Quarterly report on "A Rheometer for measuring the material moduli for granular solids."

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1.0 INTRODUCTION

A great many industrial processes involve interaction between solids and fluids (i.e. gases or liquids). Combustion, gasification of solid fuels, shales or solid wastes, drying of particles, calcining, particle heating, regenerative heat exchangers, oxidation or reduction of ores, metal surface treatments and catalytic and thermal cracking are some of such processes. Solids and fluids serve different roles and several combinations of solids and fluids can arise in a practical situation. Thus, when considering processes or plants it is necessary to be clear as to the particular purpose served by the fluids and the solids. Heating and drying of solids, for example, involve heat and mass transfer only, whereas combustors, gasifiers etc. have the additional complication of chemical reactions which have to be carried out simultaneously with heat and mass transfer(cf. Howard(1)). Again, there are many processes where just the flow of granular particles take place, for example, the flow of food grain, coal or sand particles through bin, silo, hoppers, chutes, conveyor belts, inclined planes etc.

In most of these cases, a theoretical modeling of the process requires a complete and thorough understanding of the phenomena involved and constitutive modeling of the constituents along with the usual balance laws. In a process, where both a fluid and a solid constituents are involved, it is essential to model both the constituents such that the models accurately describes the characteristics of the constituent concerned. While there are many different models available for fluids, the models for granular materials lack from an understanding of the material parameters.

*Parenthetical references placed superior to the line of text refer to the bibliography.
1.1 Solid Constituent

In order to have a complete and thorough understanding of the whole process, it is required that we understand the rheological behavior of the granular material involved. This need is further strengthened by the fact that a better and economically efficient process would require a design based on the material involved in the process and the various other factors which govern the flow characteristics of the granular materials. This has motivated researchers to investigate the behavior of granular materials experimentally and model them theoretically such that their model describes the known experimental observations. Despite all this, even at this stage of the advancement of science, there is still a lack of understanding of the mechanics involved in the flow of these materials because of the fact there is not one universally accepted constitutive relation that governs the flow of granular materials. There are many different constitutive models for these materials; but before discussing them I would like to discuss the phenomena and characteristics which are typical of granular materials.

A granular medium is not a solid continuum since it deforms to the shape of the vessel containing it; it cannot be considered as a liquid for it can be piled into heaps; and it is not a gas for it will not expand to fill the vessel containing it. Another important phenomena observed in granular materials is a unique property called "dilatancy". This was first observed by Reynolds(2). Dilatancy is described as the phenomena of expansion of the voidage that occurs in a tightly packed granular arrangement when it is subjected to a deformation. Many of the existing theories for flowing granular materials use this observation to relate the applied stress to the voidage and the velocity. Moreover granular materials exhibit phenomena such as "normal-stress effects", similar to non-Newtonian fluids. It is very difficult to characterize bulk solids, which are composed of a variety of materials. This is mainly due to the fact that small variations in some
of the primary property of the bulk solid such as the size, shape, hardness, particle density, and surface roughness, can result in a very different behavior. Furthermore, secondary factors such as the presence or absence of moisture, the severity of prior compaction, the ambient temperature etcetera, which are not directly associate with the particles, can have significant effects on the behavior of the bulk solid. This gives an idea about the complexity of the behavior of granular materials and a complete understanding of such kind of materials will require a thorough investigation of the material parameters involved.

These materials parameters in general depend upon the model which is used to describe the characteristics of the granular materials. There have been many attempts at describing the mechanics of granular materials based on continuum, mixture, kinetic theories, and sometime based on the assumption that granular materials behave like a Newtonian fluid. School which consider behavior like Newtonian fluid usually describe the stress tensor for these materials as if they are linearly viscous fluid exhibiting "simple Newtonian behavior"; however, experimental observations do not suggest so. Another, and a major drawback is the absence of the knowledge for the term $p$, i.e., spherical part of the Cauchy's tensor.

Kinetic theory suffers from the fact that a theory based on that assumption can only describe flow behavior of granular materials when particle velocity is tremendously high and there are collision of particles taking place and a concept of mean free path should exist. This type of behavior is usually observed in avalanche or rapid flow of granular materials. But in such a situation determination of the material parameters involved in building that particular model is quite a challenging task. Recently, Massoudi\(^{(3)}\) based on continuum and mixture theory has attempted to model the granular materials. There he has tried to overcome the common problem described above, but in his model for describing the Cauchy's stress tensor for the granular material, there are quite a few number of material parameters involved. I will describe, in brief, the model as devised by Massoudi\(^{(3)}\) based on continuum theory.
1.2 Constitutive modeling of granular materials based on the continuum theory

A body $B$ is a smooth manifold of dimension three whose elements are called particles. Let the body $B$ occupies an arbitrary reference configuration $\Omega_0$, where $X$ designates the spatial position of the particle in the reference configuration $\Omega_0$. The motion $\chi$ is a one-to-one, continuous and invertible mapping which takes the particle at the spatial position $X$ to $x$, the spatial position of the particle in the current configuration, $\Omega_t$, i.e.,

$$x = \chi(X, t).$$  

(1-1)

This motion is assumed to be smooth enough such that all the required derivatives are defined. We define the following kinematical quantities:

1. **Deformation Gradient**: $F(X, t)$,

$$F(X, t) = \frac{\partial \chi(X, t)}{\partial X},$$  

where, $F$ is assumed to be invertible,  

(1-2)

2. **Velocity**: $v(X, t)$,

$$v(X, t) = \frac{\partial \chi(X, t)}{\partial t}$$  

(1-3)

3. **Velocity Gradient**: $L(x, t)$

$$L(x, t) = \frac{\partial v(x, t)}{\partial x}$$  

(1-4)

4. **Stretching Tensors**: $D(x, t)$

$$D = \frac{1}{2} \left( L + L^T \right).$$  

(1-5)

The theory of continuous media is applied to granular materials by various

*Note: A bold quantity designates either a tensorial or a vectorial quantity."
investigators, Goodman and Cowin (4), (5), Savage (6) to name a few. Their model is later modified by Massoudi (3). Massoudi (3) assumed that the Cauchy stress tensor $T$ in a granular material depends on the volume fraction, $v$, of the material, the manner in which the granular material is distributed, i.e., the gradient of the volume fraction, $\nabla v$, and the stretching tensor, $D$, i.e.,

$$T = f(v, \nabla v, D).$$

(1-6)

Based on material symmetry, frame indifference and representation theorems (using standard arguments from continuum mechanics) a constitutive model that can predict normal-stress difference and is properly frame indifferent, Massoudi (3) arrived at

$$T = \left[ \beta_0(v) + \beta_1(v) \nabla \cdot \nabla \beta_1 + \beta_2(v) \text{tr}(D) \right] 1 +
\beta_3(v) \nabla \nabla \beta_3 + 2 \beta_4(v) D + \lambda (D)^2,$$

(1-7)

where, $D$ is the stretching tensor for the granular particles, $v$ is the volume distribution function, $\beta_0(v)$ plays the role akin to pressure in a compressible fluid, $\beta_1(v)$, $\beta_3(v)$ are material parameters that reflect the distribution of the granular solids, $\beta_2(v)$ is viscosity akin to the second coefficient of viscosity in a compressible fluid, $\beta_4(v)$ is viscosity akin to the first coefficient of viscosity in a compressible fluid, $\lambda$ is referred to as "Cross-Viscosity" in a Reiner-Rivlin fluid, and $\otimes$ is the dyadic or the outer product.

As described earlier, any model which describes the behavior of granular materials involve a number of material parameters, for example in the model devised by Massoudi (3) the material parameters $\beta$'s are unknowns. Knowledge of these parameters is crucial for the success of these models. The determination of them, experimentally, is again a task in itself. This is more important because the theory should corroborate experimental results. Theory and experiment, therefore, go hand in hand. In order to have any validity of the theory proposed, experiments are required. Since the theory satisfies the accepted balance law,
and it incorporates the physical behavior of the material in question, it is upto the experimentalist to devise an experiment which will be able to predict the physical behavior of the material accurately.

