FAMU-FSU COE

CERN Team
Collaboration with Romania

Group 13

Final Design Report

December 5th, 2006

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1 Executive Summary

The CERN Team has successfully developed a method to detect imbalances in rotating shaft segments. A machine capable of mounting the shaft segments and rotating them at controlled speeds was effectively built. Further, analysis software was developed, able to perform necessary calculations on sensor data to characterize shaft imbalance. However, it was not possible to demonstrate this method, due to technical difficulties with data acquisition equipment.

Regarding machine design: several concepts were considered, and the one chosen was the least expensive ($826) and most robust design – the D3 Balance Detection Machine concept. The machine uses 80/20 railing as a framing system, uses a 1hp DC motor with controller, includes all hardware for mounting and supporting the shaft segment, and uses accelerometers (to derive radial displacement) and a photoelectric tachometer (for angular position). A special, lightweight split collar was precision fabricated to fit over the shaft without interfering with its end-fittings, slip into a ball bearing, and be used as a pulley.

The software is capable of performing all mathematical functions necessary to calculate mass imbalances in CERN's shaft segments. The graphical output from the LabView program gives results in the frequency domain to show individual vibration sources, and in the time domain to show amplitude of displacement and phase.

2 Introduction

The CERN senior design team is comprised of Dumitru Moldovan, Derrick Nickerson, and David Sediles. The team is working under the guidance of Dr. Luca Bottura and Dr. Nathan Brooks of the Magnet Testing and Measurement group within CERN's Accelerator Technology Division (MTM-AT). Further collaboration is done with Dr. Juan Ordonez of the FAMU-FSU College of Engineering, Dr. Alexandru Morega of the Polytechnic University in Bucharest, Romania, and his senior design group: Ionut Andronache, Adrian Mihai, Cosmin Mogos, and Ion Alexandru Morega.

2.1 CERN

CERN, the European Organization for Nuclear Research, is a large particle physics laboratory headquartered in Genève, Switzerland. The organization is home to many European scientists conducting research under medical and technological applications, as well as astronomy research. Founded in 1954, CERN has existed for 52 years.

2.2 Magnetic Measurement

CERN is in the process of constructing the world's largest particle collider, the LHC (Large Hadron Collider). The facility will operate on an array of superconductive magnets, interconnected to form a circle. With over 2000 of these magnets, quality control becomes a serious issue. All magnets must be calibrated against reference magnets to ensure operation is to specification.

CERN has developed a device for this purpose. The apparatus is a rotating measurement system, composed of several shaft segments connected together (see Appendix). The segments contain coils that rotate with the shaft; rotation is provided by a Twin Rotating Unit or TRU (see Appendix **Error! Reference source not found. Error! Reference source not found.**). Upon rotation, the magnetic field induces current in the coils; the output signals from the coils give the magnetic flux, as a function of angular position. This data is gathered for all dipole and quadrupole magnets used in the LHC, and checked against data collected from reference magnets. (Here forth, this measurement device will be referred to as a Rotating Coils Unit or RCU).

There exist two different length RCU's (one for dipoles and one for quadrupoles), made up of different length shaft segments (1.2m and 0.75m, respectively). The segments use ceramic shafts (Al_2O_3) to support the coils and other components (see Figure 2-1). These shafts are manufactured to tight geometric tolerances, and further, the segments themselves are manufactured with care.

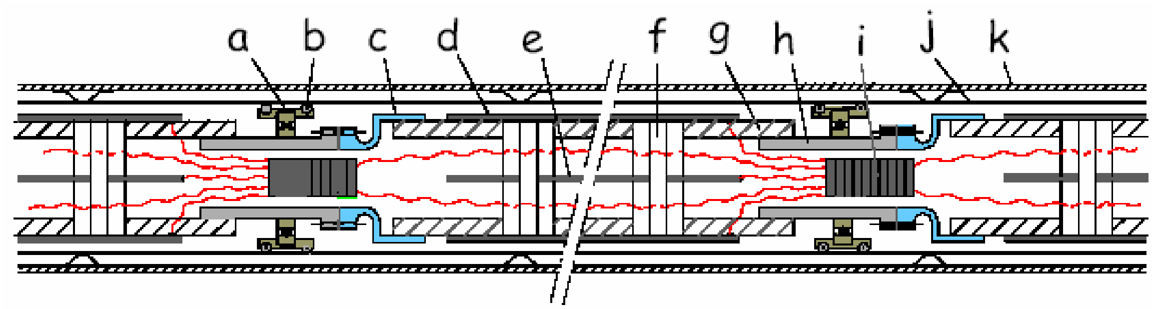

Figure 2-1 – Schematic of a shaft segment showing main components: (a) ball bearing, (b) bronze cage with roller, (c) Ti-bellow, (d) tangential coil, (e) central coil, (f) dowel pin, (g) ceramic support, (h) SiN Flange, (i) cable connector, (j) anticryostat, (k) cold bore.

Currently, RCU's rotate 3 times in each opposite direction before reaching a constant speed (1 Hz maximum) for data acquisition, a process that takes about 15 seconds. However, faster measurement times are desired. The revised method of operation calls for continuous rotation of the RCU at 2 to 3 Hz (10 Hz maximum), resulting in a measurement time of less than 1 second. Still, problems may arise from this new operation method: mechanical vibrations during rotation may cause measurement errors. At present, a maximum rotation rate of 1 Hz is used in order to avoid such problems, however, since the segments have never been balanced before (just carefully manufactured), they may be inevitable at higher speeds.

3 Project Scope

Through collaboration with electrical engineers in Romania, the team is to produce a machine that checks for mechanical vibrations in rotating shaft segments. The device and correction method are meant to ensure accuracy of field measurements done by RCU's. Ultimately, the work done in this project will contribute to quality control performed by the MTM-AT.

In order of priorities, the objectives of the project are:

1. Design a device to detect imbalances in a shaft segment.
2. Construct the detection device.

4 Product Specifications

General description:
Product must detect imbalances in shaft segments.

Detection:
- Range of detection frequencies: 1 Hz to 10 Hz.
- All three modes of imbalance must be able to be detected (see section 5.1 Balance Theory

The following sections outline fundamental theory required for discussion of rotor imbalances and their detection.

4.1.1 *Imbalance Types*

A rotating component is balanced when its principle axis of inertia (mass axis) is aligned with its geometric axis of symmetry (in the case of a cylinder, the shaft axis). There are three types of mass imbalances that rotating components may experience. They are:

1) *Static imbalance* – this occurs when the mass axis is displaced from the shaft axis, but still parallel to it. The mass center is no longer on the shaft axis in this case. See Figure 5-1.

Figure 5-1 – Static imbalance.

2) *Couple imbalance* – the mass center is on the shaft axis, however, the mass axis is offset by some angle from the shaft axis. See Figure 5-2.

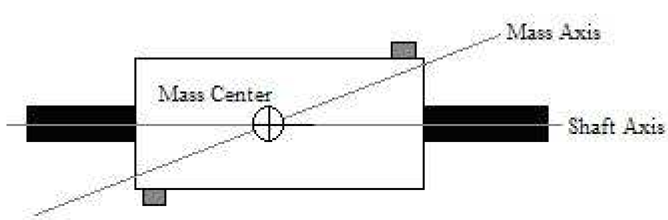

Figure 5-2 – Couple imbalance.

3) *Dynamic imbalance* – a combination of the first two types. The mass axis is at an angle with the shaft axis, however, the mass center is no longer on the shaft axis. This is the most common type of imbalance seen in rotating components. See Figure 5-3.

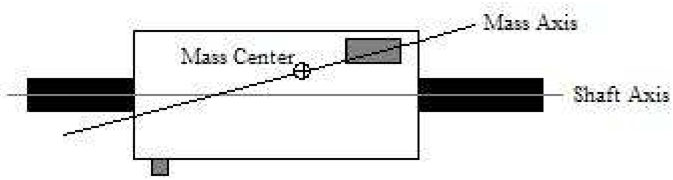

Figure 5-3 – Dynamic imbalance.

To detect these types of imbalances, radial displacement must be observed at (a minimum of) two positions along the length of the shaft, then correlated to the angular position at which displacements are measured.

- Balance Theory)
    - Static
    - Couple
    - Dynamic

Overall:

- Product must be standalone.
- Maximum weight of product: 250 lbs.
- Overall dimensions of product: 6' x 2' x 2'.
- Accommodation of the following shaft dimensions is required:
    - Length: 0.75m to 1.2m
    - Outer diameter: 34mm
    - Inner diameter: 25.5mm

5 Background Research

5.1 Balance Theory

The following sections outline fundamental theory required for discussion of rotor imbalances and their detection.

5.1.1 *Imbalance Types*

A rotating component is balanced when its principle axis of inertia (mass axis) is aligned with its geometric axis of symmetry (in the case of a cylinder, the shaft axis). There are three types of mass imbalances that rotating components may experience. They are:

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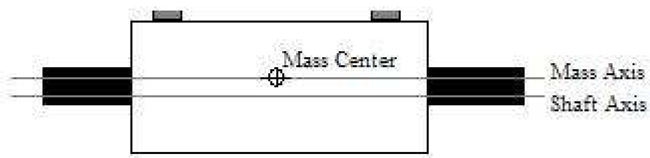

Figure 5-1 – Static imbalance.

5) *Couple imbalance* – the mass center is on the shaft axis, however, the mass axis is offset by some angle from the shaft axis. See Figure 5-2.

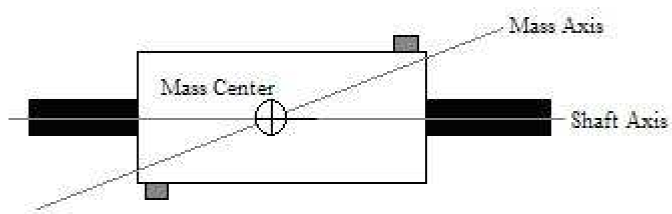

Figure 5-2 – Couple imbalance.

6) *Dynamic imbalance* – a combination of the first two types. The mass axis is at an angle with the shaft axis, however, the mass center is no longer on the shaft axis. This is the most common type of imbalance seen in rotating components. See Figure 5-3.

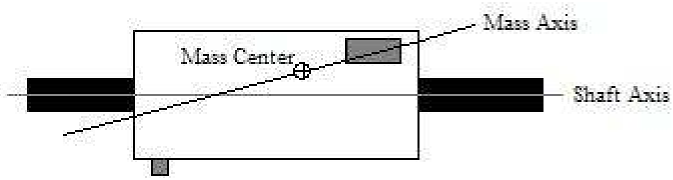

Figure 5-3 – Dynamic imbalance.

To detect these types of imbalances, radial displacement must be observed at (a minimum of) two positions along the length of the shaft, then correlated to the angular position at which displacements are measured.

5.1.2 *Balance Theory*

In general, balance detection is done by observing the radial displacement of a rotor in one or more planes (see figure below), then correlating this displacement to the rotor's angular position.

Figure 5-4 – Shaft shown with planes where radial displacement may be observed in two-plane balance detection.

For rotors such as thin discs, one-plane balance detection works well since the difference in displacement at the ends of the rotor are negligible due to its thinness. For long rotors (such as the shaft used by CERN, with a length to diameter ratio of ~34), one-plane balance detection does not give a complete picture of the mode of shaft vibration. Readings in one plane can be indicative of any of the three imbalance types described in the previous section.

