanism, we cannot isolate them from the system and calibrate each load cell individually. One of the main reason being the interaction between load cells[11]. So, a calibration setup must be designed to apply reference loads on the hub while the load cells are inside it. To accommodate for applying loads on the hub, Michelin designed a 'Calibration Bracket' as shown in the figure The calibration bracket is mounted onto the hub like a tire.

Reference Forces are then applied close to the contact patch of the tire to simulate tire testing[12]. As mentioned earlier, the SAE tire coordinate system is used throughout this research. The positive axes of the Forces and Moments are depicted in the figure by following SAE tire axis. The following sections show the concept of applying F_y, M_x and M_z on the calibration bracket.

3.1.1 Calibration of F_y

The calibration of F_y requires a force in the $+ve$ and $-ve$ Y-axis be applied. The calibration bracket is designed such that a force can be applied as close to the road wheel as possible (as it is close to the tire contact patch while testing) along Y-axis . The point of application of the load is depicted in the figure A reference load cell is used while applying the load to determine the accurate load that is being applied always. This causes the three strain load cells E5 , D51 and D52 to reach a static equilibrium that is discussed in detail in chapter 5.

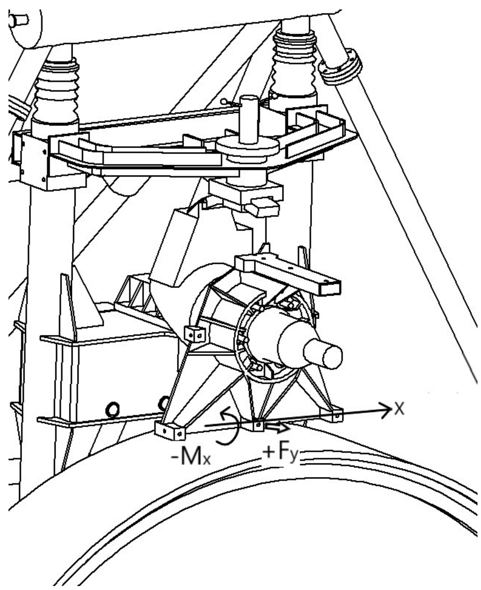

Figure 3.1: Applying F_y and M_x

Due to the design of the carriage, the calibration bracket is free to rotate about the hub's center axis and steer along with the carriage. This freedom to rotate can cause the calibration bracket to react unpredictably when applying load in the F_y direction. To prevent this motion the steer angle is locked using a pneumatic system. By applying F_y accurately along the F_y direction the freedom to rotate about hub's center axis is also automatically adjusted and fixed. But this force not only applies Lateral Force (F_y), it also applies an Overturning Moment (M_x) as shown in the calibration of M_x.

3.1.2 Calibration of M_x

The calibration of M_x requires a force in the $+ve$ and $-ve$ Y-axis be applied. So, It can be easily calibrated along with the calibration of F_y. Like that of the F_y pull, the Force applied is as close to the road wheel as possible, along the $Y - axis$. The figure covers the depiction of the Overturning Moment, M_x. It is intuitively that among the three load cells, E5, D51 and D52 although D51, D52 are reading reaction forces, the load cell E5 reads the maximum reaction force.

3.1.3 Calibration of M_z

The Calibration of M_z requires a couple to be applied on the hub with the help of the calibration fixture. For the application of couple about z-axis in both $+ve$ and $-ve$ directions mount points are provided on the calibration bracket 600mm apart. The point of application of forces is shown in figure. By locking the steering angle with the help of the pneumatic system, aligning moment can be applied. Since the M_z does not require forces as high as the F_y or M_x, standard dead weights and pulley system is used to apply forces for generating the M_z.

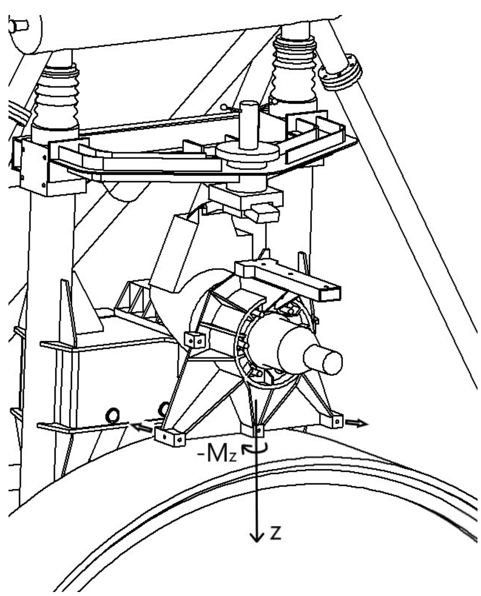

Figure 3.2: Applying $+M_z$

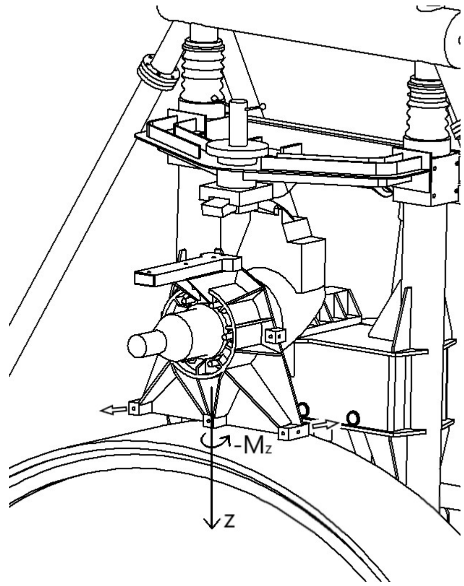

Figure 3.3: Applying $-M_z$

3.2 Overview of Calibration Setup

The calibration setup consists of number of parts working together such as pulleys, airbags, pneumatic lines, etc to perform calibration of the load cells in the hub. The list of components used, and their working is discussed below. By referring to the figures it is easy to understand the functions of each component.

The list of main components involved in calibration are shown in the figure below. While the main component to be designed for the calibration is the 'Calibration Fixtures', number of other parts are mounted on the calibration fixtures such as: airbags, pulleys, connecting elements, dead weight stands, reference load cell, pneumatic lines etc. The main components involved and the functions of each of these components are discussed in detail below.

Airbag: Referring to the range of the load cells, application of the Lateral Force (F_y) using dead weights is not possible. So, pneumatic air bellow is used to apply the force along Y-axis direction. The airbag chosen for calibration is a Dunlop Pneuride, 2 lobe, 10 in diameter airbag. Three airbags are used at each calibration fixture for pulling in the Y-axis direction.

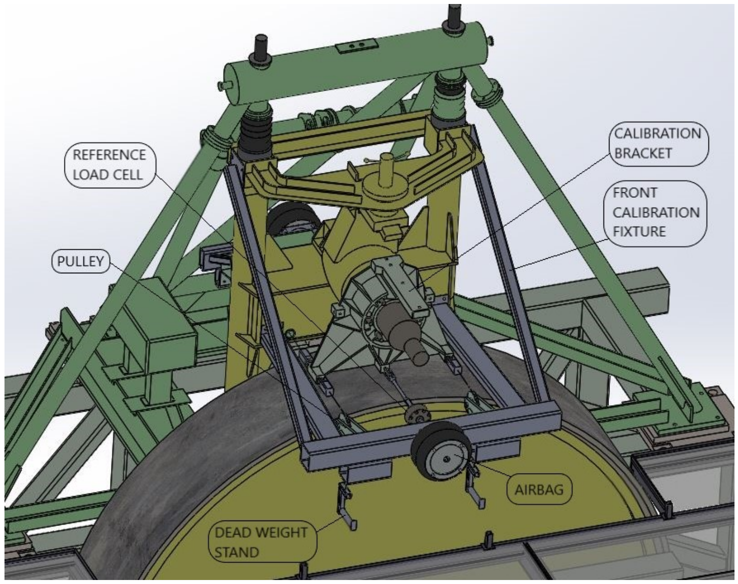

Figure 3.4: Applying $+M_z$

Pulley: The pulleys are designed to apply the moment Mz on the calibration bracket. They are mounted on the calibration fixture as shown and run a wire rope in tension to transmit the gravitational force due to dead weights horizontally into the calibration bracket in diagonally opposite directions. To balance the moments all four cable and hangers are hung continuously over the pulleys regardless of use of the dead weights.

Dead Weights: The dead weight hangers are used to easily load and unload the dead weights to apply the Aligning Moment, Mz as required. The standard dead weights used are designated for calibration purposes. Similar to the airbags, the dead weights are chosen as four 10lbs rings used at each end based on the recommended Mz values by SAE protocol.

Reference Load Cell: Although the calibration dead weights are self-referenced, the airbags need a reference load cell to determine the load that is being applied. Therefore, a reference load cell from Load Cell Central with 200 lbf capacity is used to determine the load applied by the airbag. This reference load cell is used at all the airbags interchangeably as each test is isolated and does not require simultaneous testing.

Connecting Elements: Several connecting elements are used in the setup such as fasteners, clevises, cotter pins, wire ropes, wire rope fittings, rod-end bearings, spacers, etc. An accurate use of these elements is important to prevent unnecessary loads due to sudden tightening of the connecting elements. Especially rod-end bearing are used for joining each component as they are self-aligning and prevent twisting or side loads on the reference load cell.

Calibration Fixture: The fixtures used to mount all the essential components involved in the calibration are known as calibration fixtures. For the Michelin M-15 TTM custom calibration fixtures are designed and manufactured in the lab to be used for the calibration. The calibration fixture must be strong enough to withstand the reaction forces without failure. Since there are no moving parts, only static stress analysis is done on the fixtures using Abaqus CAE software to check for the feasibility of the fixture design to withstand the loads involved.