1.3 Outline of this report

In chapter 2, we discuss the design of the Orthogonal Rheometer to measure the material properties of granular particles. Chapter 3 describes the experimental investigation into the properties of granular materials. In chapter 4, we evaluate the present design and the modification to the present rheometer.
2.0 ORTHOGONAL RHEOMETER

2.1 Introduction

Rheology is that branch of science which studies the behavior of materials under deformation. A rheometer characterizes the material response. Rheological properties are very important for manufacturing, fabrication, end use, transportation, bulk handling, and various other uses of the materials. Flow properties of a material govern how, and even if, it can be processed or transported in the form desired. Interest in the flow properties of granular materials has been primarily motivated by design problems in the bulk handling of grain, coal powders and particles, sand and gravel, and other particulate solids as well as slurries. In processing these materials, such as transportation of these granules and particles, it is absolutely essential to understand the flow properties of these materials. Failure to do so could result in design failure of the system; subsequently resulting into an enormous loss of revenue, and sometimes human lives also. One of those many examples is the design consideration for the transportation of coal particles in energy industries. Due to the lack of the knowledge of material parameters involved, the design of the transportation system quite often lacks the efficiency, and sometimes results into the failure and complete shut down of the system. This has prompted researchers into looking more closely at the various ways to characterize the material parameters. Characterizing the material parameters theoretically involves a complete understanding of the various governing factors and parameters, such as shape and size of the material, hardness of the particle, roughness of the surface, diameter of the granule, water content of the material and many other various factors. Any theory which attempts at characterizing these materials would have to take all of these and other relevant factors into account. Very often these
theories fail due to the lack of proper characterization of the behavior of the material. All these theories usually require support from some kind of experiment which can perhaps supply reliable data; data which researchers can correlate with the theory and predict the values of the material parameters involved in their models; thus providing a complete rheological characterization of the material. Hence, theoreticians usually rely on experimentalists to provide an experiment or a series of experiments which can help them in their theoretical modeling of the material. Thus theory and experiments go hand in hand. Here, we are exploring one such attempt.

Modeling granular materials theoretically has been an area of interest for many researchers. Here, I will not go into the discussion of theoretical modeling. A more detailed analysis and discussion of various models can be found in the recent work of Gudhe(7). My aim here, is to provide you with the details of the experiment which we have designed for characterizing granular materials.

As there are many different methods available for measuring the properties for viscoelastic solids and fluids, our aim here is to devise a method and an instrument which is suitable for measuring the properties of granular solids or slurries. The rheometer devised is superior to other existing rheometers when it comes to measuring the properties of granular materials. Firstly, the rheometers based on the pressure hole phenomenon cannot be used for granular materials. A cone and plate rheometer is unsuitable as there is difficulty near the cone tip where the diameter of the particles can pose a serious problem. A helical screw rheometer is not appropriate as the kinematics of the problem is not well understood. Our rheometer is superior to the above suggested rheometers because first it eliminates most of the complications involved in cone and plate rheometer, and the kinematics is well understood. Moreover, this can be easily modified into a torsional rheometer.
2.2 Operating Principle of Orthogonal Rheometer

The instrument which we have developed for measuring the material properties of the granular solids is the orthogonal rheometer. This instrument traces its origin to an instrument used for measuring the properties of viscoelastic solids. Maxwell and Chartoff later modified this instrument to measure the properties of polymer melts and viscoelastic fluids. Non-linear materials exhibit phenomena called "dilatancy" and "normal-stress effect" and this is the main principle on which this rheometer works.

The test material is placed between two parallel plates which are rotating eccentrically (cf. Figure 2.1, Appendix A) at the same angular speed and in the same direction. If the material is non-linear and when it is subjected to shear flow due to the rotating disks, orthogonal forces develop. This fact can be easily verified because when such a material is subjected to such kind of shearing forces, additional forces perpendicular to the plane of shearing motion are required to keep the plates apart at a constant distance. By measuring these orthogonal forces and the moments, we can characterize the material.

2.3 Design Considerations

The Rheometer should meet the following design considerations in order to be able to fulfill its requirements.

1. *Simplicity:* The rheometer should be simple in design and operation. An ideal and simple design is the design when the rheometer can be used by a variety of personnel with a minimum of instruction.

2. *Portability:* One should be able to move the rheometer from one place to another with a minimum of effort. Hence, the size and the portability of the rheometer is a major consideration.
3. **Fixtures:** The testing cell and other accessories should be easy to assemble. It should have rapidly interchangeable sample fixtures.

4. **Testing Cell:** The testing cell should be able to handle a variety of testing material. The following are important considerations:

   a. The testing plate should be able to meet the different roughness requirements of the particles to be tested.

   b. The testing plate should be able to handle various sizes of the particles.

   c. The testing plate should not be small, since edge effects are important consideration, and it should not be very big either as vibration of the plates would be a very important factor; both might lead to bad data.

   d. Hardness of the plate surface should be comparable to the hardness of the material tested. Otherwise, the plate might be grinding the particles and thus changing the material characteristics. At the same time, wear of the plates would be a major concern.

   e. The plate surface should be perfectly orthogonal to the axis of rotation. Otherwise, the plates would not be rotating in one plane and thus would result in erroneous data collection.

   f. Machining of the plates should be perfect and the interchangability of the plates to handle variety of situations should be simple and rapid.

   g. Distance between the plates should be sufficient in order to have easy material handling operations.

5. **Motor:** The motors should be able to meet the speed and torque requirements. The linearity and the precise controls of the motor characteristics are important factors.

6. **Transducers:** Since the success of the rheometer depends upon the reliable data collection, it is very important to have the transducers which can capture the deformation (the forces) with a great degree of accuracy. The linearity of the transducers and ranges where it can be operated would also limit the rheometer capabilities. Hence, they should be checked. They should be calibrated in the operational regime again to ensure that they meet their specifications.
7. **Amplifiers**: Amplifiers are required to bring the output voltages of the transducers to a range where the data acquisition can read them with minimum of interference and noise. Hence, an amplifier which can amplify the voltages precisely is also required.

8. **Data Acquisition**: A perfect and reliable data acquisition is a must to ensure that the data obtained by the rheometer is reliable. The data acquisition system should be able read the forces and the moments which are experienced by the transducers. It should also be able to read all the forces and the moments simultaneously and a graphing facility with the data acquisition system is also desirable. One should also look for a data acquisition system which can collect data and store them on a computer diskette as well as can print the data and graphs with a minimum of effort and time, and with a minimum of instruction. A user friendly software along with the data acquisition would also enhance the usability of the rheometer.

9. **Vibrations**: The vibration of the structure is a major problem in many designs. Hence, the structure should be rigid and should have the least vibration possible.

10. **Operation Table**: Since in an orthogonal rheometer both the shafts are rotating about different axes, it is also desirable to have an easy way of changing the axes of rotation.

11. **Precise Controls**: All the controls for motors, tables, data acquisition should be very precise. Since the speed at which both shafts are rotating, is the same and constant, it is desirable to have voltage stabilizer and some kind of feedback control and speed comparison facility.

12. **Machining and Assembly**: Machining and assembly should be precise and within allowable tolerance. Otherwise erroneous data collection and interpretation would result.

13. **Economics**: Last but not the least it is desirable to have a rheometer which is not only inexpensive to start with, but easy to fix in case something breaks down, with minimum of effort, money and time.
2.4 Design of the Orthogonal Rheometer

Figure 2.2 shows the instrument in the assembled form. One of the important aspect of the design of the rheometer is to make this rheometer simple, portable, and as versatile as possible. The basic unit is housed in a rectangular shaped box of dimensions, height 5', length 27", breadth 15". There are two units in the basic structure. The upper unit contains the top disk, two biaxial load cells, one uni-axial load cell, a motor, one pulley and belt drive, and the upper shaft. The lower unit contains the positioning table, lower motor, the torque sensor, bearings, lower shaft and the testing cell. We will describe the various parts of these units, in detail, in the following section.

2.4.1 Positioning Table

The main component of the rheometer consists of two disks rotating at the same angular speed but at about different axes. In order to make this instrument versatile, we have designed the instrument so that we can control the distance between the axes of rotation. We have provided for horizontal movement of the platform on which the lower unit of the system supporting the lower disk is mounted. This platform will also have the capability to move vertically. This is necessary for the following reasons:

1. Handling of the material that is going to be tested.

2. To ensure that the upper disk is in proper contact with the material that is placed on the lower disk. This is essential to avoid any kind of slippage between the upper disk surface and the material to be tested.