This ambiguity may be eliminated by measuring in two planes. Correlating magnitude, radial position, and phase in both planes to each other, a comprehensive model of the vibration mode may be achieved. For this reason, this application in particular requires two-plane balancing, with displacement readings taken in at least two planes.

5.1.3 *Balance Tolerance*

Note: The following review of balance tolerance is adopted from "Armature Balancing" under Appendix **Error! Reference source not found. Error! Reference source not found.**.

The balance tolerance of a rotating component is a quantity that denotes its acceptable imbalance level. Its units are *mass* x *distance*, which represents the moment of mass by which a component may be imbalanced.

It is the eccentricity (e), together with the mass (m) of the component, that will determine the balance tolerance. *Eccentricity* is defined as the radial displacement of the mass center from the shaft axis. Balance tolerance (I) is given by the following equation:

$$\mathbf{I = m \times e} \qquad \textbf{(Eq. 1)}$$

To summarize: balance tolerance, given by component mass and eccentricity, defines the maximum imbalance allowed under rotation.

5.1.4 *Analysis*

Note: This section describes, in brief, the analysis that is necessary to arrive at the shaft mass-moment imbalance from sensor data. This is the process that the LabView software designed by the Romanian team is based on. It was researched and developed by the US team.

As a general description, the shaft mass-moment imbalance is determined by measuring the effect of an added trial mass on the radial displacement of the rotating system. From the measured effect, together with the radial displacement of the shaft alone, it is possible to back calculate the shaft imbalance.

To begin, the amplitude and phase angle ϴ (with respect to an arbitrary zero reference) of radial displacement for vibration with and without the addition of a trial mass must be acquired for one plane (see figure below).

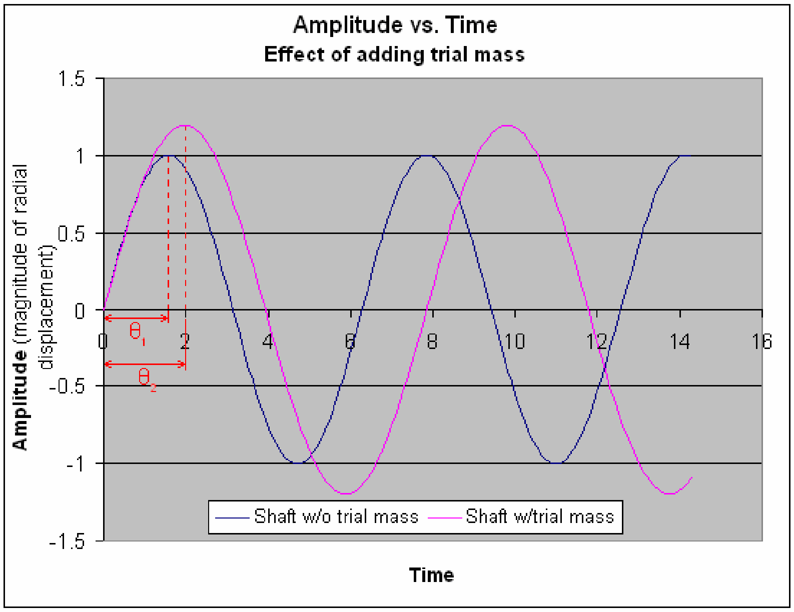

Figure 5-5 – Graph of radial displacement vs. time for runs with and without a trial mass.

From this information, two vectors may be defined (see figure below). As shown, the vector for the imbalance with trial mass can be represented by the summation of two vectors: the "imbalance without trial mass" vector, and a vector that represents the "effect of the trial mass".

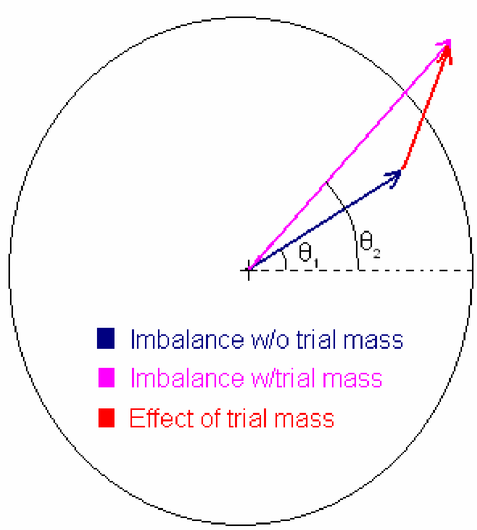

Figure 5-6 – Polar representation of displacement vectors with and without trial mass.

Using vector manipulation, the magnitude of the “effect of trial mass” vector may be determined, and from this, a triangle may be formed (with all three lengths known). A ratio between the “imbalance w/o trial mass” vector and the “effect of trial mass” vector can now be found, and used to calculate the mass-moment imbalance of the shaft. The shaft imbalance is found from multiplying the mass moment caused by the trial mass (its mass times the radius at which was placed on the shaft, m*r) by the ratio found earlier.

The idea behind this last point is that the mass moment caused by the trial mass is used to “scale” radial displacement readings to the desired units (g*cm, for example).

5.2 CEMB

CEMB (Construzioni Elettro Meccaniche ing. Buzzi & C. Spa) is a vibrations analysis company based in Mandello del Lario, Italy. They manufacture balance machines and portable vibration analysis devices for automotive and industrial markets.

6 Concept Generation and Selection

6.1 Overview

The designs discussed herein are split into two sections: detection and correction – the two objectives of the design project. This section of the report provides preliminary descriptions and analysis of each design. A final design for each objective will be chosen, and the project will move forward with those designs.

6.2 Judging Criterion

The following is a breakdown of the criteria used to evaluate the feasibility of the designs presented in this document, and the reasoning behind the weight factor assigned to each.

1. *Simplicity* (weight: 2)
Simplicity is desired for lowered cost and greater reliability. The more elegant solutions will be rated highest. Simplicity is rated below cost and performance because these criterion make-or-break the feasibility of a design, whereas simplicity does not.

2. *Durability* (weight: 1.5)
This rating reflects the probability of designs to withstand use. Worst-case operating conditions and common user errors are considered, and the toughest designs are given the highest ratings. Given the importance of the other judging criterion, durability is considered the least important of the four. Specifically, a simpler design is more advantageous than a durable design.

3. *Performance* (weight: 3.5)
Certain restrictions may limit the likelihood of a design to function properly. These restrictions vary from design-to-design, and so they are grouped together under the umbrella of "Performance." Fewer foreseeable restrictions yield higher Performance ratings. Performance is regarded as the most important criteria since designs will not work if restrictions hinder them from doing so.

4. *Cost* (weight: 3)
The more cost-effective concepts will be rated highest. Since the budget for the project is fairly limited at $1000, this criteria is regarded as more important than simplicity or durability, however, not as important as performance. The reason for this is that the budget may be increased if needed.

6.3 Detection Concepts and Analysis

Existing and original designs are presented here; feasibility analysis used for the Decision Matrix is also provided. Background research has shown the following: balance detection is generally done by rotating the component of interest, and using a sensor to detect displacement or force in a direction *perpendicular* to the shaft axis. Concepts shown below are variations on this theme.

6.3.1 *Repositioning-Sensor*

6.3.1.1 **Description**

With this design, the shaft is mounted on a chuck and a bearing (see **Error! Reference source not found.**). The chuck is driven by a motor; it rotates the shaft at a desired rate. To detect this rotation rate, a sensor (not pictured) may be used in the motor housing. The bearing mentioned earlier is mounted at the opposite end of the shaft, used for support.

As the segment rotates, an electronic sensor is used to take displacement readings in a direction perpendicular to the shaft axis. This is done at multiple locations along the shaft length, one position at a time. The sensor may be mounted to a track for repositioning. Information from the sensor is sent to a computer which analyzes the data, then reports the state of imbalance in a form the operator may use to correct the shaft (not pictured).

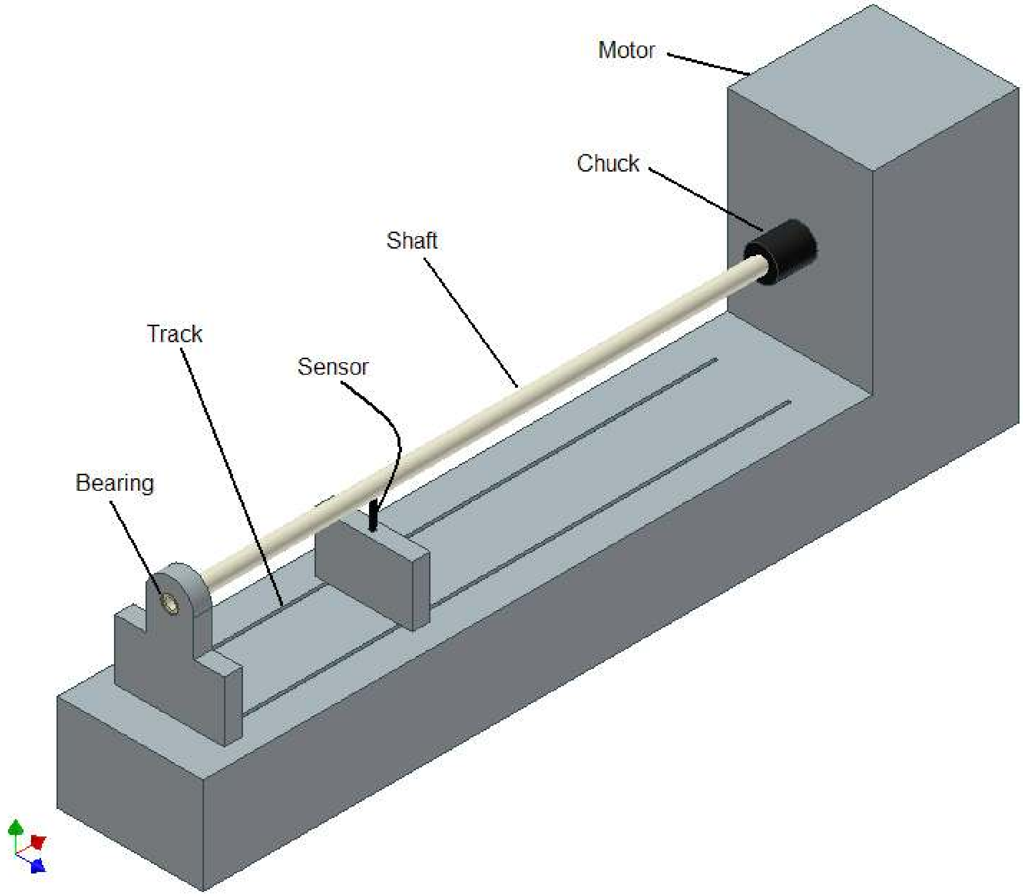

Figure 6-1 – Repositioning-sensor concept

The central idea with this design is that balance detection is done by taking several readings along the length of the shaft.

6.3.1.2 **Analysis**

Given appropriate fabrication methods, materials and operating considerations, durability should be of no concern. Since weight limitations are high, this machine could be designed in a "bulky" fashion using cheap, strong metals. An initial survey shows that design components are not too expensive. Further, performance may be satisfactory; the sensor takes readings at more than one location, which makes the detection of all three modes of shaft imbalance (see section 4 Product Specifications) possible. There are no foreseeable limitations on the proper functioning of the device.