Pneumatic System: The pneumatic system consists of a pressurized air supply, air pressure regulator and a four-way valve. The pneumatic system has two main functions. It is used to lock the steering angle to 0° while applying force in the y-axis direction. This helps prevent any unnecessary aligning moments from applying on the calibration bracket. The pneumatic system also controls the airbags with the help of the pressure regulator. It is controlled manually with hand using the reference load cell reading as a reference to limit the test.

3.3 Design of Calibration Fixtures

Although the basic calibration design criteria remain the same, to apply forces and moments in all the directions, three different calibration fixtures are designed. Their design is discussed in detail in the following sections.

3.3.1 Front Calibration Fixture

The front calibration fixture is designed to apply Lateral Force, $+F_y$, Overturning Moment, $-M_x$ and Aligning Moment, $\pm M_z$. For both F_y and M_x, application of load in only one direction is possible as the airbags can apply only pulling force when pressurized. The moment Mz can be applied in both directions with the help of rear calibration fixture.

From the figure shown below, we can see that the basic criteria for the design of the front calibration fixture is to create mounting for the airbag and two pulleys. It also needs be strong enough to withstand the forces without showing compliance in the frame. Since the frame is not being subjected to any kind of dynamic loads, a simple static finite element analysis is performed to check the factor of safety and rigidity of the frame.

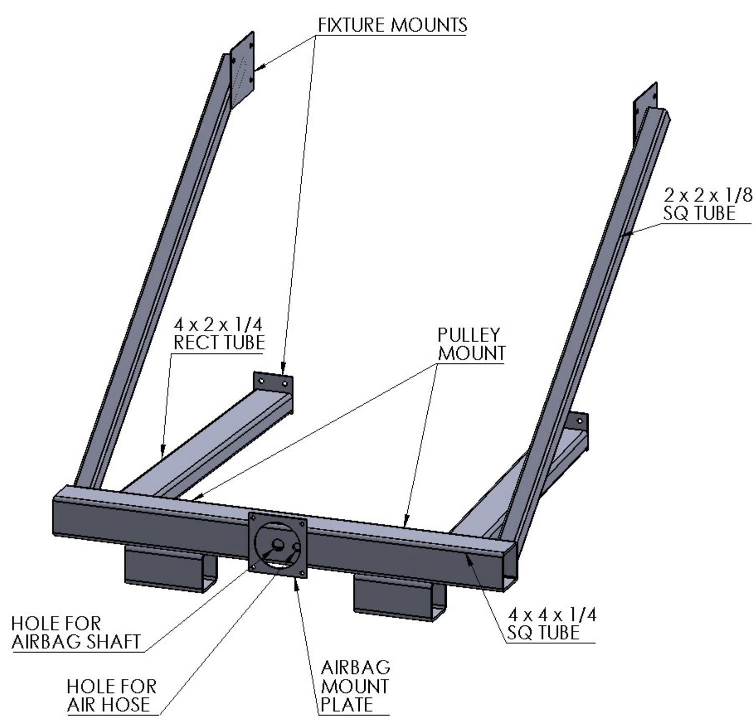

Figure 3.5: Front Calibration Frame

Further, the material is selected is ASTM A500 Grade B structural steel. A combination of sq tubes, rectangular tubes are used as shown in the model below. The selection of tubes used is based on the availability of material as well as maintaining rigidity of the structure during test. The wall thickness of .25in has made is easy to drill and tap holes to screw the pulleys directly onto the fixture instead of using nuts on the other end. An important feature of the fixture is the air bag mounting plate that is mounted at the center and has a guide hole to properly fit the airbag into the plate. This helps in aligning the airbag accurately for maintaining precise distance. To facilitate the airbag shaft and air hose fitting, two holes have been made in the main mounting member.

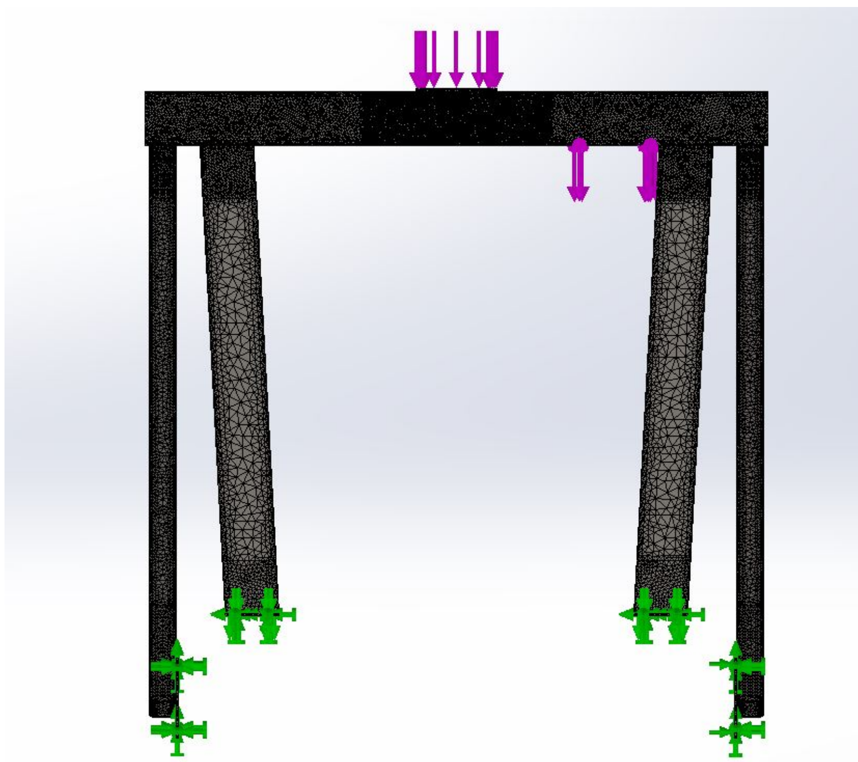

Figure 3.6: Front Fixture Meshing and Boundary Conditions

The fixture has been analyzed with Finite Element Analysis (FEA) using Solidworks Simulation software. By performing baseline and further refined simulations it was observed that the mesh quality shown in the figure is sufficient to obtain converged solution with 1365870 nodes. The main focus was to determine the approximate Factor of Safety (FOS) in the structure of the calibration fixture. The results may be intuitive, as it shows that the stress is only concentrated in the airbag plate. However, the maximum stress in the airbag mount plate is about 98.52 MPa and the Yield Strength of the steel is about 325 MPa. Thus, determining the min FOS in the fixture to be 3.23. A close up of view of the stress distribution on the airbag plate is shown in the figure below.