This platform was custom made for precision and proper accuracies, in the flatness of the surface, in movement and positioning. One of the important considerations in designing this platform was to ensure that it can handle the
load of the system. Hence, we decided to buy a precision made platform from "DAEDAL" (positioning tables and controls) which makes this kind of instrument, 'linear positioning system,' professionally. This platform is easy to assemble and equipped with a display unit to accurately indicate the movement of the platform upto ten thousandth of an inch. It can move horizontally and vertically by ± 2 inch (4 inch total movement). The surface of the platform is made of anodized stainless steel to avoid corrosion of the surface and to ensure that the flatness of the surface is maintained.

2.4.2 Bearings

The bearings which are installed on the lower unit are essential to ensure that there are no radial loads on the torque sensor. There are two bearings in the lower unit.

There is a thrust bearing, in the upper unit, between the upper shaft and the uni-axial load cell. This is a split thrust bearing. Split bearing is required in order to ensure that the portion of the bearing which is in touch with the load cell is not in motion. Thus, the axial load which is experienced by the upper disk is transmitted to the load cell, which is a compressive load.

There are two bearings which are installed in the biaxial load cells. These bearings are required inside the load cells in order to indicate the load which is experienced by the rotating shaft at that location. The housing deformations are transmitted to the load cell which in turn indicate the load experienced by the bearing. These are self-aligning ball bearings of the double row type with a spherical raceway in the outer ring. This feature gives the bearing self-aligning properties and allows it to compensate for misalignment, shaft deflections and housing deformations. The bearings also have tapered adapter sleeves which serve to locate bearings on cylindrical shafts, which is positioned with the help of a locknut.
2.4.3 Threaded rods

The entire lower and the upper units are based on a set of aluminum plates and acme threaded rods. These threaded rods are required to give us flexibility to assemble the unit easily and with precise controls in positioning, and allow us to make changes as desired.

2.4.4 Braces and Clamps

There are four sets of braces which are made out of aluminum. These braces are necessary to ensure that the lower and the upper units are rigid, and are vibration free. With the help of four clamps and these braces, the lower and upper units are locked in places to ensure their rigidity.

2.4.5 Couplers

Since the torque sensor is mounted with the housing, unsupported, a single flex coupling is required at each end of the torque shaft to connect it to the drive and loading devices. Each "single-flex" coupling compensated for angular misalignment due to assembly and/or machining.

2.4.6 Belt and Pulley drive

The upper shaft is rotated with the help of a belt and pulley drive unit. It is a timing belt drive in order to avoid slippage.
2.4.7 Shafts

There are two shafts. Both the shafts are made of hardened C-steel. The shafts are made stepped at the ends to ensure that the mating section of the testing cells are accurately installed such that the plate surfaces are horizontal and perpendicular to the axis of the rotating shafts.

2.4.8 Testing Cells

The design of the testing cell is one of the most important in the development of this unique rheometer. Since this rheometer is designed for granular materials, powders and slurries, the size, shape and the hardness of the material tested would vary considerably. In order to make this rheometer useful to measure the properties of all these materials, it is essential to make this unit of the rheometer as versatile as possible. After doing a lot of experiments and careful thinking, we came up with different sets of design for this unit. One of the main consideration is to ensure no slippage of the testing material at the surface of the disk. To reduce the slipping at the disk we made the surface of the disk rough. There are various ways to do that. The easiest way is to sand blast the surface. This is appropriate for particles which are very fine, because sand blasting cannot roughen the surface considerably. For larger diameter of the particles, we cut grooves in the surface of the disk. These grooves were different in size and shape. After experimenting with different patterns for the grooving, we concluded that the best design for our purpose was to make the grooves which were almost of the same shape as that of the material tested. Since the materials which we were testing were almost spherical in shape, we provided almost spherical indentation on the surface of the disk. Care was taken not to provide too much depth in the surface as it would trap the particle in it and would result in the vibration of the structure. Another alternative for the disk surface was to glue the particles on the surface. But this created problem as the particles would
not remain glued on the surface while the experiment was in progress and would result in vibration of the structure. Hence, finally we decided that the best design for this unit was the disk whose surface was indented with spherical grooves for the testing material under consideration. Appendix A. shows the various dimensions for this unit (cf. Figure 2.5, Appendix A).

2.4.9 Motors and Controls

One of the main consideration in the design of this instrument is the selection of the motor. After careful investigation of the speed, torque and the power requirements, we concluded that for this rheometer we need to have a motor which can rotate at a very low speed in order to avoid inertial effects, and at the same time provide a high starting torque. The torque output should also be constant over the range of the speed we are considering in order to avoid any unsteadiness. One such motor which has the requisite characteristics, is a permanent magnet motor. This motor is able to withstand a torque of 100 lb-in and the speed range we can obtain is 3-125 rpm.

2.4.10 Transducers

A very important component of the instrument is the transducer that is used in the measurement of forces and the torque. Since both the disks (shaft) are rotating, strain gages cannot be mounted directly on the shaft to measure any of the above quantities. We have decided to use in line rotating shaft torque sensors. There are two different types of such devices available in the material:

1. Slip rings type
2. Rotary transformer type

In the slip rings type, the strain gage bridge is connected to four silver slip
rings mounted on the rotating shaft. Silver graphite brushes rub on these slip rings and provide an electrical path for an incoming bridge excitation and the outgoing signal. Whereas in rotating transformer types, only either the primary or secondary winding is rotating. One transformer is used to transmit the AC excitation voltage to the strain gage bridge, and a second transformer to transfer the signal output to the nonrotating part of the transducer. Thus, two transformers replace four slip rings and no direct contact is required between the rotating and stationary elements of the transducer. The signals obtained from these sensors are then fed into the strain gage indicator or some sort of data acquisition system, where we can convert these electrical signals into the required quantity.

To measure the axial components of forces, we are using load cells. Selection of a load cell which fits our requirements was based on many considerations. The most critical mechanical component in any load cell, as with any strain gage transducer, is the "spring element". In general terms, the spring element serves as the reaction to the applied load and focuses that load into a uniform, calculated strain path for precise measurement by the bonded strain gage. Critical to this function is that the strain level in the gage area of the spring element responds in a linear and repeatable manner to the applied load. The perfect load cell would repeatedly produce a proportional relationship between the strain and the induced load. Achievement of this goal is made difficult by the presence of numerous application, economic, and performance requirements which must be simultaneously satisfied. Compounding this difficulty, is the great number of second and third order effects, such as natural frequency and thermal sensitivity that become highly significant in the attainment of a precision force measuring device. Hence, the load cell selection is one of most important aspect for our design purpose. Apart from the problems cited above, there are other difficulties associated with our specific requirements. In our design, both the shafts are rotating and it is very difficult to measure forces which are developing on a rotating shaft. For the X and Y components (in the plane of rotation), we wanted
to measure the forces at the same place. After consulting with many companies which manufacture load cells, we discovered that very few of them manufacture load cells which can measure biaxial forces on a rotating shaft at the same place. Lebow Inc. does manufacture a loadcell which can measure X and Y component of forces at the same place, but on a stationary shaft. We finally decided to modify the existing design they had and house a bearing inside the loadcell such that the outer surface of the bearing is in contact with the loadcell. The forces which would develop at that location would deform the housing of the bearing and knowing the deformation we can find out the forces. This loadcell is based on strain gage principle. Appendix B have detailed drawing including dimensions and specifications of all the transducers.

Measuring the axial component of the force was also a challenge. Again after a long consultation with a manufacturer, Measurement Specialists, we decided that at the end of the shaft we would place a split thrust bearing, one part of which would be in touch with the shaft and the race of the bearing and the other part, which is stationary, would be in touch with the loadcell. By knowing the compression of the load cell we would be able to know the forces which are developing on the shaft.