It should be noted, however, that shaft imbalances may be detected by merely taking readings at the shaft ends. Background research has shown that proper balance diagnosis can be performed in this way. Consequently, the idea of a re-positioning sensor that takes readings at multiple positions becomes too complicated – all that is necessary are two sensors fixed at the shaft ends.

6.3.2 *D3 Balance Detection Machine*

6.3.2.1 **Description**

This design mounts the shaft on a chuck and two bearings at fixed positions (see Figure 6-2). A sensor is used in the motor housing to detect rpm and angular position (not pictured). The bearings are mounted near the ends of the shaft, used for support and to house electronic sensors. These sensors detect shaft displacement (during rotation) in a direction perpendicular to the rotation axis, similar to 6.3.1. The information is then processed and presented in a usable format.

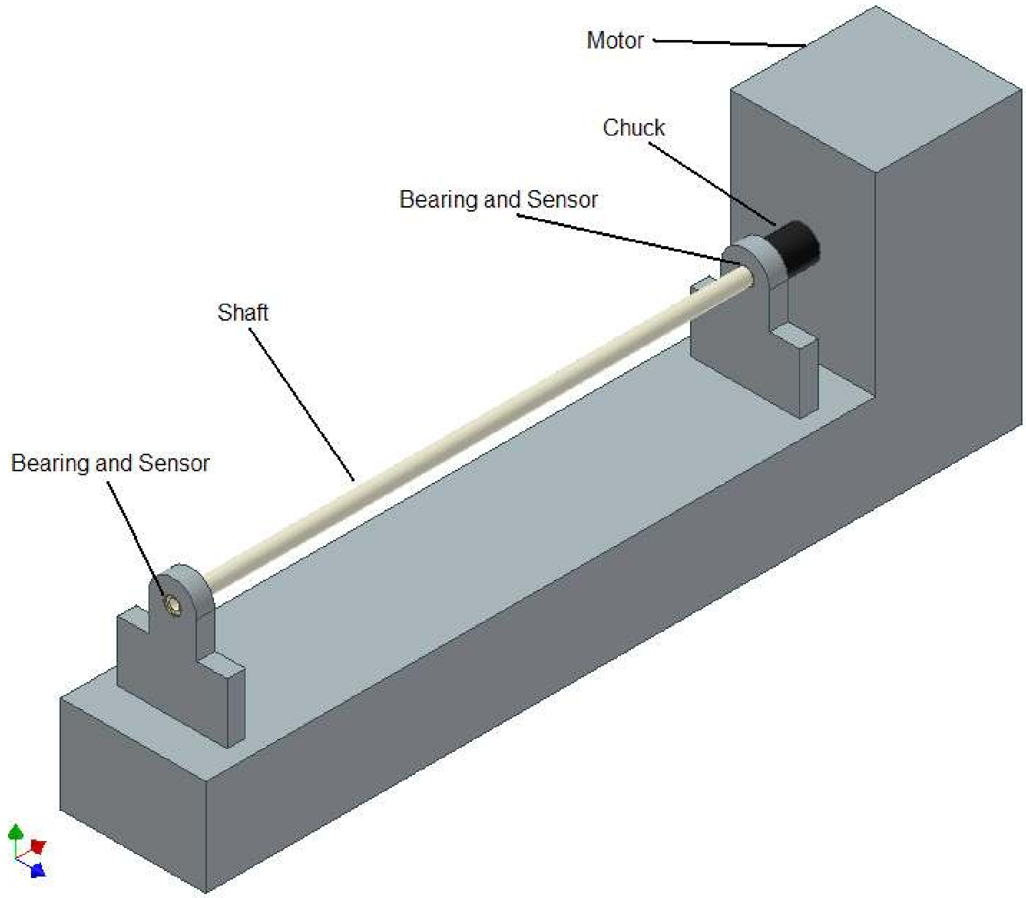

Figure 6-2 – D3 Balance Detection Machine concept

The important idea here is that all imbalances are detected by taking readings only at the ends of the shaft. This design was adopted from the drive shaft balancing machines that CEMB manufactures.

6.3.2.2 **Analysis**

As with 6.3.1 (Repositioning-Sensor), durability can be high; appropriate material selection, ease of operation, and fewer moving parts can make this design resilient to everyday use. All required functions have been accounted for, and should be performed easily. An initial parts-sourcing survey has determined total cost to be $1270. For more information, see Appendix **Error! Reference source not found.** **Error! Reference source not found.**.

6.3.3 *Z50 Balancing Machine*

6.3.3.1 **Description**

CEMB manufactures a balance detection machine that is suitable for this project (see Appendix **Error! Reference source not found. Error! Reference source not found.**). Model Z50 in particular has the capabilities necessary to accept the shafts of concern.

Capabilities:

- Range of acceptable shaft diameters: 5-70 mm
- Max shaft length: 700 mm (1500mm with extension)
- Integrated sensors and computer for balance detection
- Unbalance reported on display
- Additional specifications available in attached PDF

The Z50 is the smallest horizontal balancing machine CEMB manufactures that meets the requirements of the project.

Figure 6-3 – A CEMB horizontal balancing machine (Z50 picture not available)

6.3.3.2 **Analysis**

US pricing for the Z50 (without an extension) is $30,975. However, European pricing may be lower, since the US distributor for CEMB imports these machines from Italy.

The advantages of buying a CEMB machine are:

- Location
- Reliability (50 years of specialized experience in vibrations)

- Technical support and training available

6.3.4 *Portable Device*

6.3.4.1 **Description**

There exists imbalance detection devices that are used in field-testing applications. CEMB manufactures products along this line of thinking, such as the N402 (see Figure 6-4) and the Portalizer. These devices can be used on rotating components while still in their native assemblies. Operation is as follows: electronic sensors are positioned on-site, the assembly is activated (rotated), the computer acquires sensor data, processes it, and then reports the balance state of the shaft.

Figure 6-4 – N402 Device

Such a device may be used in conjunction with a simplified rotating machine similar to 6.3.1 (Repositioning-Sensor), or by itself, directly on the RCU (please see Appendix **Error! Reference source not found. Error! Reference source not found.** for more information on the device). For this reason, two versions of this concept are presented here: Portable Device with Rotating Machine, and Portable Device Standalone.

Portable Device with Rotating Machine

The rotating machine would not include any integrated sensors, but would keep the chuck, motor and bearing from 6.3.1 (see Figure 6-5). The portable device would be used to take readings while the segment is rotating. Subsequent analysis and reporting would also be done through the unit.

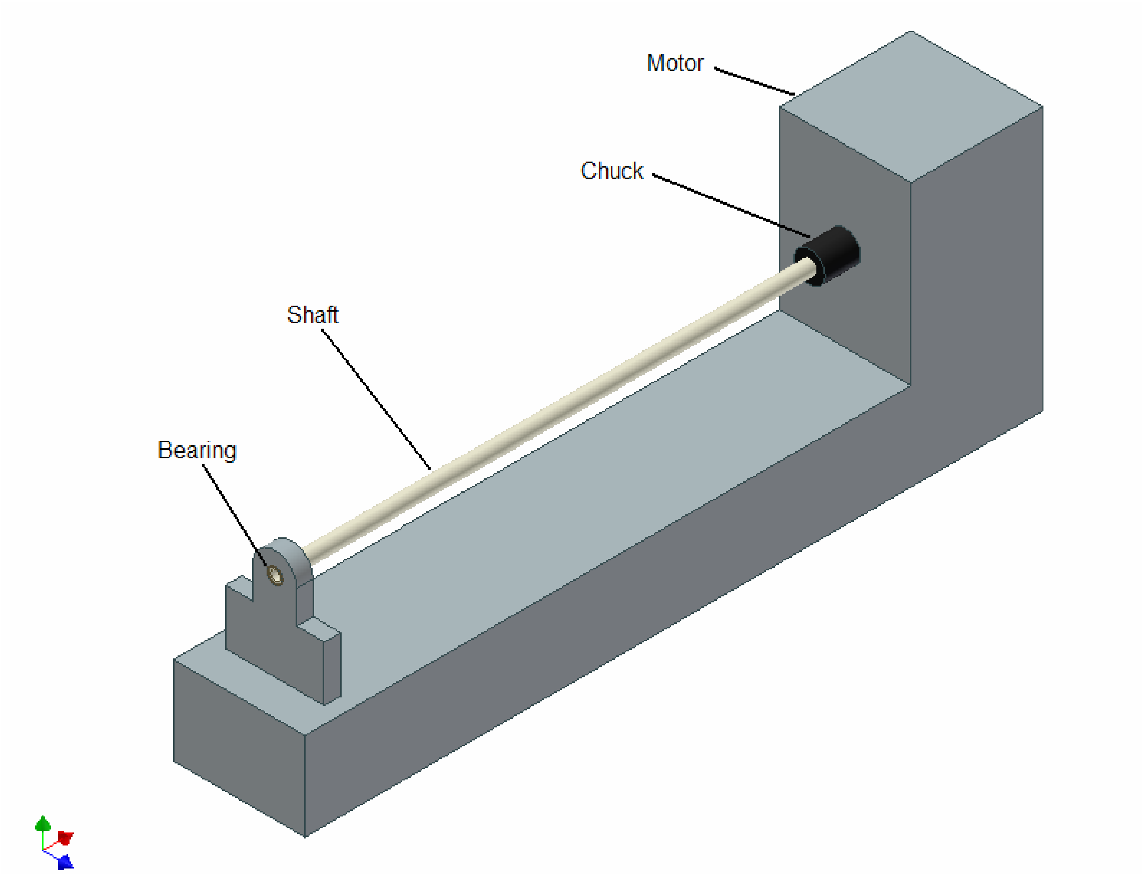

Figure 6-5 – Rotating machine for N402 concept

Portable Device Standalone

It may be possible to use the portable device on-site (see Figure 6-6) if the segments could be isolated. The cold bore and anticryostat would have to be removed, but all other components could remain. Fixtures would have to be fabricated to position the sensors appropriately.

Figure 6-6 – N402 (left, on table) in use on-site

6.3.5 *Analysis*

US pricing on the N402 is $13,500. As with the Z50, this product is imported from Italy, and so European pricing may differ. The Portalizer, the replacement for the N402, will be offered at $12,280, US pricing.

Both devices can perform all required computational functions. More specifically: data acquisition and analysis from sensor data, and reporting of balance state information on integrated LCD or digital output to desktop PC. Durability is high for the N402; the hardened external case protects the computer and accessories from damage.

Regarding the rotating machine, it is a simple design with the fewest parts of the three designs presented here. It performs its singular function well, and does so in a cost-effective manner (by virtue of its simple design). Estimated cost for this machine is $285 (see Appendix **Error! Reference source not found.** **Error! Reference source not found.** for a more detailed estimate).

6.4 Cost Summary for Detection Designs

Table 6-1 below summarizes cost estimates for most of the detection designs presented above. Detailed cost estimates for the *D3 Balance Detection Machine Concept* and *Rotating Machine* are available in Appendix **Error! Reference source not found.** **Error! Reference source not found.**. Please note: stated costs for CEMB products (Z50, N402 and Portalizer) are based on US pricing.

A price estimate was not provided for the Repositioning-Sensor concept (6.3.1) as its design is overly complex. The **Error! Reference source not found.** concept (**Error! Reference source not found.**) is in fact the improved, more cost-effective version of that same design.