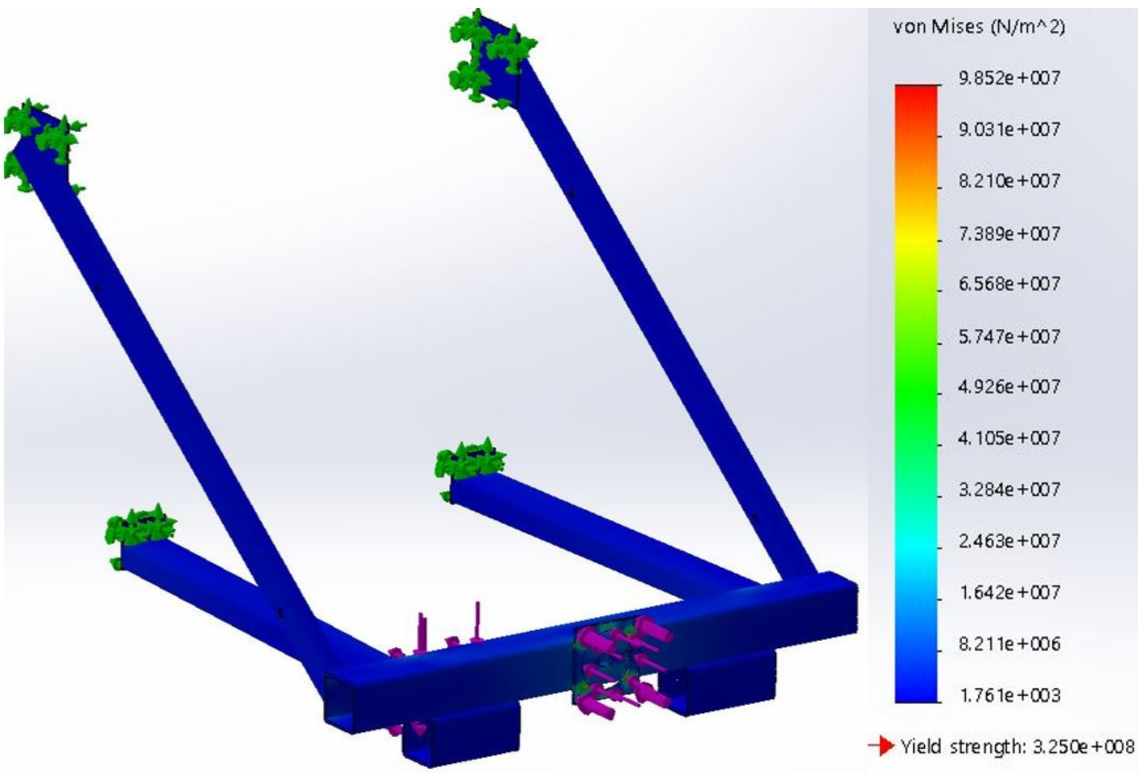

Figure 3.7: Stress Analysis of Front Calibration Fixture

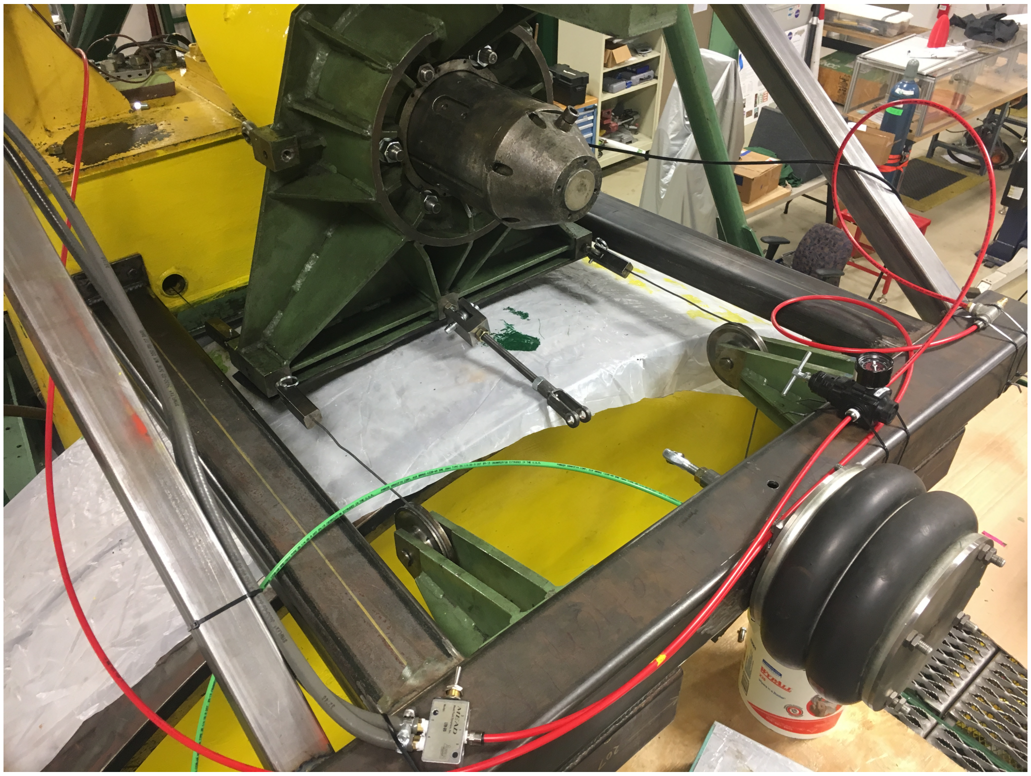

Figure 3.8: Front Calibration Fixture Full Setup

3.3.2 Rear Calibration Fixture

The rear calibration fixture is similar to the front except for its smaller size due to the geometrically constrained environment in trusses of the rear frame. It is designed to apply Lateral Force ($-F_y$), Overturning Moment ($+M_x$) and Aligning Moment ($\pm M_z$). For both F_y and M_x the load can be applied in the specified direction only. The nature of the airbag to apply only pulling load is limited to applying the above force. But the application of M_z in both the directions is possible with the help of the front calibration fixture.

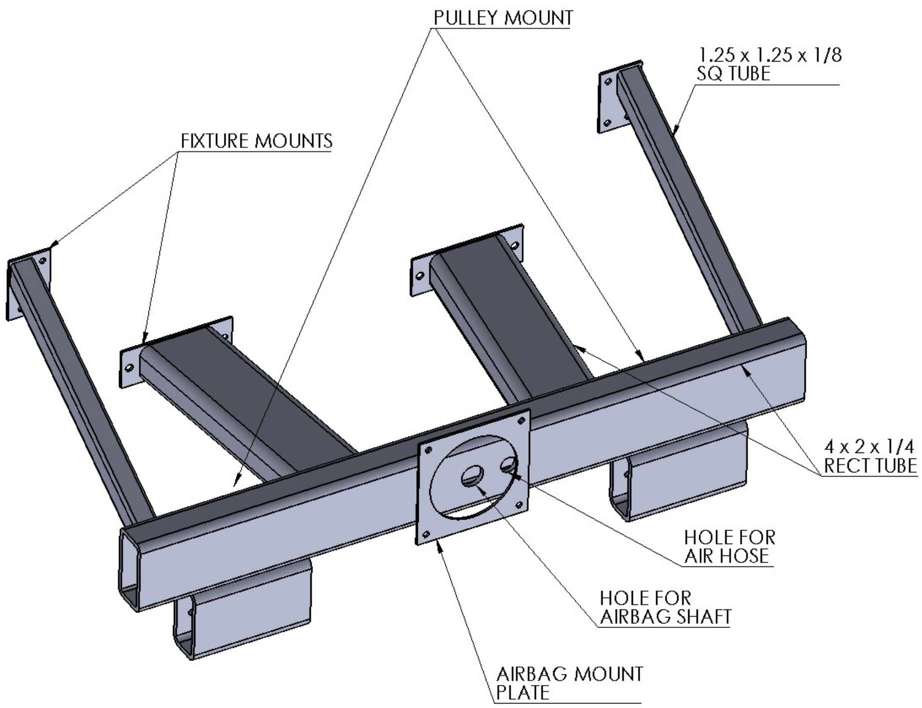

Figure 3.9: Rear Calibration Frame

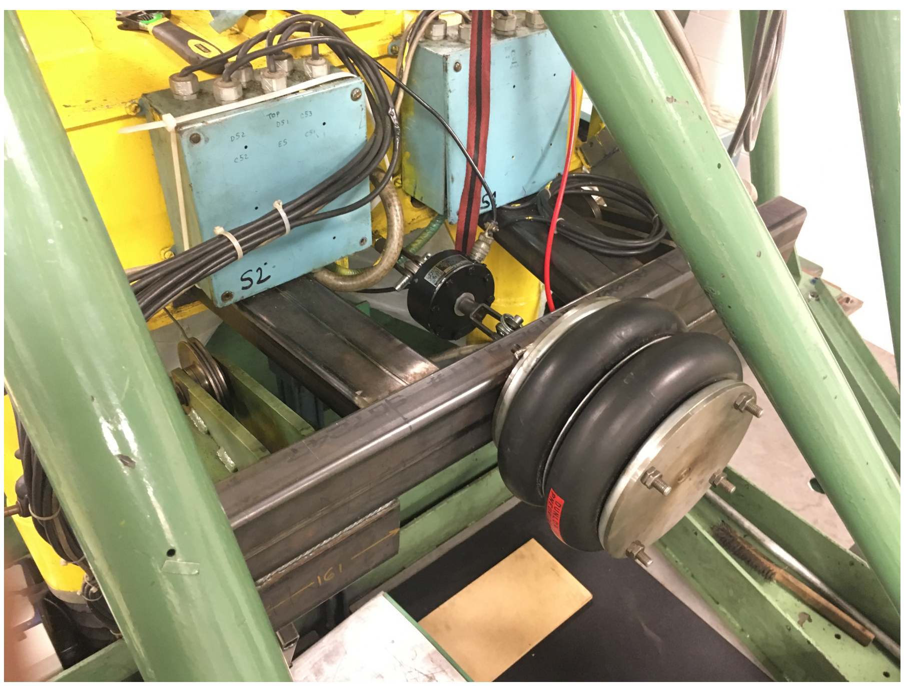

Figure 3.10: Rear Calibration Frame Full Setup

The figure shows that the main function of the rear calibration fixture is to mount the airbag and pulleys. The construction of the rear calibration fixture also provides a guide hole for mounting the airbag at a precise location as well as holes for the airbag shaft and air hose fitting. The selection of structural members is shown in the diagram. Both structural rigidity and strength are considered for this design. A 6.27mm thick material (0.25in) is used for mounting the pulleys, as it is possible to screw the pulleys onto the fixture directly without using the nuts.

Although most of the design inspiration is directly taken from the front calibration fixture, the space available for mounting the rear calibration fixture onto the yellow frame is very constrained and a tight tolerance is necessary to achieve this design.

3.3.3 Adjustable Calibration Fixture

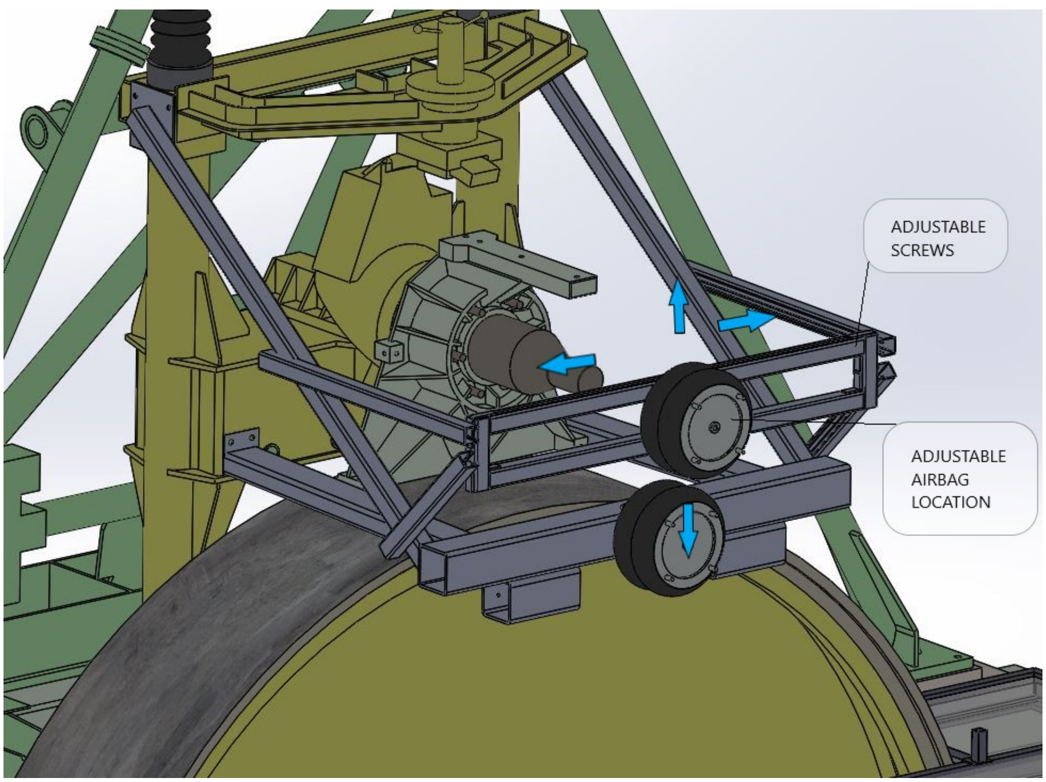

Figure 3.11: Adjustable Calibration Frame

The decision to build an adjustable calibration fixture at the hub center is made for pulling the hub both from the center and each load cell individually. It is not feasible to build a different calibration fixture for each of these cases. So, an adjustable calibration fixture can be versatile and can be adjusted according to the test being done. Unlike the front calibration fixture and rear calibration fixture, the adjustable calibration fixture is not mounted onto the tire manipulating system (yellow frame). It is mounted on the front calibration fixture itself. Although the adjustable calibration fixture does not have a system to push on the hub in $-ve$ Y-axis direction, it is helpful to apply loads at each load cell to determine the force in each load cell.