2.4.11 Amplifiers and Data Acquisition

A major consideration in the design of this rheometer is the economics. In order to keep the cost down at the same time not to compromise the reliability of the rheometer, we decided to choose a data acquisition system which would not only be able to do the job, but would be inexpensive as well. We bought OMEGA unit WB-AAI, which is an A/D card along with a terminal panel. This A/D card is used in conjunction with a computer where the analog data from loadcells are converted into the digital data, the form which the computer can understand. This system comes with a software with the help of which we can log data or
display maximum, minimum, average or difference, or set alarm limits on any input. We can also log data to a disk for later analysis, data can also be displayed on the screen in a variety of formats; columnar, graphical or picture.

The A/D card has eight or sixteen differential analog inputs and sixteen digital input/output lines. The input ranges can span signals in 25 millivolts to 10 volts and 1 milliamp to 50 milliamps. The software also has noise rejection capability and it comes with variety of other features which makes this user-friendly and at the same time maintain its high accuracy.

The output of the loadcells is in the millivolt range; even at the maximum load the output is 20 mv (excitation voltage = 10 V) for X and Y loadcells and 30 mv (excitation voltage = 10 V) for the axial loadcell. Since the electrical noise in the computer is also of the same order in magnitude, it is necessary to amplify the analog signal outputs from the loadcell. We are amplifying the signal 500 times before the signal is fed into the A/D converter and read by the computer. This minimizes the electrical noise error from the computer to the actual signal and thus improve the accuracy of the data acquisition system.

2.5 Types of Errors and their Sources

An accurate measurement system is one which has the smallest possible overall error, \( \delta_k \), i.e., the difference between the actual (true) value and the measured value. This error can be due to various factors, but broadly speaking we can classify them into two main categories:

1. Fixed bias error, \( \beta \).
2. Random precision error, \( \varepsilon_k \).

The total error is \( \delta_k = \beta + \varepsilon_k \). In order to have a reliable and accurate
measurement system, we have to keep these two errors at their minimum possible values. We now describe various types of error which constitute these errors.

2.5.1 Fixed Bias Error

The other component of total error is the bias error, $\beta$, which is the fixed error in the measurement and is present at all occasions of the measurement. This is constant for all the measurements and repeated measurements have the same bias error, and hence it is not possible to eliminate this error by repeated measurements. This error is due to the errors in the instrument itself and the total bias error for the whole instrument is the sum of individual bias errors. Most of the time, these errors are known and can not be taken out of the system completely, but can be calibrated out. Sometimes they are negligible and are ignored; other times they can be estimated and can be included in the uncertainty analysis. Maximum possible bias error present in the system is defined as the bias limit. It is very difficult to estimate the bias limit as it would require a comparison between the true value and the measured value, which in most of the cases is impossible. In order to estimate bias error from an instrument it is recommended that we do test on samples for which the results are known and compare the measured values with previously known results. Sometimes when we know that there is a bias error it is recommended that we calibrate the instrument to take this error out of the analysis.

2.5.2 Random Precision Error

These errors are observed in repeated measurements while keeping all the variables fixed. If in repeated measurements, the measured values do not agree with each other, then the measured values said to have random precision error.
These measured values may not agree with each other because of numerous error sources, for example, human errors, voltage fluctuations etcetra. This random error is termed as random precision error and can be quantified by repeated measurements. By calculating the standard deviation we can measure the precision error, $\varepsilon_k$. A large standard deviation is an indication of large scatter in the repeated measured values and can undermine the reliability of the data. Hence, in order to reduce the effect of the precision error, it is recommended to use an averaged value instead of any of the individual measured values.

The two types of errors which we have described can arise due to many sources. Broadly speaking we can classify them into two main categories.

1. Calibration errors
2. Data acquisition errors

2.5.3 Calibration Errors

As pointed out earlier, every instrument has both precision and bias errors. By calibrating the instrument, we can reduce, if not completely eliminate, these errors. This way we can reduce the uncertainty to some "acceptable" level. By acceptable level, we mean the objective of the test process, i.e., the accuracy required in a test program. We can achieve the goal of reaching the accuracy level and the required standard by exchanging the large bias error of an uncalibrated or poorly calibrated instrument for the smaller combination of the bias error of the standard instrument and the precision error of the comparison.

During the calibration process, it is recommended that the simulation should meet test-like conditions so that the instrument response may be assumed to be identical to that which would be obtained in its working environment. If this condition is not met properly, then it may result in an erroneous result and it would lead to calibration error in the instrument.
2.5.4 Data acquisition errors

This is a major source of errors in an actual measurement. Data are usually acquired by measuring the electrical outputs of the transducers. Other factors which might affect the data collections are environmental effects, probe errors, special errors, such as voltage fluctuation, temperature variation, amplifications of the signal, random noise pickup etc. One method by which one can estimate the effects of many of these error sources is to perform overall system calibrations, comparing known values with measured values. Usually, if it is not possible to do this, then it is recommended to study the effect of these error sources by evaluating the elemental errors and combine them to determine the overall error.

2.6 Error Analysis and Calibration

As pointed out earlier, the precision error is random and can be accounted for and reduced considerably, if not completely eliminated from the system, by repeating the experiments. Hence, we do not need to estimate this error, as it would vary from situation to situation.

We also carried out the calibration of the load cells. We had the calibration done from the companies which manufactured them also. We verified the calibration data from the company by carrying out various experiments. The calibration data is given in Appendix B.

Now, in this section, I am concentrating on estimating the error from data acquisition.
2.7 Calibration for Torque Sensor

Data acquisition for the torque sensor consists of model 7927 and model 7540 indicators from Lebow (*) Inc. The connections were made with the torque sensor and the speed sensor according to the directions given in the manual for model 7540 strain gage indicator. Prior to any calibration procedure the sensor housing must be ground. The output from model 7540 was fed into a digital voltmeter for LCD display. The analog output of the torque and speed sensor can be calibrated in the following way.

1. Switch model 7927 to "RUN". Choose torque for analog output on model 7540. Using coarse and fine zeroing controls for torque on model 7540, adjust the output to zero.

2. Switch model 7927 to "CAL". As specified in step 1., zero the signal while remaining in the "CAL" mode.

3. Remain in "CAL" mode. Depress and hold "+CAL" on model 7540. Using span controls for torque adjust the output to read \( +V_{\text{cal}} = 2.796 \) V.

4. Release "+CAL". If reading does not return to zero, repeat steps 2 and 3.

5. Lock the span controls.

6. Depress and hold "-CAL". The output should indicate the same value as in step 3 due to a symmetry function in the model 7540. If the output is not the same, then it can be adjusted using P-20 symmetry switch located inside (See manual for mode detail).

7. The "-CAL" is then released. The display should read zero in the "CAL" mode.

8. Switch model 7927 to "RUN" position. Adjust the reading to zero using the zero controls for torque. Lock the zero controls at this stage.

9. Depress the RPM switch on model 7540; the output should indicate zero. If not zero, repeat the whole procedure (See manual for mode detail).

10. Depress and lock "RCAL" which would enable the calibration.
resistor on the rear of model 7540 and internal switches to produce a signal equivalent to a maximum RPM of 1000. Span controls for RPM are adjusted to display the maximum signal (5 V) corresponding to this maximum angular velocity.

11. Depress and unlock "RCAL". The display should still read zero for RPM and Torque.

The system is calibrated after this step and can be implemented in the data acquisition system. Voltages for both torque and RPM will range from -5 V to +5 V. The output from the back of the model 7540 can also be directly converted by A/D converter and fed into the complete data acquisition system. The conversion factor for torque is

\[ Torque\ Conversion\ Factor\ (T.C.F.) = \frac{100\ lb-in}{10\ V} = 10.0\ \frac{lb-in}{V}, \]

and that for speed is

\[ Speed\ Conversion\ Factor\ (S.C.F.) = \frac{1000\ RPM}{10\ V} = 10.0\ \frac{RPM}{V}. \]

2.8 Calibration for the Bottom Biaxial Load Cell

Serial Number: 5877

The minimum and maximum Radial load and the Shear load that can be measured by this load cell are 0 and 250.0 lbs respectively. The specifications for this load cell are given in the appendix B. We verified the calibration chart as provided by the company and our results match the calibration results of the company. The calibration chart for this load cell is also provided in appendix B.