Detection Cost Summary	
Design	**Cost**
Bearing-Sensor Concept	$1,267
Z50 Horizontal Balancing Machine	$30,970
N402	$13,500
N402 with Rotating Machine	$13,785
Portalizer	$12,280
Portalizer with Rotating Machine	$12,565

Table 6-1 – Detection Cost Summary

The Z50 is by far the most expensive option, requiring a thirty thousand dollar investment, with the N402 and Portalizer at an intermediate (yet expensive) price of about thirteen thousand dollars.

7 Analysis Procedure

7.1 Overview

On the whole, there are two things required for computational analysis: Calibration and Balance Detection. The first is the basis for the second, and need only be performed once for each accelerometer.

7.2 Calibration

The following procedure is a mass-moment calibration of the accelerometers. This gives a direct correlation between accelerometer output (voltage) to mass-moment imbalance. It is to be performed after data is acquired from accelerometers and rotary sensor. Procedure is done for each accelerometer separately. Please note: steps 1-6 are to be performed twice: once without the addition of a trial mass, and once with. Also, it is assumed that accelerometers have been g-calibrated (voltage/acceleration relationship).

As a general description, the voltage/mass-moment calibration is determined by measuring the effect of an added trial mass to the rotating system. There is a direct proportionality between the mass-moment of imbalance the shaft has (alone) and the effect the trial mass has on displacement during vibration.

1. For the sensor data acquired from the run without a trial mass, in the time domain, **integrate accelerometer signal twice**.
    - This is done in order to derive displacement from acceleration readings.
2. Signal may be a complex sine wave (this will be the case if there are multiple sources of vibration or if there is simply noise in the signal). **Perform FFT on signal** in order to separate complex wave into its discrete parts. See Figure 7 - 1 below.

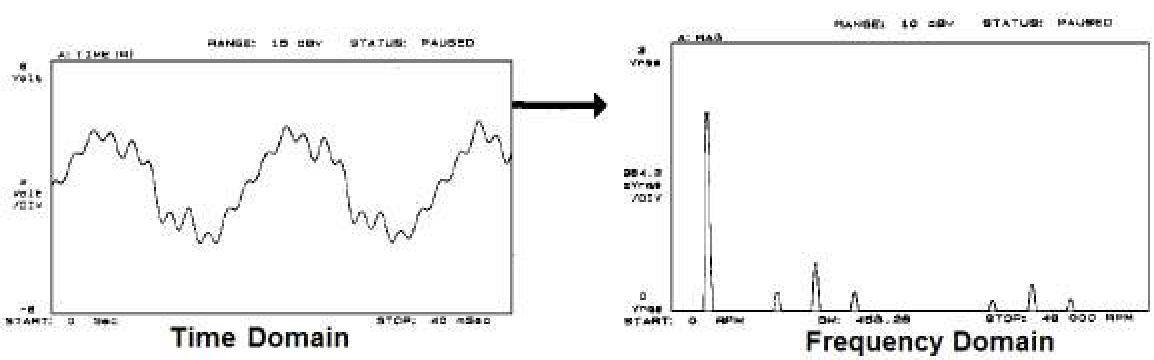

Figure 7-1 - FFT performed on the signal

3. There will be a large amplitude peak at the same frequency as the rotation of the shaft – this is the mass imbalance. (In Figure 7-1, this is the large peak on the left side of the frequency domain graph; other peaks represent noise or other vibration sources). Together with the rotary sensor data, in the time domain, **find the time** (t) **from the zero-index to the first peak** of this isolated signal. See Figure 7 - 2 below.

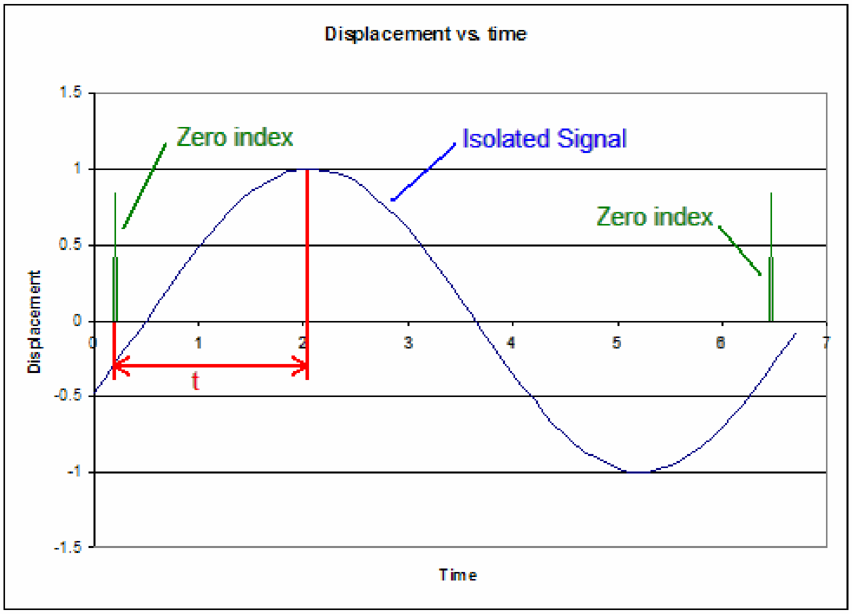

Figure 7-2 – Frequency domain graph

4. **Divide this time** (index-to-peak) **by the time between index's** (i.e. the period), **then multiply by 360 degrees**.
   - $\frac{t_{index-peak}}{t_{index-index}}(360\deg) = \theta_{imb.-force}$
   - This will give the angular orientation (ɵ) of the imbalance force from the zero reference (here forth referred to as the *phase angle*).
   - Angle may be expressed in degrees or radians (a matter of convenience).
5. **Find the amplitude** (A) **of the isolated signal**.
   - This represents the total radial displacement of the shaft as it rotates.
   - It should be noted that step 5 may be performed before step 3 as they are independent of each other.
6. With the amplitude and phase angle, **define a vector with magnitude A and angle ɵ** (polar coordinates).
7. **Repeat steps 1-6** for the data acquired from the run with the additional trial mass. See Figure 3 below.

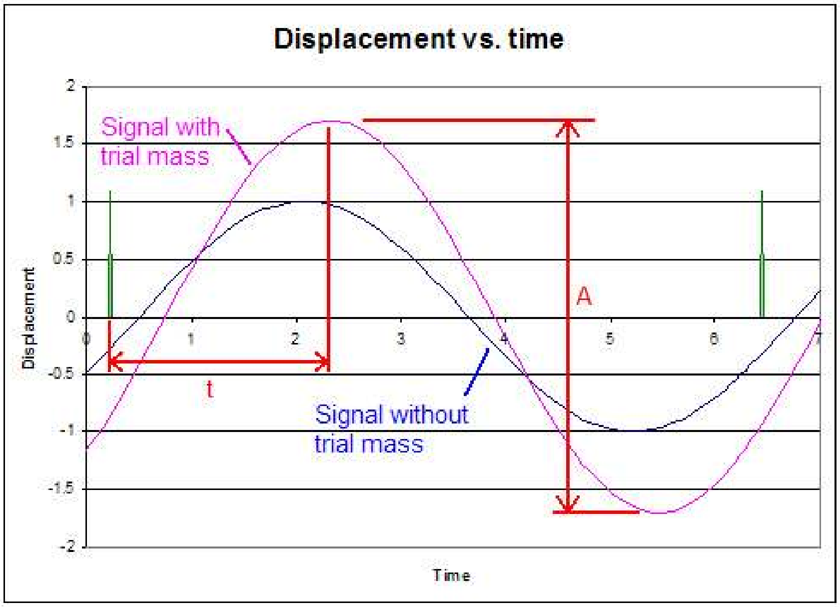

Figure 7-3 – Displacement Vs. Time

8. Let the vector without the trial mass be labeled F1, and with the mass F2. Further, let their angles from the zero-reference be labeled ɵ1 and ɵ2, respectively. When shown together, it may be seen that F2 is the result of the summation of two vectors: F1, and another vector that represents the effect of the trial mass (let this be labeled M). See Figure 4 below. Using vector manipulation, **determine the magnitude of M**.

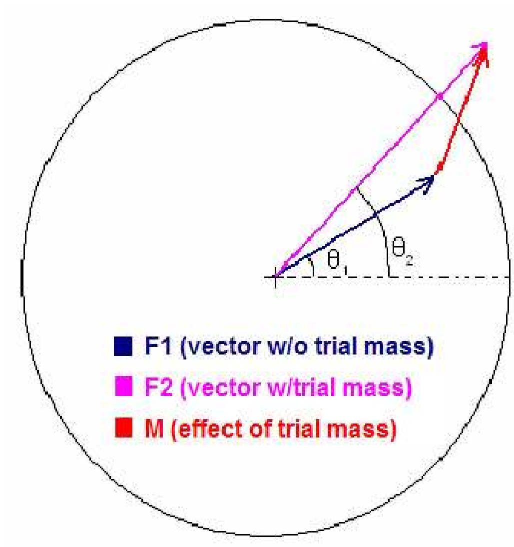

Figure 7-4 – Vector Manipulation

9. **Divide the magnitude of F1 by M**. Let this ratio be labeled n.
   - n is a ratio that will allow us to scale accelerometer output to mass-moment imbalance.
10. The mass-moment induced by the trial mass (G) is given by its mass and the radius at which it sits on the shaft ($G = m_{trial} * r$). Both terms needed to find G will be given. To find the mass-moment by which the shaft is imbalanced (H)**, multiply G by n** ($H = G * n$).
    - It can be seen here that the ratio n is used as a scaling factor; it allows us to determine the shaft's mass-moment imbalance by scaling against a known mass-moment.
11. Finally, **divide H** (shaft mass-moment imbalance) **by the magnitude of F1** (in volts). (Let this ratio be labeled *c*). This is the mass-moment/voltage calibration for the accelerometer.
    - This provides us with essentially a unit-conversion. This number, in units of gram*cm/volt for instance, provides a direct correlation between mass-moment imbalance

This procedure must be done for each accelerometer (i.e. for each plane in which acceleration readings are taken).

7.3 Balance Detection

After calibration has been performed, subsequent balance detection may be performed without steps 7-11. The following steps may be taken after Calibration steps 1-6:

vii. **Multiply amplitude A by ratio c** (as found in Calibration step 11).
   a. This will determine the magnitude of mass-moment imbalance.

viii. **Report imbalance:** Magnitude at phase angle ϴ.
   a. Example: 2.3 g*cm at 120 degrees.

ix. **Repeat for other accelerometer**.

8 D3 Balance Detection Machine

8.1 Description

The D3 Balance Detection Machine design has evolved into the form shown in Figure 8-1 below. It remains largely the same as the original D3 Balance Detection Machine concept (**Error! Reference source not found.**), however, several modifications have been made in its development. 80/20 extruded stock is used throughout the assembly as a framing system, with components bolting onto the frame using L-brackets (not pictured). The machine may be bolted down to a table for stability while in use.