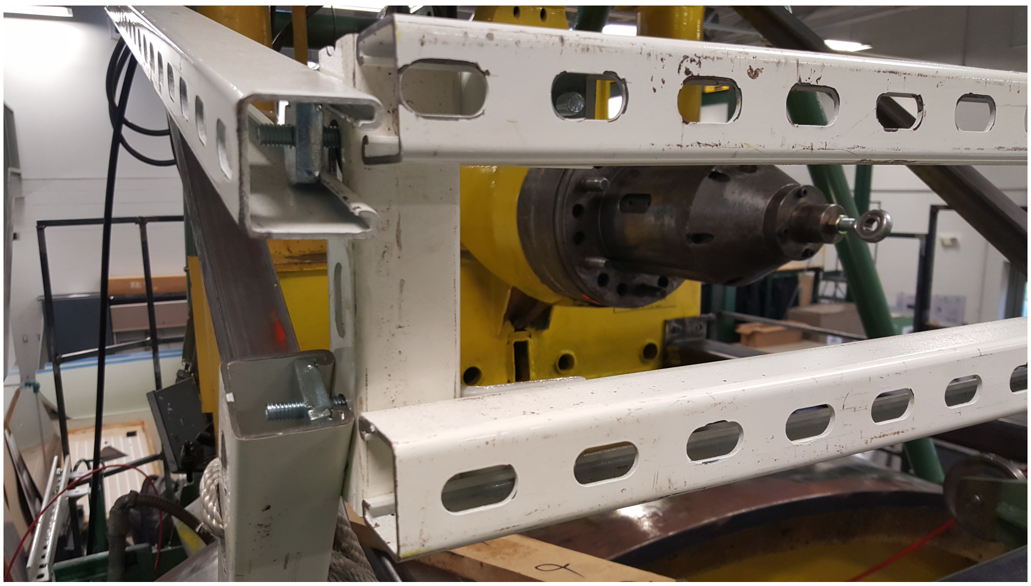

Figure 3.12: Adjustable screws on the Fixture

The figure shows the design of adjustable calibration fixture. Adjustable screws are provided to adjust the position of the airbag and slotted members provide easy tweaking in the position of the air bag in the X-axis direction. However, this design has the fundamental flaw of not being able to stay at a rigid location while applying load. This is because of the compliance in the slotted members. Having multiple screw joints not only adds to the compliance, it also creates difficult situations while changing from one test to another. The adjustments are based on measuring the angles using a precise digital angle indicator to attain a precise location for pulling.

CHAPTER 4: EXPERIMENTAL PROCEDURE

4.1 Setting up the Calibration Equipment

Setting up the calibration is done in two steps - Mounting of the calibration fixtures and setting up the DAQ system. Setting up the calibration fixtures requires the operator to carefully study the experimental procedure to determine the expected errors of the setup. Since, calibration is a precision work, setting up the fixtures and the rest of the components accurately is very important[13]. Often, mounting and adjusting the calibration fixtures take considerable amount of time compared to the setting up of the DAQ system for calibration. The sections below discuss in detail about the procedure for mounting and adjusting the calibration setup as well as the DAQ system.

4.1.1 Mounting and Adjusting the Calibration Setup

The mounting of the calibration fixtures is done using the cranes. The rear calibration fixture is mounted using the mechanical crane, whereas the front calibration fixture is mounted using the main electric crane in the front of the M-15 machine. However, the mounting of calibration setup always starts with mounting the calibration bracket. It is simple as it is directly mounted onto the hub's bolt circle.

For the front calibration fixture and the adjustable calibration fixture, they lifted onto the working platform and moved towards the hub. Once they are matched with their mount locations on the yellow frame, they are bolted down with hand just enough that they can still be adjusted but the bolts can hold the calibration fixture in place. The next step is to check if the calibration fixture is level using a digital angle indicator. By applying slight load in the +Fy direction, we can check to see if the lateral position of the airbag is correct. Thus, the front calibration fixture can be successfully mounted by tightening the fixture completely onto the yellow frame.

Figure 4.1: Mounting the Front Calibration Fixtures

For the adjustable calibration fixture, as it is already mounted on the front calibration fixture, it just needs to be adjusted using the digital angle indicator and the adjustable screws. After adjusting the position in X, Y and Z- directions individually, the resultant position can be checked to make final adjustments in the airbag using the slots in the members of the adjustable calibration fixture.

For the rear calibration fixture, it can be lifted and mounting like the front calibration fixture from behind the yellow frame using a manual crane. It is then matched with the mount locations on the yellow frame and bolted down with hands like the front calibration fixture. It is then adjusted using the digital angle indicator to check for the level of the calibration fixture[14]. Thus, accurately mounting and adjusting the calibration fixture onto the yellow frame.

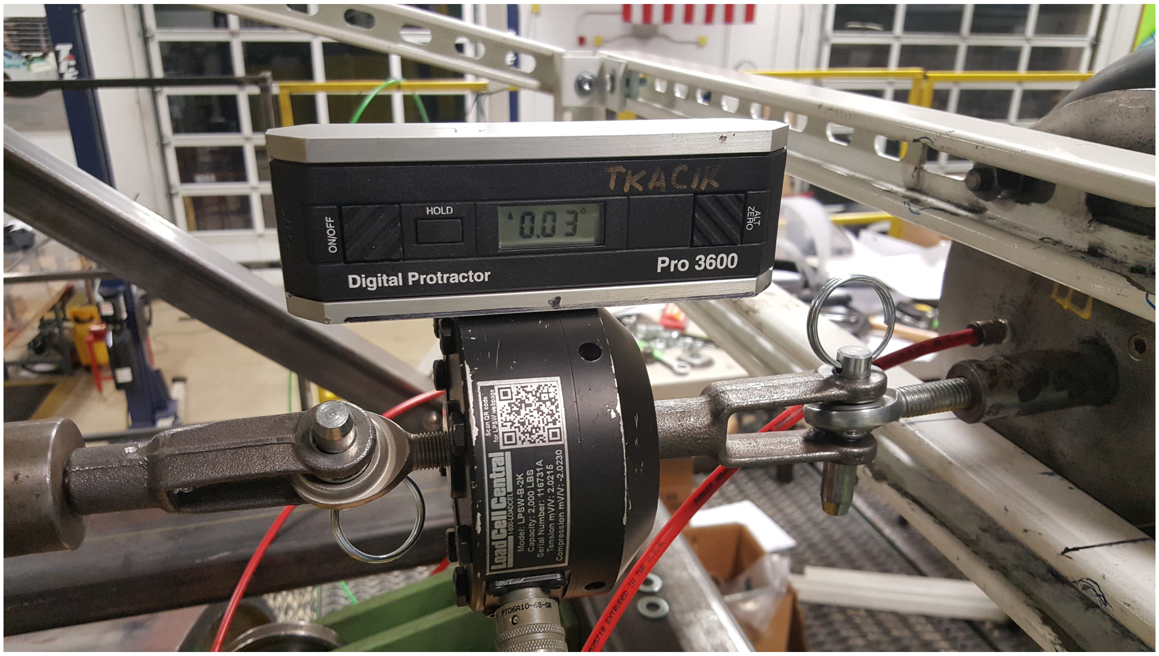

Figure 4.2: Adjustments using the angle indicator

4.1.2 Setting up the DAQ System

The setting up of DAQ system is simple compared to the setting up of the calibration fixtures. The DAQ system used for the calibration of M-15 machine is the National Instruments SCXI system. It uses the rugged SCXI 1100 chassis with the strain gauge load cell module package SCXI 1600 and SCXI 1314. The module package has the capacity to read 8 channels simultaneously. However, among the 8 channels, the DAQ system only uses 4 channels - D51, D52, E5 and Reference Load Cell. The three load cells inside the hub are read using mV as they are custom made by Michelin. However, the reference load cell can be read directly in terms of strain values as the SCXI module package has the capability of converting the voltage output of load cell into strain for a load cell for which the specifications are known.

Figure 4.3: National Instruments Data Acquisition System

The software used along with the National Instruments DAQ chassis is LabVIEW 2017. A LabVIEW program is created using a producer consumer loop to dynamically view the real-time data and log the data in the form of .xlsx files. The LabVIEW software is highly versatile in this regard, as it can process the signal from each load cell to reduce the noise and adjust the sample rate of the data being logged. The front panel can be used to view the data as shown in the figure The calibration setup also can calibrate the load cells in two formats - Offset Nulling Calibration and Shunt Calibration.