According to calibration chart, at 80% load the output for radial load is 1.6004 mv/v and that for shear load cell is 1.5964 mv/v. Since the excitation voltage used for this load cell is 10 V. This output would correspond to 16.004 mv and
15.964 mv for radial and shear loads respectively at 80% of the load carrying capacity. Since the output from the load cell is linear, the load cell would be 20.005 mv and 19.955 mv for radial and shear loads respectively at 100% of the load carrying capacity. Since the output from load cell is in millivolt and the noise in the data acquisition is also of the same range, we amplified the signals from load cell and the amplification factor we used is 500. This implies that the output for load cell would correspond to 10.0025 V and 9.9775 V for radial and shear loads respectively at full load carrying capacity, which is 250.0 lbs for both radial and shear loads. Hence the conversion factor for radial load is

\[
\text{Radial Conversion Factor 1 (R.C.F.1.)} = \frac{250.0 \text{ lbs}}{10.0025 \text{ V}} = 24.99375 \frac{\text{lbs}}{V},
\]

and that for shear load cell is

\[
\text{Shear Conversion Factor 1 (S.C.F.1.)} = \frac{250.0 \text{ lbs}}{9.9775 \text{ V}} = 25.056375 \frac{\text{lbs}}{V}.
\]

From the calibration chart, we have the error in linearity, and hysteresis error in the load cell, as 0.01 lbs and 0.03 lbs, respectively for radial load cell, and 0.05 lbs and 0.02 lbs, respectively for shear load cell.

For radial Load cell:

\[
\varepsilon_{lin}^{radial} = 0.01 \text{ lbs}
\]

\[
\varepsilon_{hyst}^{radial} = 0.03 \text{ lbs}
\]

\[
\varepsilon_{max}^{radial} = 0.01 + 0.03 \text{ lbs} = 0.04 \text{ lbs}
\]

\[
\varepsilon_{RMS}^{radial} = \sqrt{0.01^2 + 0.03^2} \text{ lbs} = 0.031 \text{ lbs}
\]

Minimum force measurable

\[
= 0.001 \text{ mv/v} \\
= 0.01 \text{ mv (Since, Excitation voltage = 10 v)} \\
= 0.005 V (\text{Since, Amplification factor = 500}) \\
= R.C.F.1. (0.005) \text{ lbs} \\
= 0.1250 \text{ lbs}
\]

For Shear Load cell:
\[ \varepsilon_{\text{lin}}^{\text{shear}} = 0.05 \text{ lbs} \]
\[ \varepsilon_{\text{hyst}}^{\text{shear}} = 0.02 \text{ lbs} \]
\[ \varepsilon_{\text{max}}^{\text{shear}} = 0.05 + 0.02 \text{ lbs} = 0.07 \text{ lbs} \]
\[ \varepsilon_{\text{RMS}}^{\text{shear}} = \sqrt{0.05^2 + 0.02^2} \text{ lbs} = 0.053 \text{ lbs} \]

*Minimum force measurable.*

- 0.001 mv/v
- 0.01 mv (Excitation voltage = 10 v)
- 0.005 V (Amplification factor = 500)
- S.C.F.1. (0.005) lbs
- 0.1253 lbs

### 2.9 Calibration for the Top Biaxial Load Cell

**Serial Number: 5878**

The minimum and maximum Radial load and the Shear load that can be measured by this load cell are 0 and 250.0 lbs respectively. The specifications for this load cell are given in the appendix B. We verified the calibration chart as provided by the company and our results match the calibration results of the company. The calibration chart for this load cell is also provided in appendix B.

According to calibration chart, at 80% load the output for radial load is 1.604 mv/v and that for shear load cell is 1.599 mv/v. The excitation voltage used for this load cell is 10 V. This output would correspond to 16.040 mv and 15.990 mv for radial and shear loads respectively at 80% of the load carrying capacity. Since the output from load cell is linear, the load cell would be 20.050 mv and 19.990 mv for radial and shear loads respectively at 100% of the load carrying capacity. Since the output from load cell is in millivolt and the noise in the data acquisition is also of the same range, we amplified the signals from load cell and the amplification factor we used is 500. This implies that the output for load cell would correspond to 10.0250 V and 9.9950 V for radial and shear loads.
respectively at full load carrying capacity, which is 250.0 lbs for both radial and shear loads. Hence the conversion factor for radial load is

\[
\text{Radial Conversion Factor 2 (R.C.F.2.) } = \frac{250.0 \text{ lbs}}{10.025 V} = 24.93766 \frac{\text{lbs}}{V},
\]

and that for shear load cell is

\[
\text{Shear Conversion Factor 2 (S.C.F.2.) } = \frac{250.0 \text{ lbs}}{9.995 V} = 25.01251 \frac{\text{lbs}}{V}.
\]

From the calibration chart, we have the error in linearity, and hysteresis error in the load cell, as 0.03 lbs and 0.01 lbs, respectively for radial load cell, and 0.04 lbs and 0.02 lbs, respectively for shear load cell.

For radial Load cell:

\[
\begin{align*}
\varepsilon_{\text{lin}}^{\text{radial}} &= 0.03 \text{ lbs} \\
\varepsilon_{\text{hyst}}^{\text{radial}} &= 0.01 \text{ lbs} \\
\varepsilon_{\text{max}}^{\text{radial}} &= 0.03 + 0.01 \text{ lbs} = 0.04 \text{ lbs} \\
\varepsilon_{\text{RMS}}^{\text{radial}} &= \sqrt{0.03^2 + 0.01^2} \text{ lbs} = 0.031 \text{ lbs}
\end{align*}
\]

Minimum force measurable

\[
= 0.001 \text{ mv/v} \\
= 0.01 \text{ mv (Excitation voltage = 10 v) } \\
= 0.005 \text{ V (Amplification factor = 500) } \\
= R.C.F.2. (0.005) \text{ lbs} \\
= 0.1247 \text{ lbs}
\]

For Shear Load cell:
\[
\varepsilon_{\text{lin shear}} = 0.04 \text{ lbs} \\
\varepsilon_{\text{rayl shear}} = 0.02 \text{ lbs} \\
\varepsilon_{\text{max shear}} = 0.04 + 0.02 \text{ lbs} = 0.06 \text{ lbs} \\
\varepsilon_{\text{RMS shear}} = \sqrt{0.04^2 + 0.02^2} \text{ lbs} = 0.045 \text{ lbs}
\]

Minimum force measurable:

- \(0.001 \text{ mv/v}\)
- \(0.01 \text{ mv (Excitation voltage = 10 v)}\)
- \(0.005 \text{ V (Amplification factor = 500)}\)
- \(S.C.F.2. (0.005) \text{ lbs}\)
- \(0.1251 \text{ lbs}\)

### 2.10 Calibration for the Top uni-axial Load Cell

The minimum and maximum loads that can be measured by this load cell are 0 and 100.0 lbs respectively. The specifications for this load cell are given in the appendix B. We verified the calibration chart as provided by the company and our results match the calibration results of the company. The calibration chart for this load cell is also provided in appendix B.

According to calibration chart, at full load the output for load is 3.000 mv/v. Since the excitation voltage used for this load cell is 10 V. This output would correspond to 30.000 mv at full load. Since the output from load cell is in millivolt and the noise in the data acquisition is also of the same range, we amplified the signals from load cell and the amplification factor we used is 500. This implies that the output for load cell would correspond to 15.000 V at full load carrying capacity, which is 100.0 lbs. Hence the conversion factor for load is

\[
\text{Axial Conversion Factor (A.C.F.) } = \frac{100.0 \text{ lbs}}{15.000 \text{ V}} = 6.66667 \frac{\text{lbs}}{\text{V}}.
\]

From the calibration chart, we have the error in linearity, and hysteresis error in the load cell, as 0.02 lbs and 0.01 lbs, respectively for this load cell.
\[ \varepsilon_{in}^{Axial} = 0.02 \text{ lbs} \]
\[ \varepsilon_{hyst}^{Axial} = 0.01 \text{ lbs} \]
\[ \varepsilon_{\text{max}}^{Axial} = 0.02 + 0.01 \text{ lbs} = 0.03 \text{ lbs} \]
\[ \varepsilon_{RMS}^{Axial} = \sqrt{0.02^2 + 0.01^2} \text{ lbs} = 0.022 \text{ lbs} \]