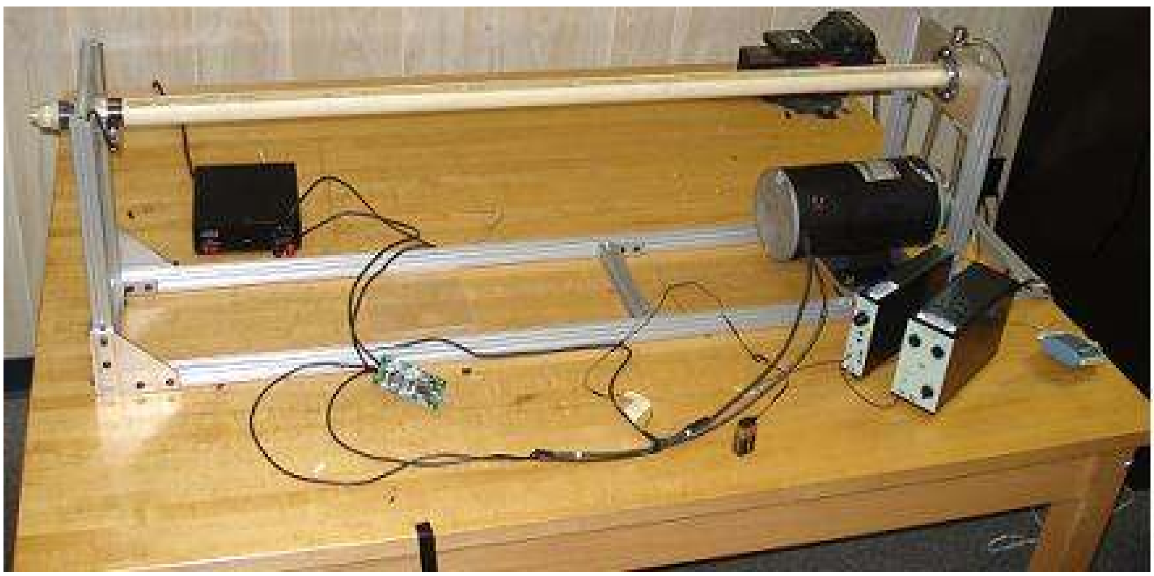

Figure 8-1 – Balance Detection Machine, pictured with 1.2m long shaft segment

Regarding the left side of the machine (see Figure 8-2), the mounting block provides support for sensor positioning and bearing housing. The rotary sensor (an optical encoder) provides data for rpm. The accelerometer (not shown, mounting hole shown on top surface of plate) detects radial acceleration, which will be used to derive radial displacement, of the shaft under rotation. Both sensors are bolted to brackets connected to the mounting block.

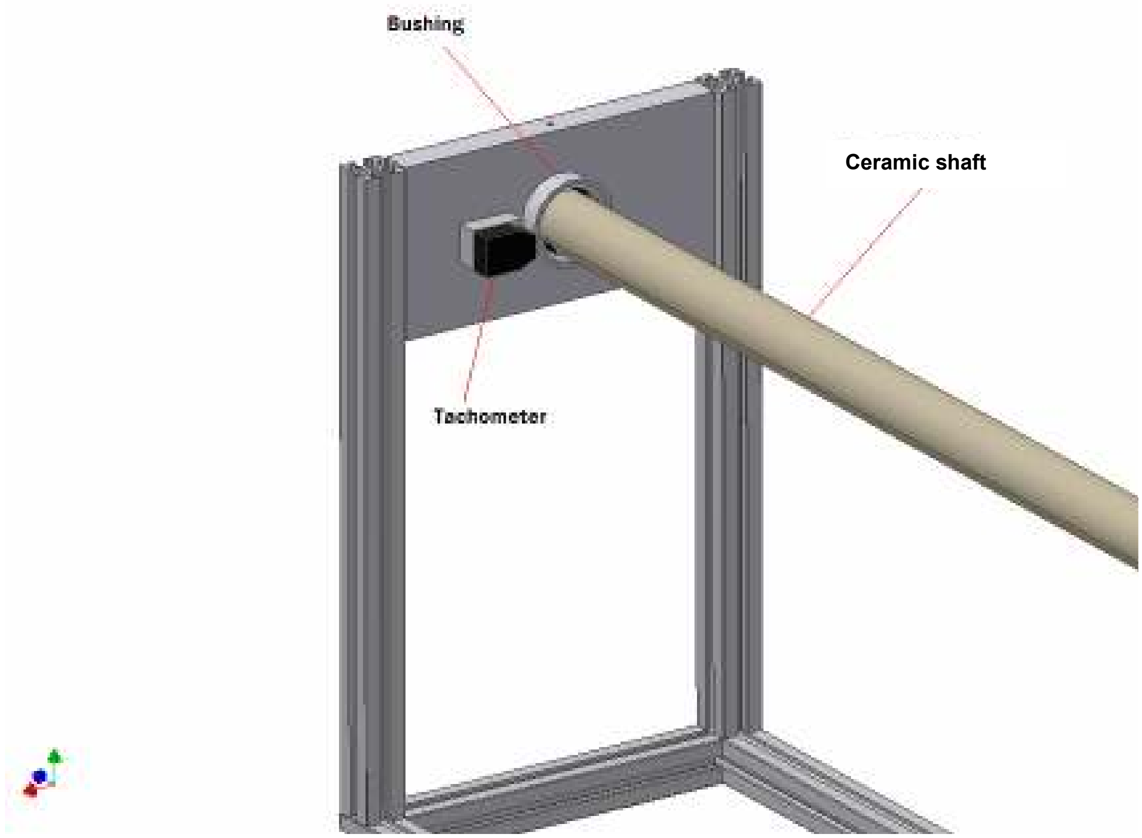

Figure 8-2 – Left side of the D3 Balance Detection Machine

The center of the mounting block has a bushing to allow for the ball bearing to fit inside it (see Figure 8-3). The flange and bearing (parts (a) and (h) from Figure 2-1) will remain connected to the ceramic shaft and used to mount the segment on the machine. For shorter length shafts, the motor and bearing-plate subassembly may be translated down and marked on the base frame for consistent repositioning in the future. The left side of the machine will remain fixed, making calibrations for both configurations easier.

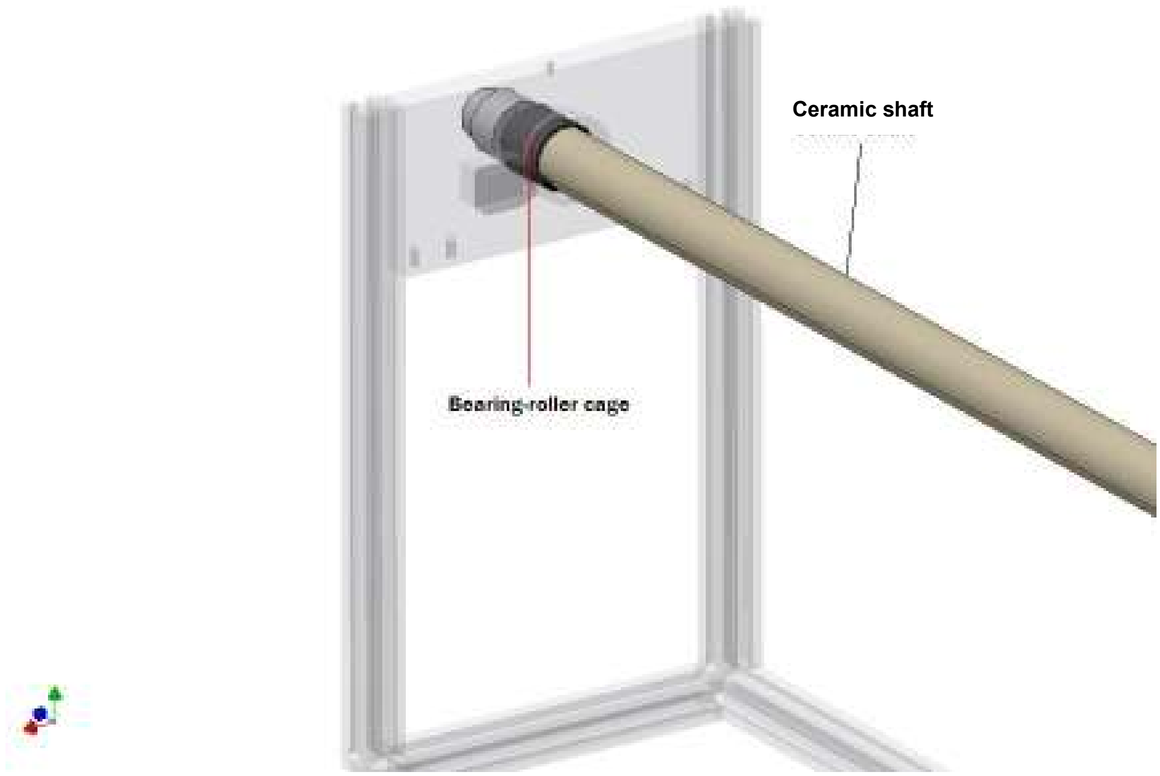

Figure 8-3 – See-through view of left side of Balance Detection Machine

Regarding the right side of the machine (see Figure 8-4), the bearing-plate houses the open-race bearing and provides a mounting surface for the accelerometer. The open-race bearing is press-fit in the plate, and the sensor is screwed into the top surface of the plate. A split-collar is positioned over the shaft, slid into the bearing, and is used as a pulley, ultimately connecting to the motor. The motor itself will be regulated by a motor controller, which has a live readout on the LabView program developed by the Romanian team.

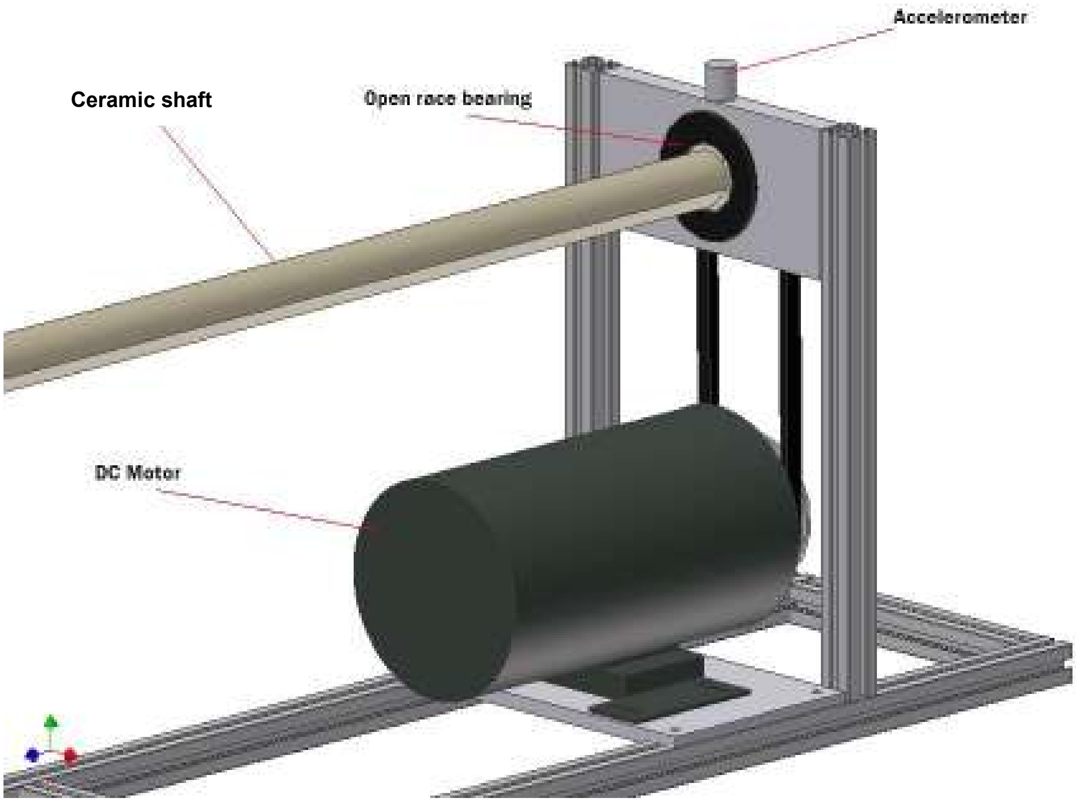

Figure 8-4 – Right side of Balance Detection Machine

The split collar (which also acts as a pulley) connects to the motor by a pulley system shown in Figure 8-5. Pulleys are mounted on the motor drive-shaft and the ceramic shaft, transmitting power from the motor to rotate the shaft segment.