The Shunt Calibration is a type of calibration where the noise due to the connections and unnecessary resistances created by the DAQ system itself can be eliminated. Shunt calibration is performed using a large and accurate resistor, that is connected in parallel to the wheat stone bridge. Then the excess reading is measured and removed mathematically from the output value.

The Offset Nulling Calibration is done every time the DAQ system is started. It is performed to tare off the zero values in all the load cells. When offset nulling is not performed, it will to give a reading even when there is no load applied on the load cells. It gets worse over the time but, the LabVIEW software, provides a simple solution by mathematically zeroing the reading when no load is applied on the load cells. This is particularly helpful when the load cells cannot be isolated from a system to calibrate them separately[15].

4.1.3 Precautions to be taken before testing

Due to the nature of calibration work, several precautions are to be taken while performing the tests to attain clean data. This data can be confidently processed to obtain the calibration constants. Although a detailed list of precautions are given below, it is recommended to measure any geometrical distances and angles that may be intuitively important and double check for the accuracy in the calibration setup. Precautions:

- Zero the steering angle by taking the edge of the road wheel as reference to the calibration bracket before locking the steering.
- Measure the inclination angle by taking the top surface of the calibration bracket as a reference surface, and ensure that it is within $\pm 0.05°$
- Perform offset nulling of the three load cells inside the hub while the dead weight stands are mounted, and the digital angle indicator is placed on top of the calibration bracket.
- Measure the angle of the wire rope connection between the calibration bracket and the pulleys and ensure that it is $\pm 0.1°$.

- Measure the angle of the connecting elements between the calibration bracket and the calibration fixtures and ensure that it is $\pm 0.1°$.
- While applying F_y, place the angle indicator on top of the calibration bracket to check if there is an Aligning Torque (M_z) that is present in the setup.
- Check for air leaks in all the fittings used for the pneumatic system.
- Remove the pressure that is trapped in the airbag using the relief valve after each test is completed.
- Check to assure the wire ropes are not touching the carriage guide holes behind the calibration bracket, used for applying the moment M_x.
- Check if all the fasteners are tightened before applying forces and moments.
- Inspect the studs, clevises, pins, rod end bearings before each test for any visible bends in them.

One of the focus of this research is to develop a systematic approach and develop a step by step method of calibrating the M-15 TTM. There are two main types of calibration tests performed - Calibration of each load cell and Main Calibration Tests. The steps to these experiments are discussed in detail below.

4.1.4 Calibration of each load cell

The calibration of each load cell is important as it helps determine the M_x that is generated even when force is applied only in the F_y direction. It also scales the less manageable volt output from the load cells to manageable force values on each load cell.

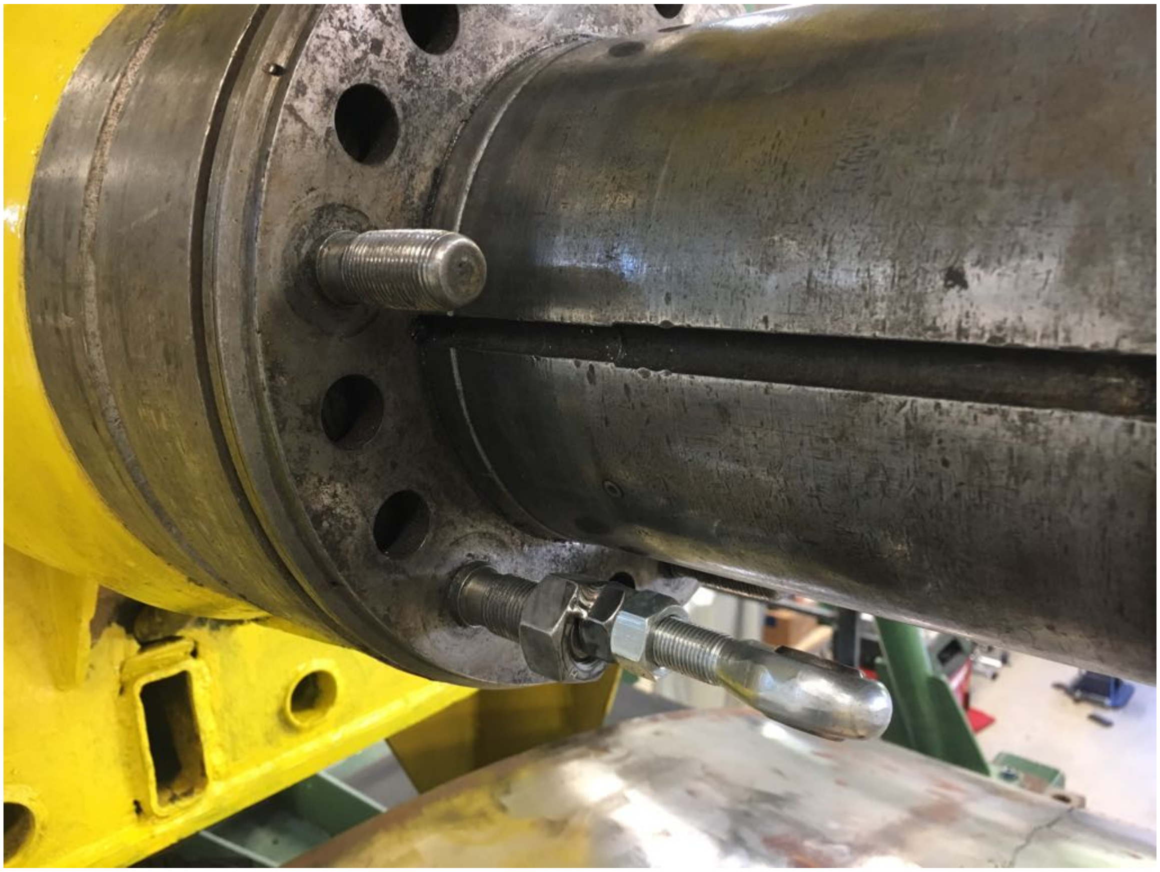

Figure 4.4: $+F_y$ pull on each load cell (notethe 2.5mm offset)

The procedure for calibration of each load cell is shown below in a step by step format. For simplicity, only D51 is shown which is like that of D52 and E5.

- Mount the adjustable calibration fixture along with the airbag onto the front calibration fixture.
- Connect the pneumatic supply, zero the steer angle using the edge of road wheel as a reference plane and lock it in position.
- Fasten the 'Offset Nut' onto the hub at one of the bolts.
- Rotate the hub and align the offset nut with the hub load cell D51.
- Now connect the airbag, reference load cell and the offset nut on the hub using the connecting elements - rod end bearings, studs, and clevises.

- Measure the angles using a digital inclino-meter and adjust the airbag location with the help of slots in the fixture and the adjustable screws.
- Select the directory of logging the data and start the LabVIEW program.
- Pull the hub in $+F_y$ direction while observing the readings of D51, D52 and E5.
- Notice that the readings in D52 and E5 are low compared to the readings in D51.
- By loading and unloading, find the most accurate location of the load cell D51 such that negligible readings are observed in D52 and E5.
- Once the spot is finalized, sweep the $+F_y$ pull from $0lbf$ to $1000lbf$ and back to $0lbf$, using the airbag and log the data.
- Release the trapped pressure in the airbag using the relief valve at the end.

4.2 Calibration tests

The calibration tests involve three different types of tests designed to apply F_y, M_z and M_x. These forces and moments are applied both individually and also simultaneously to obtain the load cell interaction matrix. The three tests performed are: Bottom Pull $+F_y$, Bottom Pull $-F_y$ and Center Pull $+F_y$. Both, Bottom Pull $+F_y$ and Bottom Pull $-F_y$ are similar carry similar test procedures whereas the Center Pull $+F_y$ test follows a different procedure.

Bottom Pull $+F_y$:

- Mount the calibration bracket and the front calibration fixture along with the airbag and pulleys onto the yellow frame.
- Connect the air supply to the pneumatic system and lock the steering angle to zero by taking the edge of the road wheel as the reference plane.

- Connect the airbag, reference load cell and the calibration bracket using the right connecting elements such that there is not too much slack in the connection initially.

- Connect the pulleys and the calibration bracket with the wire rope and dead weight mounts.

- Apply slight force in the $+F_y$ direction and load dead weights on both sides. Now measure the level of the wire ropes, connecting elements and the front calibration fixture using a digital inclino-meter. Adjustments can be made at this point to make these levels as close to zero as possible.

- Open the LabVIEW program, select the directory to log the data files and run the program.

- The setup is now ready to perform the sequential tests that are shown in the Table.

Center Pull $+F_y$:

- The adjustable calibration fixture is mounted along with the airbag onto the front calibration fixture.

- Connect the center pull sleeve with rod-end to the hub.

- By connecting the pneumatic system to the air supply, zero the steer angle and lock it, like that of the bottom pull test.

- Connect the hub to the reference load cell and the air bag using the connecting elements.

- Check the angles using an inclino-meter to adjust the fixture using the adjustable screws and the slots in the calibration fixture itself.

- Open the LabVIEW program and select the save location to log the data files. Now run the program

- The sequential tests can now be performed as shown in the table.

Table 4.1: Sequence of Tests Performed

Test Type	No of Tests	Applied F_y (N)	Applied M_z (Nm)
Front Bottom Pull	9	0 to 4450	$0, \pm 26.7, \pm 53.4, \pm 80.1, \pm 106.8$
Rear Bottom Pull	9	0 to -4450	$0, \pm 26.7, \pm 53.4, \pm 80.1, \pm 106.8$
center Bottom Pull	1	0 to 4450	0
Only M_z	8	0 to 4450	$\pm 26.7, \pm 53.4, \pm 80.1, \pm 106.8$

CHAPTER 5: ANALYSIS OF CALIBRATION TEST DATA

5.1 Calibrating each load cell

The output from the load cells inside the hub is in volts. There are two issues concerning this. The voltage values are in the order of 10^-3. Which makes it difficult to analyze the change in voltage due to the applied load. Also, by scaling the volts to force (lbf), it is easier to understand the data as well as predict the Aligning Torque (M_z) created by just the Lateral Force. It may not be intuitive to understand that a moment M_z is created by just applying the F_y force. This moment arises due to the errors in the calibration setup and the interaction between the load cells. If each of the load cells are not calibrated, it is not possible to find this error and quantify it.