Minimum force measurable:
\[ = 0.001 \text{ mv/v} \]
\[ = 0.01 \text{ mv} (\text{Excitation voltage} = 10 \text{ v}) \]
\[ = 0.005 \text{ V} (\text{Amplification factor} = 500) \]
\[ = A.C.F. (0.005) \text{ lbs} \]
\[ = 0.033 \text{ lbs} \]

In order to measure the precision error of the instrument, we repeated the experiments few times. We followed this simple procedure. We let the upper and lower shaft rotate at the same speed and collected the data a number of times. Everytime we found the maximum and the minimum measured values and then we examined these readings for the maximum and the minimum of the whole group of experiments. The difference between the maximum and the minimum measured values gives the most likely amount by which the measured value in a particular experiment would vary at that speed. We conducted a series of experiments at different speeds and tables 2.1 - 2.7 in appendix A show the results of those experiments.
APPENDIX A.
Figure 2.2 Orthogonal Rheometer
Figure 2.3 Upper Shaft
Figure 2.6 Plate Surface pattern

NOTE:
CIRCULAR PATTERN
BALL MILL:
LARGE HOLES 1/8' DIA 1/16' DEPTH
END MILL:
SMALL HOLES 1/32' DIA 1/32' DEPTH

4 HOLES THROUGH PIECE
### Measurement of Precision Error: Speed = 10 RPM

<table>
<thead>
<tr>
<th></th>
<th>Bottom Y</th>
<th>Bottom X</th>
<th>Top Y</th>
<th>Top X</th>
<th>Axial Z</th>
</tr>
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<tbody>
<tr>
<td>Expt. 1 Speed = 10 RPM ( NoLoad )</td>
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<td></td>
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<td></td>
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<tr>
<td>Max.</td>
<td>5.99</td>
<td>5.96</td>
<td>5.78</td>
<td>6.10</td>
<td>5.15</td>
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<tr>
<td>Min.</td>
<td>5.82</td>
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<td>5.21</td>
<td>5.59</td>
<td>4.97</td>
</tr>
<tr>
<td>Diff.</td>
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<td>0.30</td>
<td>0.57</td>
<td>0.51</td>
<td>0.18</td>
</tr>
<tr>
<td>Avg.</td>
<td>5.91</td>
<td>5.77</td>
<td>5.47</td>
<td>5.82</td>
<td>5.07</td>
</tr>
<tr>
<td>STD</td>
<td>0.04</td>
<td>0.06</td>
<td>0.14</td>
<td>0.11</td>
<td>0.04</td>
</tr>
</tbody>
</table>

| Expt. 2 Speed = 10 RPM ( NoLoad ) |
| Max.  | 6.08     | 5.91     | 5.71  | 6.29  | 5.15    |
| Min.  | 5.88     | 5.65     | 5.12  | 5.65  | 4.98    |
| Diff. | 0.20     | 0.26     | 0.59  | 0.64  | 0.17    |
| Avg.  | 5.96     | 5.79     | 5.42  | 5.90  | 5.08    |
| STD   | 0.04     | 0.06     | 0.14  | 0.13  | 0.04    |

| Expt. 3 Speed = 10 RPM ( NoLoad ) |
| Max.  | 6.08     | 5.90     | 5.77  | 6.34  | 5.12    |
| Min.  | 5.81     | 5.60     | 5.04  | 5.57  | 4.96    |
| Diff. | 0.27     | 0.30     | 0.73  | 0.77  | 0.16    |
| Avg.  | 5.93     | 5.74     | 5.38  | 5.84  | 5.05    |
| STD   | 0.06     | 0.07     | 0.17  | 0.18  | 0.04    |

| Expt. 4 Speed = 10 RPM ( NoLoad ) |
| Max.  | 6.01     | 5.89     | 5.72  | 6.26  | 5.16    |
| Min.  | 5.83     | 5.62     | 5.13  | 5.64  | 4.98    |
| Diff. | 0.18     | 0.27     | 0.59  | 0.62  | 0.18    |
| Avg.  | 5.92     | 5.75     | 5.45  | 5.85  | 5.09    |
| STD   | 0.04     | 0.07     | 0.15  | 0.12  | 0.04    |

| Max. of Max. | 6.08 | 5.96 | 5.78 | 6.34 | 5.16 |
| Min. of Min. | 5.81 | 5.60 | 5.04 | 5.57 | 4.96 |
| Diff.        | 0.27 | 0.33 | 0.74 | 0.77 | 0.20 |
Measurement of Precision Error: Speed = 20 RPM

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<td>Max.</td>
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<td>5.03</td>
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<td>Max.</td>
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<td>0.56</td>
<td>0.61</td>
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<td>Avg.</td>
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<td>4.98</td>
</tr>
<tr>
<td>Min.</td>
<td>5.83</td>
<td>5.60</td>
<td>5.19</td>
<td>5.58</td>
<td>4.69</td>
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<td>Avg.</td>
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<td>Min.</td>
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<td>0.14</td>
<td>0.11</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Max. of Max. | 6.13     | 6.14     | 5.78  | 6.19  | 5.14    |
Min. of Min. | 5.72     | 5.33     | 5.12  | 5.46  | 4.69    |
Diff.        | 0.41     | 0.81     | 0.66  | 0.73  | 0.45    |
## Measurement of Precision Error: Speed = 30 RPM

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<th>Top X</th>
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<td>lbs</td>
<td>lbs</td>
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<td>Expt. 1 Speed = 30 RPM (NoLoad)</td>
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# Measurement of Precision Error: Speed = 50 RPM

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Max. of Max. | 5.98 | 5.69 | 5.78 | 6.17 | 5.31 |
Min. of Min. | 5.68 | 5.31 | 5.21 | 5.54 | 4.98 |
Diff.        | 0.30 | 0.38 | 0.57 | 0.63 | 0.33 |
Measurement of Precision Error: Speed = 60 RPM

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Max. of Max.: 5.91 5.56 5.74 6.22 5.76
Min. of Min.: 5.65 5.16 5.22 5.62 5.56
Diff.: 0.26 0.40 0.52 0.60 0.20
**Measurement of Precision Error: Summary**

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<td>40.00</td>
<td>0.17</td>
<td>0.31</td>
<td>0.71</td>
<td>0.85</td>
<td>0.12</td>
</tr>
<tr>
<td>50.00</td>
<td>0.30</td>
<td>0.38</td>
<td>0.57</td>
<td>0.63</td>
<td>0.33</td>
</tr>
<tr>
<td>60.00</td>
<td>0.26</td>
<td>0.40</td>
<td>0.52</td>
<td>0.60</td>
<td>0.20</td>
</tr>
<tr>
<td>Max. Error</td>
<td>0.41</td>
<td>0.81</td>
<td>0.74</td>
<td>0.85</td>
<td>0.45</td>
</tr>
<tr>
<td>Min. Error</td>
<td>0.17</td>
<td>0.31</td>
<td>0.52</td>
<td>0.60</td>
<td>0.12</td>
</tr>
</tbody>
</table>
APPENDIX B.
<table>
<thead>
<tr>
<th>Model BSP 100</th>
<th>Load cell for measuring the axial thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Excitation Voltage</strong></td>
<td>VDC 10 Nom</td>
</tr>
<tr>
<td><strong>Rated Output mV/V</strong></td>
<td>Max 3.003</td>
</tr>
<tr>
<td><strong>Zero balance (%FS)</strong></td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Non-Repeatability (%FS)</strong></td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Temperature range:</strong></td>
<td></td>
</tr>
<tr>
<td>Compensated (F, C)</td>
<td>0 to 150 - 15 to 65</td>
</tr>
<tr>
<td>Operating (F, C)</td>
<td>-65 to 200 - 50 to 90</td>
</tr>
<tr>
<td><strong>Element Material</strong></td>
<td>Stainless</td>
</tr>
<tr>
<td><strong>Seal</strong></td>
<td>Hermite</td>
</tr>
<tr>
<td><strong>Safe overload (%FS)</strong></td>
<td>150</td>
</tr>
<tr>
<td><strong>Ultimate overload (%FS)</strong></td>
<td>300</td>
</tr>
<tr>
<td><strong>Safe sideload (%FS)</strong></td>
<td>100</td>
</tr>
<tr>
<td><strong>Deflection (in, mm)</strong></td>
<td>0.008, 0.2</td>
</tr>
<tr>
<td><strong>Weight (lbs, Kg)</strong></td>
<td>3, 1.4</td>
</tr>
<tr>
<td><strong>Combined Error (%FS)</strong></td>
<td>0.03</td>
</tr>
</tbody>
</table>

Note: Combined error includes the maximum deviation for both increasing and decreasing load from a straight line between no load and rated load at constant temperature. Includes effects of nonlinearity and hysteresis.
SHUNT CALIBRATION TRANSFER

The purpose of this technique is to provide the transducer user with a means of easily performing an accurate system calibration using an Eaton-Lebow supplied shunt resistor and its electrical signal equivalent value.