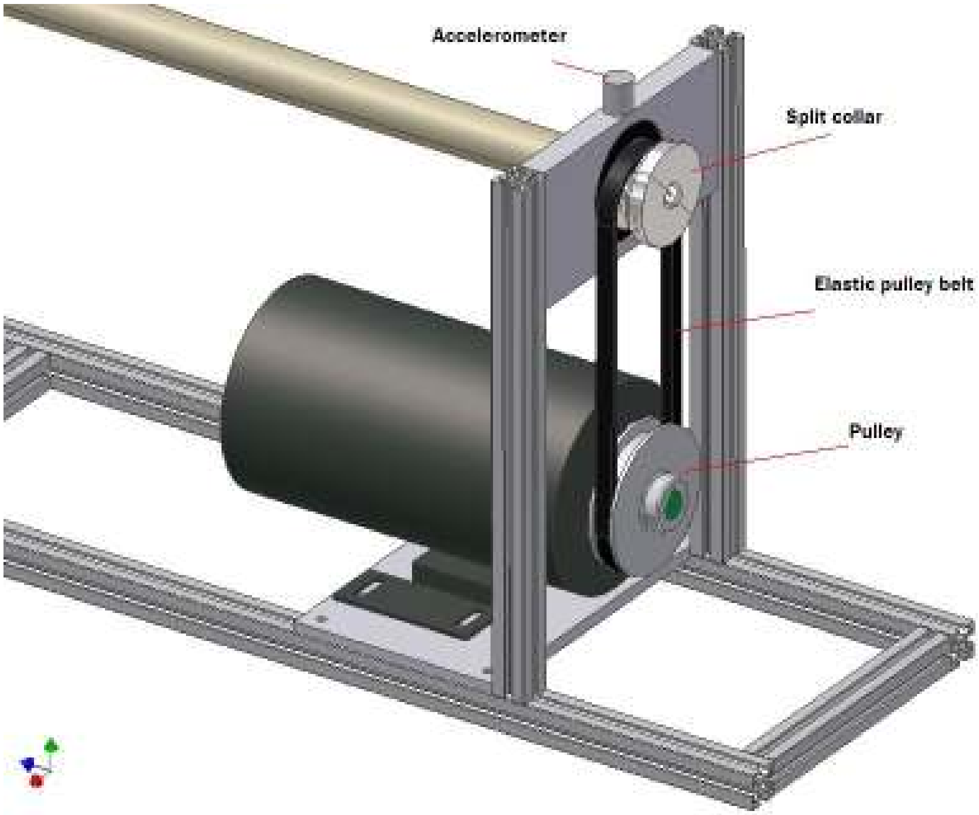

Figure 8-5 – Right side of Balance Detection Machine showing pulley system

8.2 Components

The following is a description of the reasoning used to select components used in the Balance Detection Machine. Detailed calculations are included in Appendix **Error! Reference source not found. Error! Reference source not found.**. The Romanian team is exploring sensor selection at time of writing, hence only descriptions of required specifications are included here. Further, since these components are still being sources, "ballpark" figures (derived from initial market surveys) were used to estimate cost at this stage.

8.3 <u>Mechanical</u>

8.3.1 *Coupling*

The split collar is one of the most sophisticated mechanical components of the whole assembly. It is specifically designed for this application. The inner surface matches the cross-section of the shaft. The outer surface is designed to have a slip fit with the bearing. The split collar is also machined to act as the pulley that connects the shaft to the motor. Once attached on the shaft the two halves are bolted together. The inner surface is also machined to go around and not touch the inner components of the shaft.

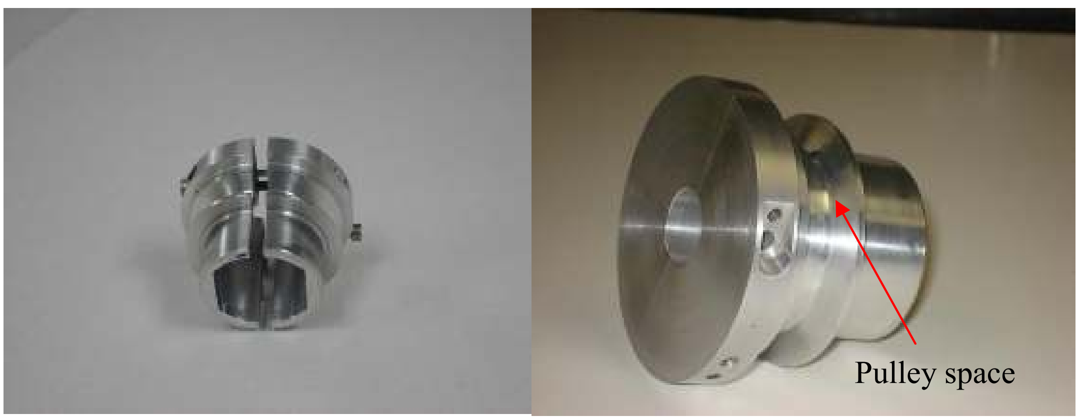

Figure 8-6 - Split Collar

8.3.2 *Bearing*

The bearing is an open ball bearing designed for high speed applications. It has an 85 mm outer diameter and it fits 45 mm diameter shafts. The bearing can handle up to 8800 Maximum RPM. As shown in the picture the bearing was press-fit into the bearing plate.

Figure 8-7 - Bearing

8.3.3 *Pulleys and Drive Belt*

8.3.3.1 **Pulleys**

The pulley that is mounted on the Motor shaft is a standard V-belt drive Pulley purchased through *McMaster-Carr*, with a 10.16 cm outer diameter. The other pulley is enclosed in the split collar and it has a 6.0 cm outer diameter. The diameters of both pulleys were specifically designed to be different so the motor vibrations can distinguished from the mass imbalances of the shaft when doing the FFT.

8.3.3.2 **Drive Belt**

The belt is made out of thermo-plastic and it can be welded together for the desired length. It is 0.95 cm in diameter and 65.56 cm long.

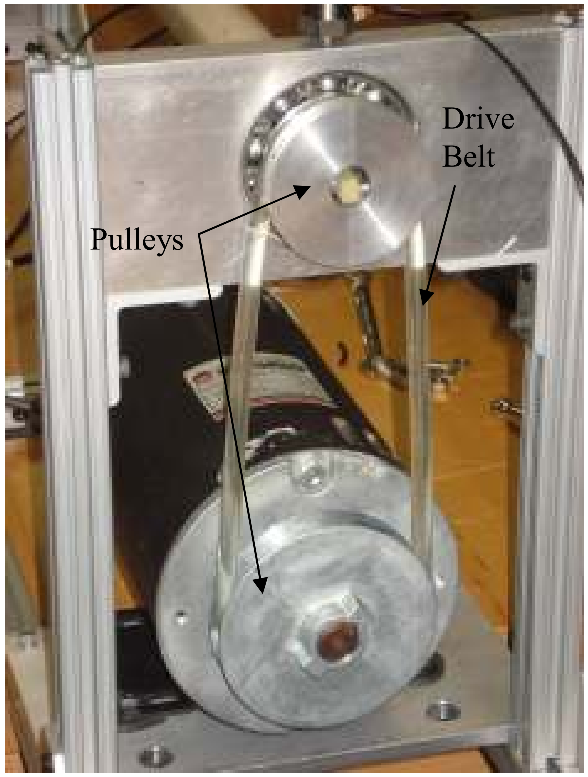

Figure 8-8 Pulleys and drive belt

8.3.4 *Machine Frame*

The supporting frame is relatively simple. It consists of 80/20 railings cut to precision and Aluminum plates that the shaft and electric motor rest on (see picture). The frame is assembled together with L and T brackets. Since most of the material is Aluminum the frame is light which allows for extra mobility, but it will need to be bolted down to a much heavier platform so no extra vibration is induced.

8.4 <u>Electronics</u>

8.4.1 *Motor*

The motor is very robust, total power being rated up to 1 Hp. At full load it draws up to 41 Amps of DC current and a potential of 24 Volts. However it will never reach these specs because it is limited by the power supply (see below). One of the advantages of this motor is the weight, being the heaviest component of the whole assembly, which helps with damping the system. Also very little vibration comes from the motor, even when operated at high frequencies. But to minimize the motor vibration even more a damping material is places in between the motor and motor plate. One little disadvantage is that it is a little noisy when operated at low frequencies.

Figure 8-9 – One horsepower motor

8.4.2 *Motor Controller*

The motor controller was bought as a kit and put together by soldering all the components to the PC board. Originally the controller was rated 12-32 Volts DC at 5 Amps, but some modifications were made by adding 16 Gauge wire through to the mosfets channels (see picture). With this modification the controller can handle motors rated up to 47 Amps. Motor speed control is done by manually rotating the potentiometer. Also a nice feature although not required about this controller is that it allows bi-directional rotation.

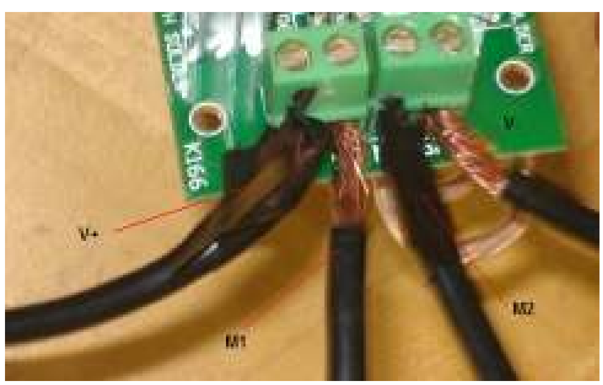

Figure 8-10 – Motor controller configuration

8.4.3 *Motor Power Supply*

The motor power supply was bought directly from *Radioshack* store. It outputs up to 15 Amps at 13.8 Volts DC. The nice feature about this Power Supply is that it plugs directly into the wall outlet, eliminating the need of a battery source. Also the On/Off switch can be used as an emergency power cutoff.

Figure 8-11 – AC/DC Power supply

The following electronic equipment was borrowed from Dr. Hollis for running the experiment. Once shipped to CERN, similar Equipment will be purchased for the machine.

8.4.4 *Accelerometers*

The accelerometers are Bruel & Kjaer brand, type 4381. It is a high sensitivity piezoelectronic charge accelerometer (98 pC/g) that can be used for low frequency measurements. It is being powered be the Sensor power Supply that connects through the Charge Amplifier. A more detail accelerometer data sheet and description is in the Appendix.