Since the calibration of each load cell by isolating it form the hub of the carriage is not possible, the calibration needs to be done by applying the forces on the hub itself. The procedure for calibrating each load cell is mentioned in a systematic fashion in the section 4.2.1. By referring to the test procedure, we can understand that applying $+F_y$ force on each load cell may not eliminate reaction forces in the other two load cells but it is experimentally determined that 99.5 percent of the force is transmitted into the desired load cell. Refer the figure for the pictorial representation of this concept. Therefore, although this procedure may not provide the best accuracy, it is proven to be a reasonable approach towards calibration of the individual load cells inside the hub.

The above procedure gives the multipliers (constants) for D51, D52 and E5 to convert the voltage output to force in lbf. Refer the figures for the equations.

5.2 Calibration Model

The calibration model deals with the theory behind the calibration of the M-15 machine. The three main tests involved in the calibration are the Bottom $+F_y$ pull, Bottom $-F_y$ pull and Center $+F_y$ pull. Both the Bottom F_y pulls are trying to simulate the forces observed at the tire contact patch[16]. But this limits the calibration setup to a single radius of $.3m$, where the calibration bracket is pulled. To prevent the calibration setup from freezing the calibration constants to this single radius, we pull at the center of the hub to create a radius dependent scenario. Although the center pull creates a zero-radius test, it helps to understand that the calibration constants are not biased towards a single radius.

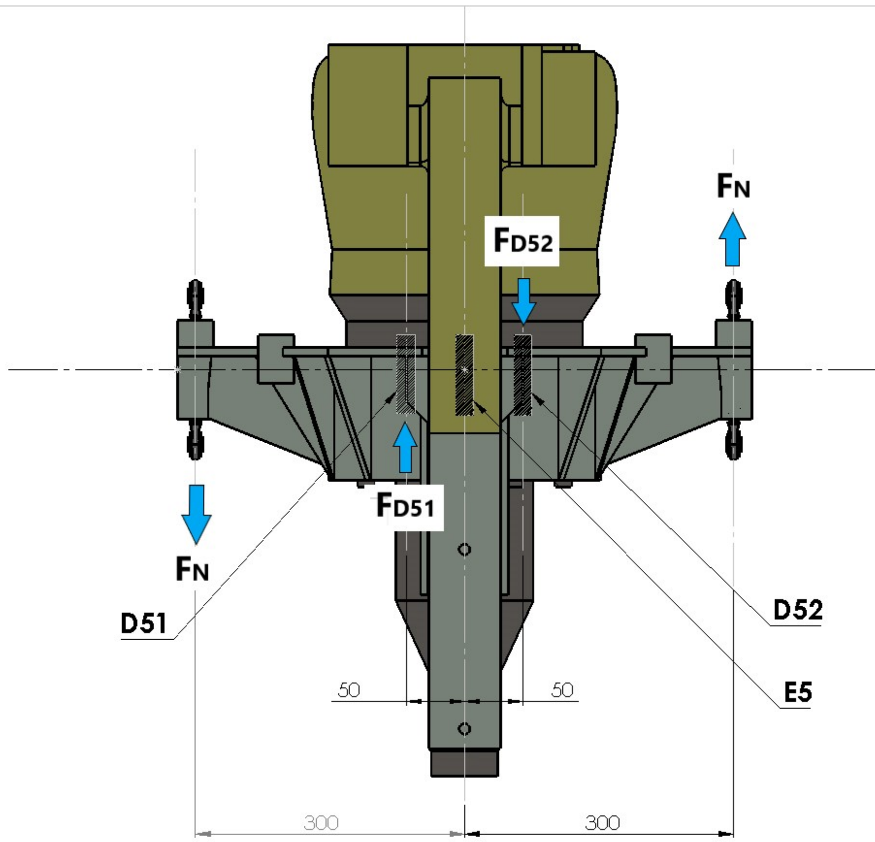

Figure 5.1: Free Body Diagram Showing Moment M_z

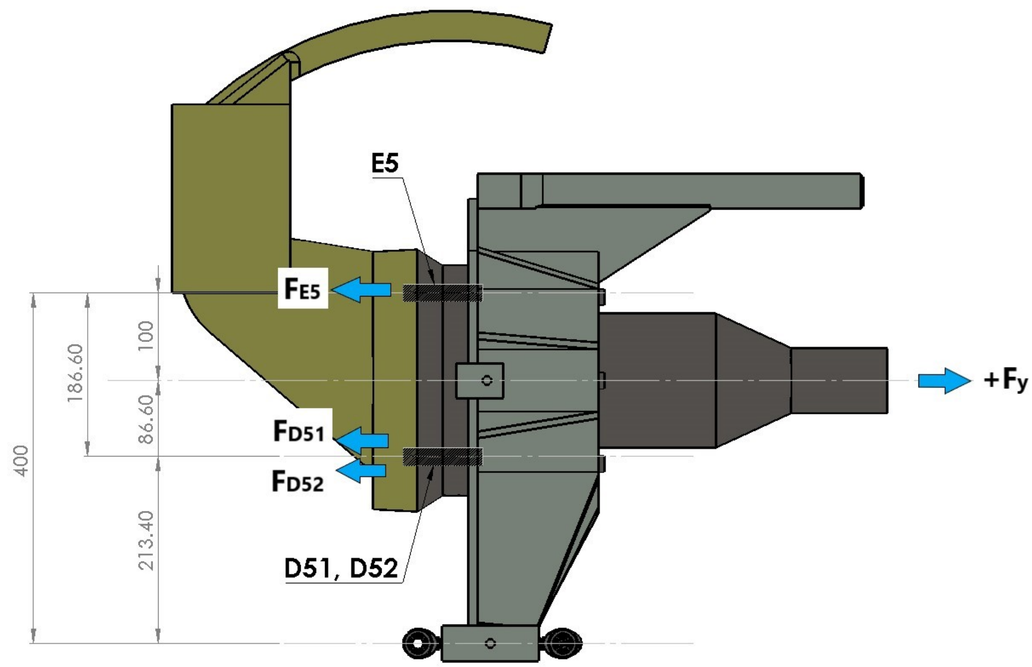

Figure 5.2: Free Body Diagram Showing Force F_y - center Pull

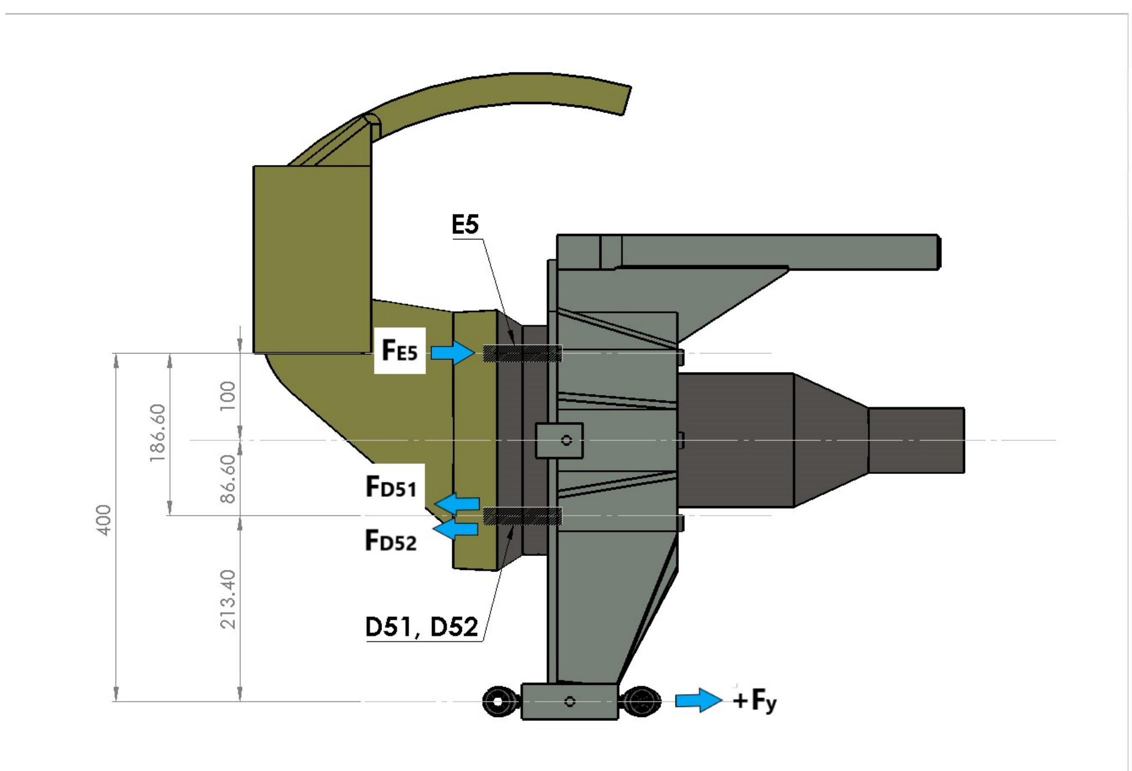

Figure 5.3: Free Body Diagram Showing Moment F_y - Bottom Pull

The fig show the forces applied on the calibration bracket and the reaction forces received by the load cells in the hub.