Possibility One - The instrument and interconnecting cable were provided to Eaton-Lebow for the actual calibration: Use the electrical signal equivalent value supplied by Eaton-Lebow and adjust the instrument display or output to the equivalent load value with the shunt resistor connected on the instrument and activated.

Possibility Two - The instrument and interconnecting cable were not provided to Eaton-Lebow for the actual calibration: The actual calibration was performed using Eaton-Lebow's instrument and a short interconnecting cable to determine electrical equivalent value with a shunt resistor. Since a different cable and instrument will be used in your application, the following method should be used to calibrate the system:

1. Connect the instrument to the transducer using the actual interconnecting cable.
2. Shunt the appropriate pins at the transducer receptacle with the shunt resistor provided by Eaton-Lebow, using short pigtail leads.
3. Adjust the instrument readout or output for the electrical equivalent value supplied by Eaton-Lebow.
4. Disconnect the pigtailed and shunt resistor from the transducer receptacle.
5. Install the shunt resistor on the instrument.
6. Press the cal buttons one at a time. Read and record the display or output on the instrument. This is the new electrical equivalent value to be used when the shunt resistor is installed and activated on the instrument and using actual cable.
7. Steps 1 through 6 should be repeated whenever the cable and/or instrument is changed.

NOTE: WHILE THIS METHOD OF SYSTEM CALIBRATION IS USUALLY VERY RELIABLE AND ACCURATE, IT IS RECOMMENDED THAT THE EQUIVALENT LOAD VALUES BE PERIODICALLY VERIFIED BY CALIBRATING THE SYSTEM WITH KNOWN, ACCURATE MECHANICAL MEANS. EATON-LEBOW RECOMMENDS A MAXIMUM OF ONE YEAR BETWEEN CERTIFICATION.
TWO COMPONENT LOAD CELL
FOR TIRE TESTING

MODEL 6443

Installation Instructions

All units are made identical. There are no left- and right-hand units. Consequently, one unit is installed upside down with respect to the other. This means that the polarity of the excitation leads (pins B,C) must be reversed on one unit.

The system is to be installed with a preload of approximately 250 lbs. on the side load cells. The following installation procedure is suggested:

1. Install the bottom, or right-hand cell with all 4 keys. (Some installations are with shaft vertical; others are with shaft horizontal.)

2. The keys parallel to the radial load direction are not used on the second cell.

3. The side load preload can be accomplished by installing the mounting bolts partially tight on this second cell.

4. Connect readout instrument to one side load circuit.

5. Tap the second cell in a direction away from the bottom or right-hand so as to put a tension preload of approximately 250 lbs. in the side load direction.

6. Tighten the mounting bolts.

7. If desired, dowels can be installed in the rim of the load cell, but must be drilled and reamed for dowels (see drawing D-6443 for doweling area).
Jin Terminal

Lebow Code

FUNCTIONS

- SIGNAL

- EXCITATION

+ SIGNAL

+ EXCITATION

NOTES:
1. R = STRAIN GAGE RESISTANCE
2. Rm = MODULUS & OUTUT MATCHING RESISTANCE
3. THE WIRING CODE FOR THIS TRANSDUCER IS CIRCLED
4. COMPRESSION LOADING OR CLOCKWISE TORQUE WILL PRODUCE A POSITIVE OR UPSCALE READING.

WIRING CODES FOR LEBOW TRANSDUCERS OLD CODE

LEBOW ASSOCIATES, INC.
THOY, MICHIGAN

DRAWING NO. OLD-221
MODEL 6443-146 LOAD CELL

Serial Number 5877  Calibration Date 12/5/91

Specifications:

Rated capacity radial load.......................... 250 Lbs.
Rated capacity side load........................... 250 Lbs.
Max. load (without zero shift)......................... 50% overload (150% rated capacity)
Signal sensor........................................ 4 arm bonded strain gage bridge
Max. bridge excitation................................ 20 volts DC or AC RMS
Compensated temp. range.............................. 30°F to 50°F
Useable temp. range................................. -50°F to +200°F
*Effect of temp. on zero............................. ±0.002% of rated capacity/°F
*Effect of temp. on output.......................... ±0.002% of reading/°F
Linearity............................................. 20.1% of rated capacity
Output.................................................. 2.000 mv/v ±0.25% at rated capacity

*with compensated temperature range

Electrical Connections:

Receptacle: Cannon MS-3102E-14S-5P  Connector MS-3108B-14S-5S

<table>
<thead>
<tr>
<th>Pins</th>
<th>Function</th>
<th>Resistance Across Pins</th>
<th>Load Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B and C</td>
<td>Excitation</td>
<td>395.8 Ohms</td>
<td>171.4 Lbs.</td>
</tr>
<tr>
<td>A and D</td>
<td>Signal</td>
<td>350.0±1% Ohms</td>
<td>172.6 Lbs.</td>
</tr>
</tbody>
</table>

A precision wire wound resistor, when shunted across one leg of the strain gage bridge, produces an electrical signal equivalent to an applied load. The shunt calibration is valid only when used with high input impedance indicators. The equivalent values below were determined by factory calibration.

Resistor supplied
## Eaton Corporation Calibration Data Sheet

**Test Equipment**
- **Deadweight Machine**
  - Inch Beam Control Number: __________
  - Deadweight: __________ LBS SN: __________

**Std Load Cell**
- Model Number: __________
- Control Number: __________ SN: __________
- Instrument: __________
- SN: __________

**Test Equipment**
- **Deadweight Machine**
- Inch Beam Control Number: __________
- Deadweight: __________ LBS SN: __________

**Instrumet**
- Model Number: __________
- Control Number: __________ SN: __________
- Increment: __________
- SN: __________

### Load Applied | Theor. RDG. | Comp. Clockwise | Ten. Counter CW
<table>
<thead>
<tr>
<th>Lbs</th>
<th>%</th>
<th>Run 1</th>
<th>Dev</th>
<th>Run 1</th>
<th>Dev</th>
<th>Run 1</th>
<th>Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>40.00</td>
<td>40.01</td>
<td>40.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>80.00</td>
<td>80.00</td>
<td>80.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>40.00</td>
<td>40.98</td>
<td>40.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>+0.1</td>
<td>+0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Load Applied**
- **Radial**
- **Side**

### Calibration
- **Radial**
  - @ 80% + 160.04 mV/V
- **Side**
  - @ 80% + 15%4 mV/V

**Additional Calibration Details**
- **Exc** 391.1 ohms
- **Sig** 349.9 ohms
- **Zero Bal** -1.17 -0.9%
- **10-20 Volts** 14.54%

**Before Trim**
- R/+ 1.7398 mV/V
- S/- 1.7495 mV/V

**After Trim**
- R/+ 1.896 mV/V
- S/- 1.896 mV/V

**Notes**
- **Temp**: 63.7°F
- **HumD**: 17.4% RH
- **Date**: 12/5/91
- **By**: Dave
- **Job**: 8074810

**Model Number**: 6443 - 146
- **SN**: 5887
- **Capacity**: R-250 Lbs / S-250 Lbs
EATON Lebow Products Product Information

MODEL 6443-146 LOAD CELL

Serial Number 5878  Calibration Date 1/17/92

Specifications:

Rated capacity radial load............ 250 Lbs.
Rated capacity side load............ 250 Lbs.
Max. load (without zero shift)........ 50% overload (150% rated capacity)
Signal sensor....................... 4 arm bonded strain gage bridge
Max. bridge excitation................ 20 volts DC or AC RMS
Compensated temp. range.............. 30°F to 50°F
Useable temp. range.................. -50°F to +200°F
*Effect of temp. on zero.............. ±0.002% of rated capacity/°F
*Effect of temp. on output............ ±0.002% of reading/°F
Linearity............................ ±0.1% of rated capacity
Output.............................. 2.000 mv/v ±0.25% at rated capacity

*with compensated temperature range

Electrical Connections:

Receptacle: Cannon MS-3102E-14S-5P  Connector MS-3108B-14S-5S

<table>
<thead>
<tr>
<th>Pins</th>
<th>Function</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>B and C</td>
<td>Excitation</td>
<td>Side 370.5 Ohms</td>
</tr>
<tr>
<td>A and D</td>
<td>Signal</td>
<td>350.0±1% Ohms</td>
</tr>
</tbody>
</table>

Calibration:

A precision wire wound resistor, when shunted across one leg of the strain gage bridge, produces an electrical signal equivalent to an applied load. The shunt calibration is valid only when used with high input impedance indicators. The equivalent values below were determined by factory calibration.