Figure 8-12 - Accelerometer

8.4.5 *Tachometer*

The Photoelectric Tachometer is Bruel & Kjaer brand as well, Probe MM-0012. It can be powered up by simply connecting it to a 9 Volts battery. The BNT cable that connects to the tachometer was modified so it can be connected to the battery and the DAQ. The tachometer emits a infrared light that is reflected back by a reflective strip attached on the shaft. Also the distance between the tachometer and reflective strip was minimized to about 4 mm for better feedback. A more detailed explanation is available in the Appendix.

Figure 8-13 - Tachometer

8.4.6 *Sensor Amplifiers*

The Sensor Amplifier is also Bruel & Kjaer brand, model 2651. It enables a charge amplification of up to 10x. That way the sensitivity of the accelerometer can be increased up to 980 pC/g. It also connects the accelerometers to the DAQ and Sensor Power Supply.

8.4.7 *Sensor Power Supply*

The sensor power supply powers up the accelerometer and Charge amplifier, by simply plugging it into the wall. It caries a Bruel & Kjaer name brand as well.

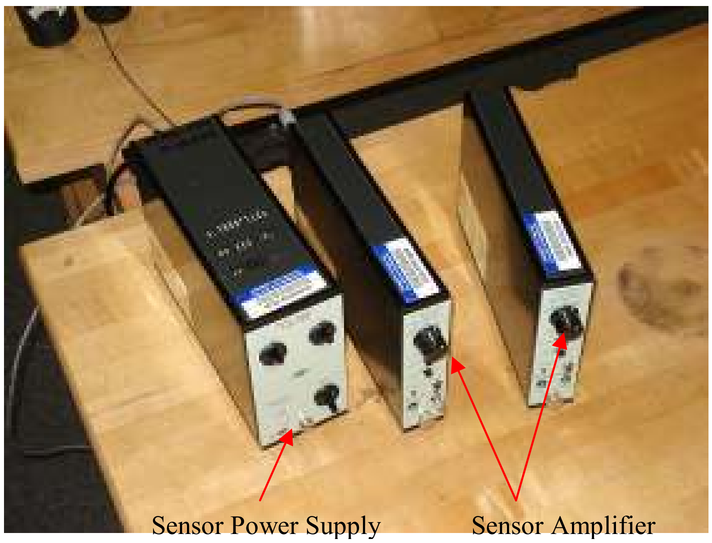

Figure 8-14 – Power supply and Charged Amplifier

8.4.8 *Data Acquisition Board*

The Data Acquisition Board (DAQ) transmits the accelerometer signal to the computer where it can be further analyzed. It is Computing Measurements brand model USB-1208FS. It connects to computer through USB cable and has an up to 12 bit resolution. The scan rate is 50,000 scans/second. More detailed info can be found in the Appendix.

8.4.9 *Machine Frame*

80/20 manufactures industrial erector sets, t-slot extruded stock that may be used for quick assembly of machinery. The stock is made from 6105-T5 Aluminum, and is readily available through industrial suppliers such as McMaster-Carr or Reid Supply. A whole line of accessories are sold for the stock as well, including T-nuts and L-brackets, necessary for bolting frame pieces together. At $3.35 per ft from McMaster-Carr, it is ideally suited for this application.

9 Results

9.1 Success

The team was able to build a mechanically functioning machine. The split collar fits almost perfectly on the shaft and in the bearing, and is very well balanced (by virtue of its fabrication on a balanced lathe). The delicate shaft mounts appropriately on its supports without damage, and is rotated very easily by the motor. The motor speed is varied successfully with the controller built by the team, and it receives enough power from the AC/DC converter to rotate the shaft at and above the maximum speed of interest (by visual inspection).

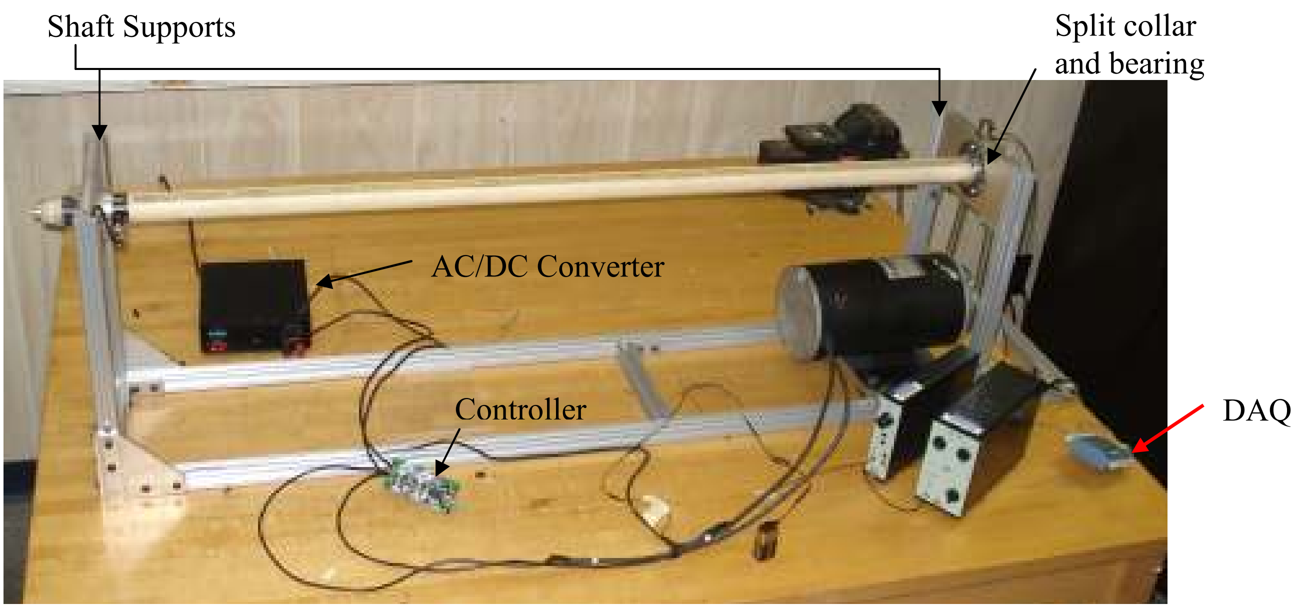

Figure 9-1 – Complete set-up

The analysis portion of the software was a success as well. Tested with simulated signals, it acquires the raw data from both the tachometer and accelerometer, processes them through filters and FFT, and performs all the required calculations appropriately. Results are shown on the Front Panel display on the Measure tab. See figures below.

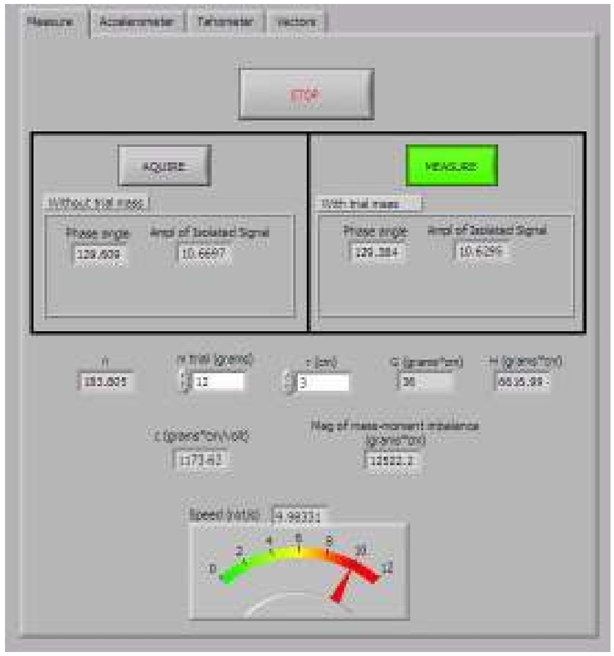

Figure 9-2 – Front panel display showing operation buttons, tachometer readout for rot/s, and inputs for trial mass and radius of trial mass.

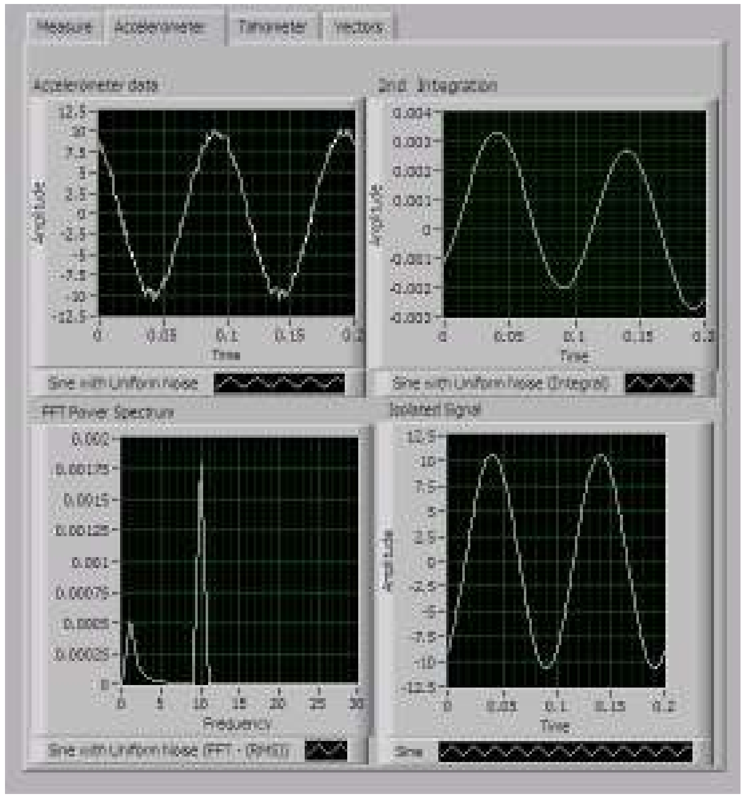

Figure 9-3 – Graphs showing output for raw accelerometer data with noise, FFT power spectrum, and the isolated shaft signal with displacement amplitude (cm).

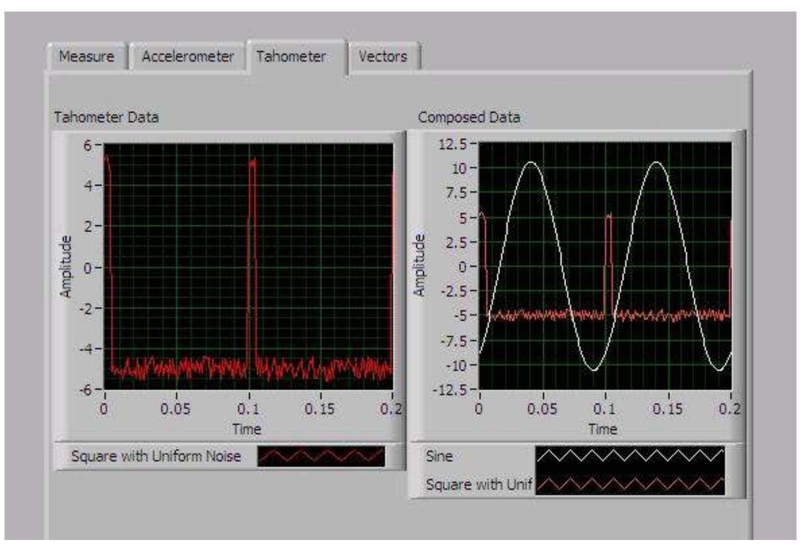

Figure 9-4 – The tachometer tab shows the output of the tachometer and the isolated shaft signal overlaid on each other. This information is used to find the phase of the signal.