The Aligning Torque applied on the calibration fixture is depicted in the figure and the reaction forces can be calculated by using static equilibrium condition on the calibration bracket,

$$F_{E5} = 0 \tag{5.1}$$

$$F_{51} = F_{52} \tag{5.2}$$

By applying simple static equilibrium condition at the bottom pull $+F_y$, we arrive at the following equations,

$$F_{E5} = (\frac{213.4}{186.6})F_y \tag{5.3}$$

$$F_{D51} = F_{D52} = (\frac{200}{186.6})F_y \tag{5.4}$$

Similarly, the center pull F_y test causes the reactions as shown in the figure and by applying simple static equilibrium we can derive the following equations,

$$F_{E5} = (\frac{186.6}{86.6})F_y \tag{5.5}$$

$$F_{D51} = F_{D52} = (\frac{213.4}{100})F_y \tag{5.6}$$

The above equations can be used to calculate forces on each load cell. This is also accurately verifiable when the forces are applying as depicted in the figures. But simultaneous application of the forces causes the load cells the interact among themselves to cause erroneous results[17]. However, this can be eliminated using a curve fitting model developed through a solving software like MATLAB[18]. The theoretical approach is simple and can be intuitively obvious to some. By assuming that F_y, M_x and M_z are all functions of D51, D52 and E5 we can develop a load cell interaction matrix as shown below:

$$F_y = k_{11}(D51) + k_{12}(D52) + k_{13}(E5) + k_{14} \tag{5.7}$$

$$M_x = k_{21}(D51) + k_{22}(D52) + k_{23}(E5) + k_{24} \tag{5.8}$$

$$M_z = k_{31}(D51) + k_{32}(D52) + k_{33}(E5) + k_{34} \tag{5.9}$$

$$\begin{pmatrix} F_y \\ M_x \\ M_z \end{pmatrix} = \begin{pmatrix} k11 & k12 & k13 & k14 \\ k21 & k22 & k23 & k24 \\ k31 & k32 & k33 & k34 \end{pmatrix} \begin{pmatrix} F_y \\ M_x \\ M_z \end{pmatrix} \tag{5.10}$$

5.3 Analysis of Calibration tests

Thus, the sequence of the tests shown in table, can all be curve fitted together to calculate the calibration constants. The developed MATLAB program has the capability to generate these curve-fitted constants.

5.3.1 Processing the test data

Once the collected data is saved at a desired file directory and the data has been cleaned by checking the excel data files, we can load the directory into the MATLAB file. All the data is then loaded into the software in the form of an array consisting of all tests with each column corresponding to one test.

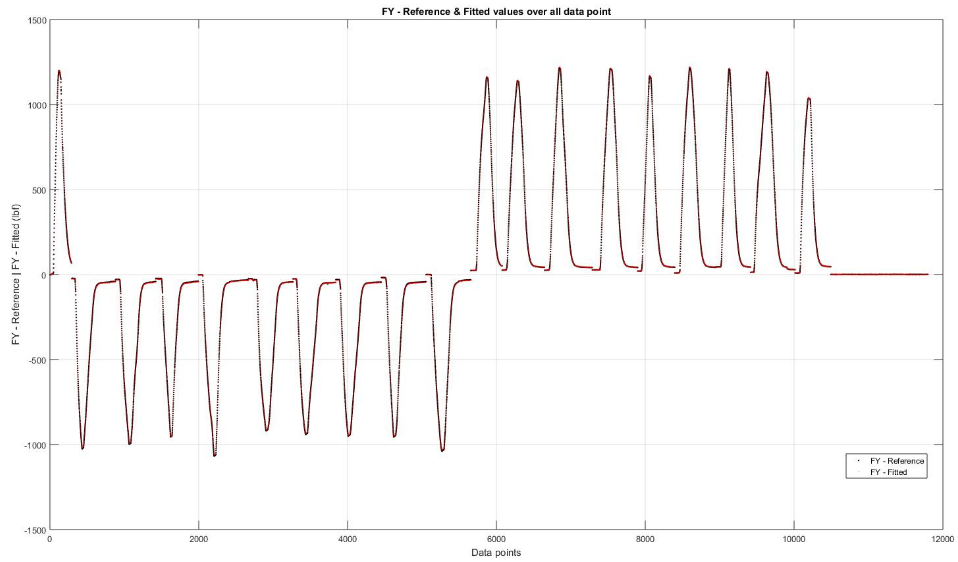

Figure 5.4: Curve fitted Force - F_y over all data points

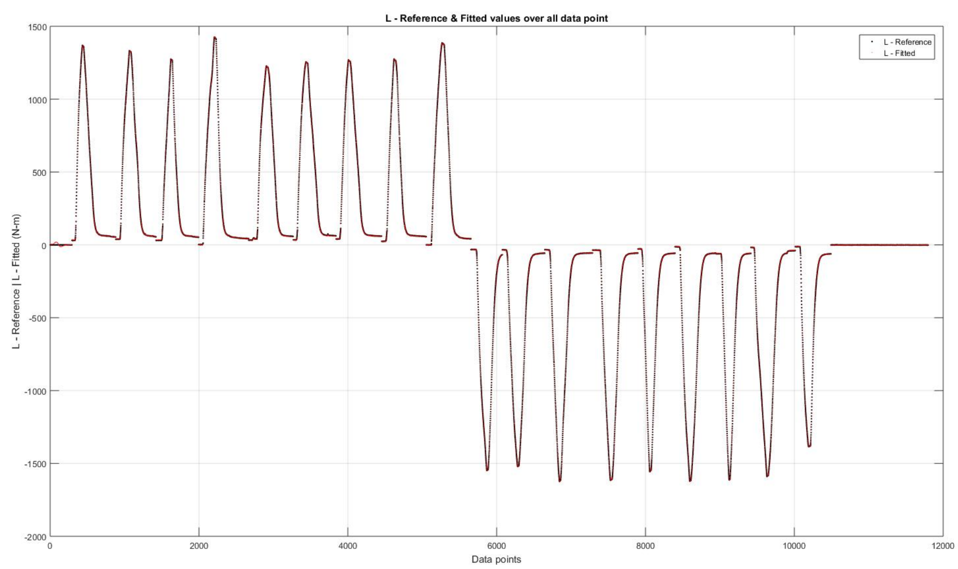

Figure 5.5: Curve fitted Force - M_x over all data points

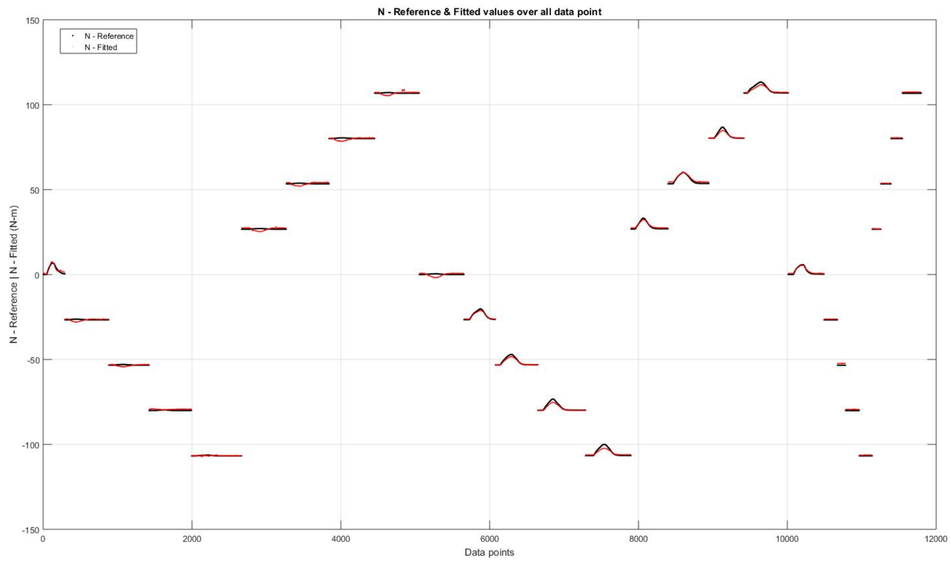

Figure 5.6: Curve fitted Force - M_z over all data points

An erroneous moment arm is sometimes generated which is calculated with the help of Bottom pull of only $+F_y$, $-F_y$ and the center pull of $+F_y$. This is due to the fact that the calibration fixture may have inherent geometrical limitations. To eliminate this, the moment M_z is calculated and added to the reference M_z. This acts as a correction to the aligning moment, M_z and gives more accurate calibration constants.

The data is then curve fitted[19] to reference F_y, M_x and M_z values using the load cell interaction matrix model. Each of these constants are calculated using linear curve fits. The plots shown below has the calibration constants with the curve fitted plots.

5.3.2 Error Analysis

The error analysis is an important criterion for calibration work. The accuracy is quantified and analyzed in this section. The idea behind this is to calculate the difference between reference values of F_y, M_x, M_z and the curve fitted values of F_y, M_x, M_z. The different types of plots highlight different scenarios in the test results.