<table>
<thead>
<tr>
<th>Resistor Value</th>
<th>Across Pins</th>
<th>Load Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial 60 K ohms</td>
<td>B and D</td>
<td>172.9 Lbs.</td>
</tr>
<tr>
<td>Side 60 K ohms</td>
<td>B and D</td>
<td>188.9 Lbs.</td>
</tr>
</tbody>
</table>

Resistor supplied
**EATON CORPORATION**  
**CALIBRATION DATA SHEET**

**TEST EQUIPMENT**
- **Deadweight Machine**
- **Inch Beam Control Number**
- **Deadweight**
- **LBS**
- **SN**
- **OZ**
- **SN**

**STD LOAD CELL**
- **K Model Number**
- **SN**

**INSTRUMENT**
- **FLUKE**
- **CONTROL NUMBER**
- **195**
- **SN**
- **2**
- **LIN**
- **8/03**
- **S/01**
- **HYST**
- **8/04**
- **S/02**

<table>
<thead>
<tr>
<th>LOAD APPLD</th>
<th>THEOR. RDG.</th>
<th>COMP. CLOCKWISE</th>
<th>TEN. COUNTER CW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RADIAL 0</td>
<td>SIDE 0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>40.00</td>
<td>39.97</td>
<td>40.01</td>
</tr>
<tr>
<td>200</td>
<td>80.00</td>
<td>80.00</td>
<td>80.00</td>
</tr>
<tr>
<td>100</td>
<td>40.00</td>
<td>40.00</td>
<td>39.99</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>-0.01</td>
<td>0</td>
</tr>
</tbody>
</table>

**RADIAL**
- @ 80% = 1.604 mV/V
- @ 80% = 1.599 mV/V

**SIDE**
- @ 80% = 1.604 mV/V
- @ 80% = 1.599 mV/V

**Exc**
- 370.5 ohms

**Sig**
- 350.3 ohms

**Zero Balance**
- ±0.2%

**10-20 Volts**
- ±0.23%

**Before Trim**
- R = L.745 mV/V
- S = L.794 mV/V

**Model Number**
- 6443 - 146

**SN**
- 5.878

**Capacity**
- 250 lbs

**Date**
- 1/17/92

**Temp**
- 69.7° F

**Humo**
- 24.2% RH

**Made by Dave**

**Job No.**
- 77800
ROTOR
TRANSFORMER
TORQUE SENSORS—continued

Specifications
Output at rated capacity: millivolts per volt nominal ........... 2
Nonlinearity: of rated output .................................. ±0.05%
Hysteresis: of rated output ..................................... ±0.05%
Repeatability: of rated output .................................. ±0.05%
Zero balance: of rated output ................................... ±0.1%
Temperature range, compensated: °C ...................... -70 to +170
Temperature range, uncompensated: °C .................. +21 to +77
Temperature range, usable: °F .............................. -20 to +170
Temperature range, usable: °C .............................. -20 to +77
Temperature effect on output: of reading per °F .......... ±0.001%

Specifications
Temperature effect on output: of reading per °C ............ =0.0018%
Temperature effect on zero: of rated output per °F .......... =0.001%
Temperature effect on zero: of rated output per °C ........ =0.0018%
Excitation frequency ........................................ 3.28 KHz AC
Optimum ......... 
Excitation voltage ........................................ 1 to 10 VAC rms
Bridge current at 5 VAC .................................. 50 ma.
Insulation resistance, bridge/case megohms at 50 VDC .... >5000
Number of bridges .................................... 1

Note: Dimensions and specifications are purely theoretical. Calculations from standard English electric control drawings. Actual designs and specifications are subject to change without notice.
FEATURES
- High accuracy
- High overload protection with high signal output (sensitivity)
- Extended speed range
- Minimal maintenance due to "bearings only" contact
- Carrier frequency excitation provides increased signal/noise immunity
- 100 to 10,000 lb. in. capacities

<table>
<thead>
<tr>
<th>Model</th>
<th>Capacity</th>
<th>Mech. Capacity</th>
<th>Torque</th>
<th>Distance</th>
<th>Torque Limiter</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RPM*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1804-100</td>
<td>100</td>
<td>27,000</td>
<td>300</td>
<td>12,500</td>
<td>2.59 x 10⁻⁶</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2500</td>
<td>20</td>
<td>1,525</td>
<td>3.0 x 10⁻⁶</td>
<td>8.2</td>
</tr>
<tr>
<td>1804-200</td>
<td>200</td>
<td>27,000</td>
<td>600</td>
<td>33,000</td>
<td>2.59 x 10⁻⁶</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>27,000</td>
<td>60</td>
<td>3,713</td>
<td>3.0 x 10⁻⁶</td>
<td>8.2</td>
</tr>
<tr>
<td>1804-500</td>
<td>500</td>
<td>27,000</td>
<td>1,500</td>
<td>85,000</td>
<td>2.59 x 10⁻⁶</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>27,000</td>
<td>135</td>
<td>9,503</td>
<td>3.0 x 10⁻⁶</td>
<td>8.2</td>
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<tr>
<td>1804-1K</td>
<td>1,000</td>
<td>27,000</td>
<td>3,000</td>
<td>150,000</td>
<td>2.59 x 10⁻⁶</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>105</td>
<td>27,000</td>
<td>340</td>
<td>18,946</td>
<td>3.0 x 10⁻⁶</td>
<td>8.2</td>
</tr>
<tr>
<td>1804-2K</td>
<td>2,000</td>
<td>27,000</td>
<td>3,000</td>
<td>225,000</td>
<td>2.59 x 10⁻⁶</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>255</td>
<td>27,000</td>
<td>340</td>
<td>29,420</td>
<td>3.0 x 10⁻⁶</td>
<td>8.2</td>
</tr>
<tr>
<td>1805-2K</td>
<td>2,000</td>
<td>22,000</td>
<td>6,000</td>
<td>700,000</td>
<td>6.41 x 10⁻⁶</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>22,000</td>
<td>675</td>
<td>79,025</td>
<td>9.6 x 10⁻⁶</td>
<td>13.2</td>
</tr>
<tr>
<td>1805-5K</td>
<td>5,000</td>
<td>22,000</td>
<td>15,000</td>
<td>950,000</td>
<td>8.41 x 10⁻⁶</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>565</td>
<td>22,000</td>
<td>1,650</td>
<td>107,500</td>
<td>9.6 x 10⁻⁶</td>
<td>13.2</td>
</tr>
<tr>
<td>1805-10K</td>
<td>10,000</td>
<td>22,000</td>
<td>20,000</td>
<td>1,000,000</td>
<td>8.41 x 10⁻⁶</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>7,150</td>
<td>22,000</td>
<td>2,250</td>
<td>112,579</td>
<td>8.6 x 10⁻⁶</td>
<td>13.2</td>
</tr>
</tbody>
</table>

*Constant velocity for higher speed drives when using with lower speed drives.

SAFETY CONSIDERATIONS: "It would be unsafe to exceed the rated speed by more than 5% or the maximum rpm of the equipment. The user of this device is responsible for ensuring that proper safety precautions are taken when using the device beyond its rated specifications. Safety considerations include, but are not limited to: proper grounding, proper electrical connections, and adequate ventilation to prevent moisture buildup."
References