This helps to debug any faulty assumptions taken in the calibration setup. Often, both error values and error percentages are required to understand test results fully.

$$Er_F = F_{calc} - F_{Ref} \tag{5.11}$$

$$Erp_F = \frac{(F_{calc} - F_{Ref})}{F_{Ref}} * 100 \tag{5.12}$$

$$Er_M = M_{calc} - M_{Ref} \tag{5.13}$$

$$Erp_M = \frac{(M_{calc} - M_{Ref})}{M_{Ref}} * 100 \tag{5.14}$$

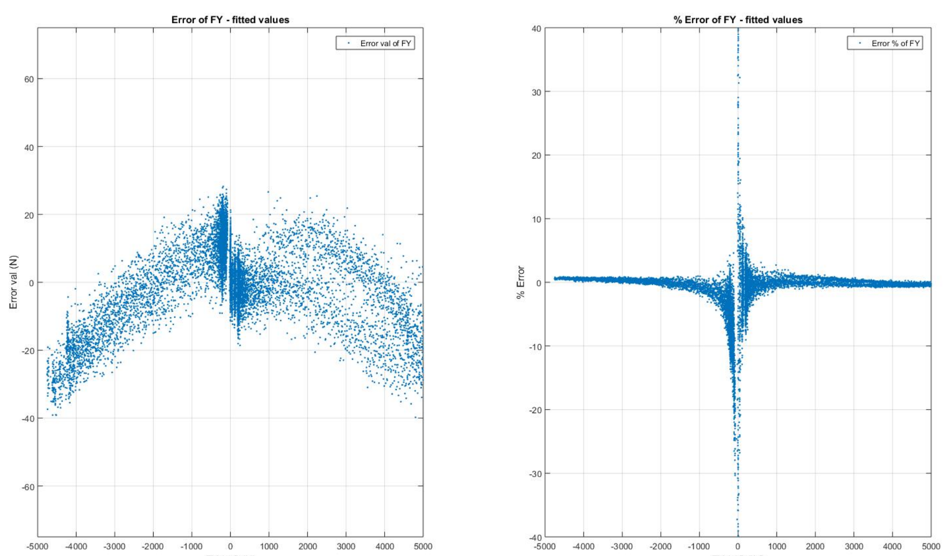

Figure 5.7: F_y - Error Value and % Error plots

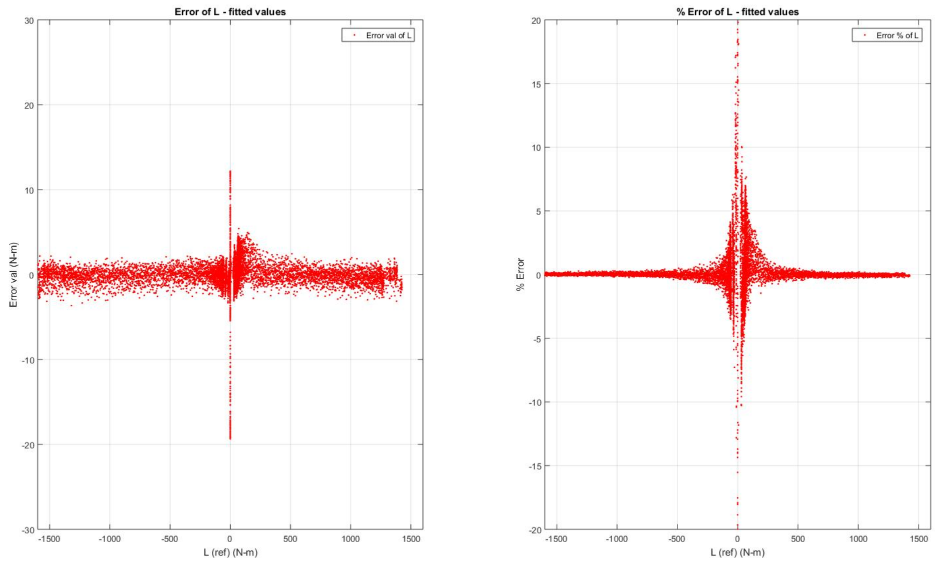

Figure 5.8: M_x - Error Value and % Error plots

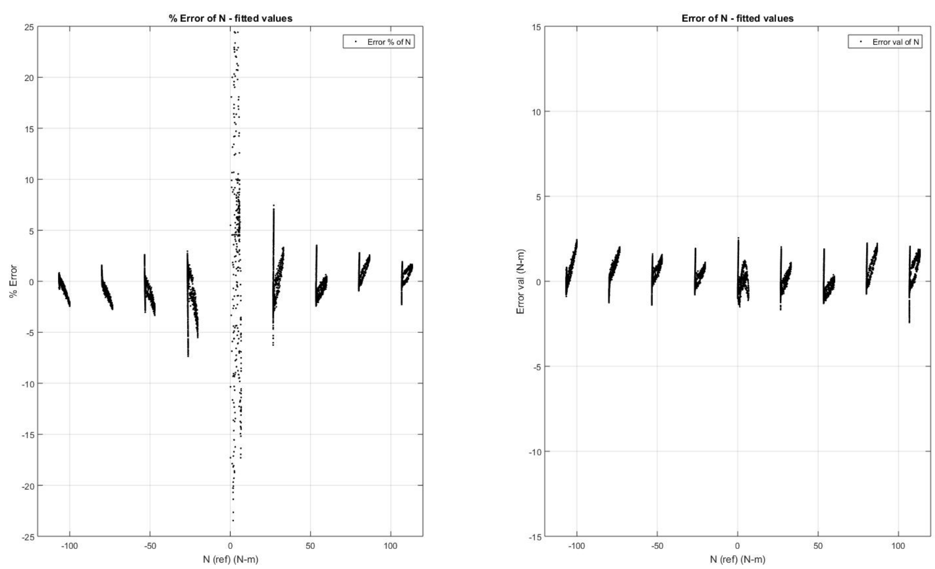

Figure 5.9: M_z - Error Value and % Error plots

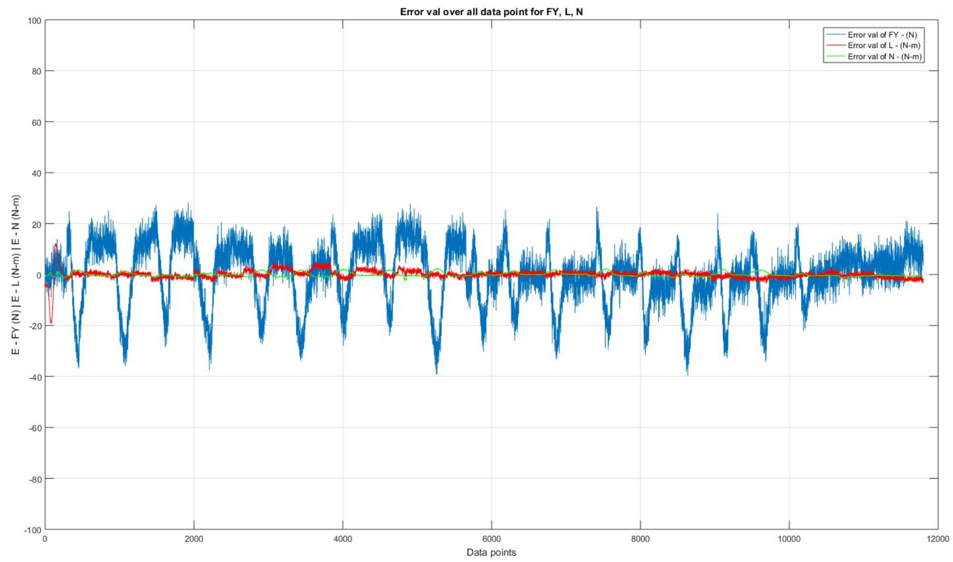

Figure 5.10: F_x, M_z and M_x - Error values over all the tests

Every tests result was analyzed to find the error at a particular area. This is analyzed until the root-cause of the error is found. Necessary adjustments to the calibration fixture are done to correct the error. This iterative process is very effective in the sense that, it can be objectively analyzed to obtain a counter measure for the main source of errors. Thus, the final minimized error plots are presented.

Table 5.1: Comparing Accuracy to SAE Standards

Measurement	Desired Accuracy	Accuracy Obtained
Lateral Force (F_y)	$\pm 150N$	$\pm 40N$
Overturning Moment (M_x)	$\pm 100Nm$	$\pm 17Nm$
Aligning Moment (M_z)	$\pm 10Nm$	$\pm 7Nm$

CHAPTER 6: RESULTS AND CONCUSION

6.1 Results

The aim of this research is to calibrate the M-15 TTM to find the calibration constants. The calibration constants are nothing but multipliers that are generated for the system of load cells D51, D52 and E5. These multipliers can be used for tire testing to calculate the forces and moments F_y, M_x and M_z.

To achieve this,

- Calibration fixtures are designed to apply forces and moments on the hub of the M-15 machine as desired.
- All the components required for calibrating the TTM are manufactured and assembled to carry out experiments.
- Several calibration tests are performed while tuning the setup to obtain results with desired accuracy.
- The obtained test results are processed and analyzed in an iterative fashion to minimize the errors as much as possible.

The table shows the calculated final load cell interaction matrix:

6.2 Conclusion

Due to the complexity of calibration procedures and large number of required tests, a systematic approach to calibrating the M-15 TTM has been developed. This procedure can be followed for future calibration work saving a lot of time trying to setup the fixture and perform calibration tests. A comprehensive report like this can also be utilized as a handbook or guide to calibrating a TTM.

The error analysis suggests that the final errors that are observed in this calibration setup are within the range of accuracy recommended by SAE Tire Force and Moment Test Method. Therefore, by calibrating the M-15 machine using the developed calibration procedure, reliable tire data can be obtained.

6.3 Future Scope

A broad research like this can have a scope of future work in multiple areas. But the important subjects of interest from the author's experience are listed as follows:

- The maximum range of forces and moment applied in this research are sufficient given the range of the hub load cells. But increasing this range with reference to the SAE recommended Full-Scale Forces and Moments is advised.

- The adjustable calibration fixture is designed to have the flexibility of adjusting it to apply +Fy force at a desired location. But the time required to adjust the fixture from one position to another is high. Therefore, this design can be further developed to reduce the time taken to adjust it.

- The calibrated M-15 machine can be used to test a tire for which, tire data already exists. So that a comparison of test data can be made to validate the accuracy of the calibration.

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