9.2 Difficulties

The CERN Team was not able to demonstrate the method of balance detection. This is due in large part to the fact that the MCC DAQ could not interface with LabView correctly. To ensure the DAQ was functioning properly, it was tested using oscilloscope software that comes with it (TracerDAQ). The accelerometer was screwed onto an exciter that produces a signal used to calibrate the sensor. See figure below.

Figure 9-5 – Picture of exciter with accelerometer installed.

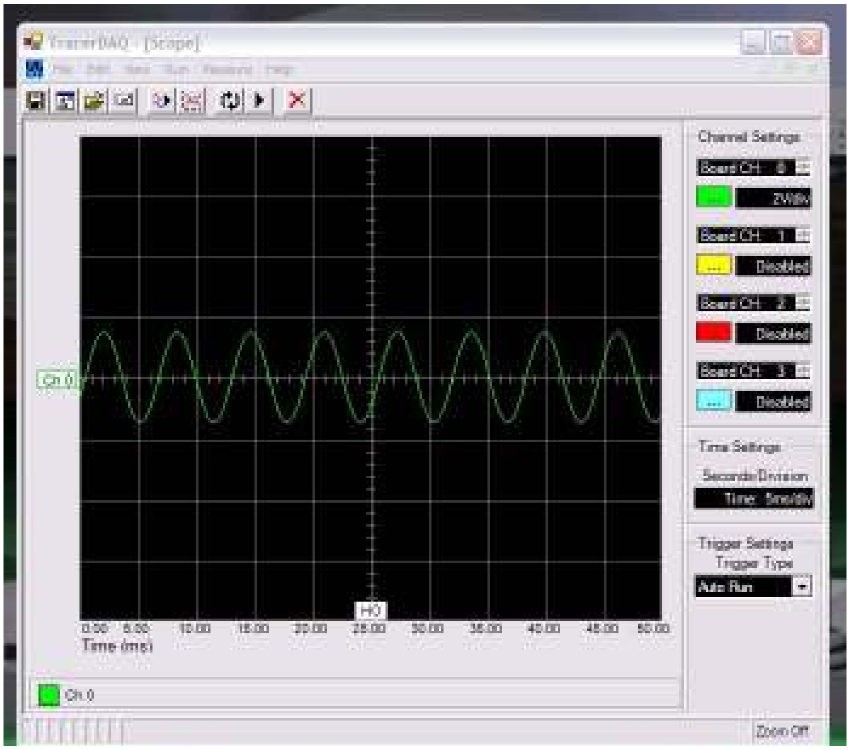

Figure 9-6 – TracerDAQ showing output from accelerometer connected to exciter.

The software showed a clean sine wave, clearly showing that the DAQ is outputting the accelerometer signal successfully.

When attempting to create input blocks in LabView, several problems occurred. Voltage range errors, false conversions from analog to digital, and finally, a failure to output waveform graphs, stopped the flow of usable data to the analysis portion of the software. Of importance, most of the analysis performs graphical manipulation on the data, so without waveform graphs, no analysis was possible (see figure below). Because of this, no results from real data were achieved.

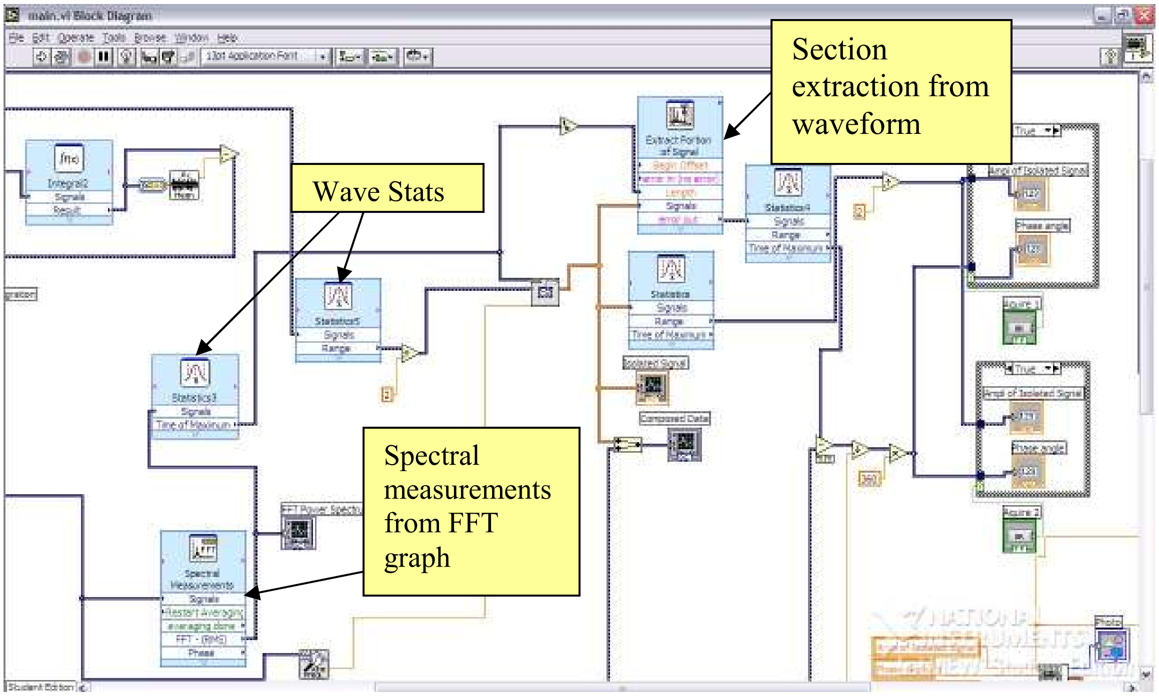

Figure 9-7 – Section of Labview block diagram used for analysis

10 Budget

Below is a table outlining the final budget for the 2006-2007 academic year.

Component	Qty	Unit Price	Extended Price
Electrical Motor	1	$180	$180
Motor controller kit	1	$25	$25
80/20 Railing 8ft	4	$27	$108
Pulleys	2	$6	$12
Pulley Belt	1	$8	$8
AC/DC Converter	1	$85	$85
Auxiliary Materials, shipping	1	$200	$200
Paper Printing	1	$88	$88
Open House	1	$100	$100
Bearing	1	$20	$20
Total			**$826**

Table 10-1 – Updated budget for project

The 2007 CERN team was allotted $1000 by Boeing to construct the D3 machine. The budget has changed dramatically in the second semester of the project. As many components were excluded due to design modifications, and other were added the budget has been modified constantly. The biggest and the final change, however was when the decision was made to borrow the electrical equipment from Dr. Hollis, one of the professors at FAMU-FSU College of Engineering. This equipment included accelerometers, charge supply and amplifiers, Data Acquisition board, and tachometers. These are the most expensive components of the design, altogether running around $900. That brought the budget to less than a half of its original value. The compromise, to which the sponsor and Dr. Hollis agreed on, was to send the borrowed equipment to CERN for a limited time until they acquire some similar equipment themselves.

11 Romanian Collaboration

11.1 Responsibilities

Something unique about CERN Project at FAMU-FSU College of Engineering was the collaboration of students from the college with students form Polytechnic University of Bucharest, Romania. Thus the whole team was composed of Team USA and Team Romania. Team Romania was made up of the following team members:

- Cosmin Mogos
- Ion Alexandru Morega
- Adrian Mihai
- Andronache Ionut

All of the members are fifth year students in Electrical Engineering. Accordingly to major concentration the project responsibilities were divided in the following manner:

Team USA:	Develop and demonstrate balance detection method
Team Romania:	Software Design and assistance with electric equipment

11.2 Communication

Since in person collaboration was not possible, other means of communication were necessary. Also another obstacle that had to be overcome was the 7 hours time difference between US Eastern Standard Time and Romania Time. Email, Instant Messenger and Voice over Internet proved to be the most successful ways of communication.

- **Email** was done through www.gmail.com that both parties opened an account with, and it was the most common and frequent method of contact between the teams. The advantage of email was that a message with files could be sent and the other party did not had to be online to receive. Email communication was the only method that did not depend on the seven hours time difference. GMAIL also offers many user friendly features like storing and sharing Documents and Pictures, 2 GB of Storage and Chatting, which were used quite numerously throughout project evolution.

- **Instant Messenger (IM)** feature was used through Yahoo! and GMAIL Chat. The IM communication was not used as often as the email feature. The reason for that was again the seven hour time difference, which lead to confrontations schedules. The nice feature about IM though was that the exchange in information occurred much faster and more efficient than email. Towards the end of the project, the IM communication was used more frequently because one of the Romanian teammates was able to receive IM messages on his mobile device.

- **Voice over Internet** was the fanciest way the communication between parties could be done, by having the luxury of a phone quality conversation overseas. However, it was still depended on the time differences between the two countries, thus making it very difficult to organize. Also the file transfer could not be possible, unless using the email at the same time. Because of the difficulty to organize was big, Voice over Internet was only used just a couple of times.

12 Future Work

12.1 Structural

The shaft, once mounted, is not constrained from translating along its length. Such movement may cause the belt to rub against the bearing-plate, or a portion of the roller cage may "walk" out of the bushing. This may be corrected by machining a groove near the edge of the split collar (on the side that goes through the bearing), and placing a c-clip in the groove. The clip would keep it in place during rotation. See the figure below.

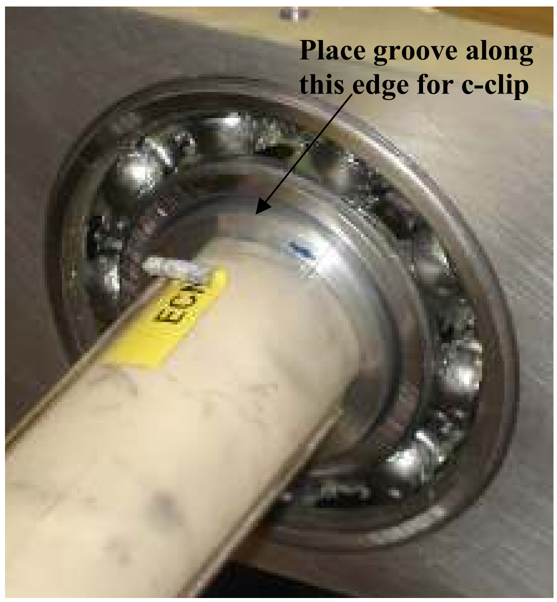

Figure 12-1 – View of slit collar with possible position for c-clip retaining ring

Both the bearing-plate and the bushing-plate are only bolted to the vertical arms by L-brackets along their bottom edges. This gives the top portion of the plate some freedom to vibrate, and as a result, may affect sensor readings. One possible solution is bolt the top portion of the plate to the top face of the vertical arms, so that there is no relative motion between the parts. See figure below.

Figure 12-2 – Picture of bearing-plate showing its L-bracket support (4-bolts, two on each side, not fully shown).

The vertical arms that hold the plates in place are only bolted to the frame at the base of the legs, which leaves the top portion of the arms with some freedom to vibrate. Diagonal arms connecting the top-most portion of the vertical arms to the base frame (at 45 degrees, for example) would help stop this problem. See figure below.

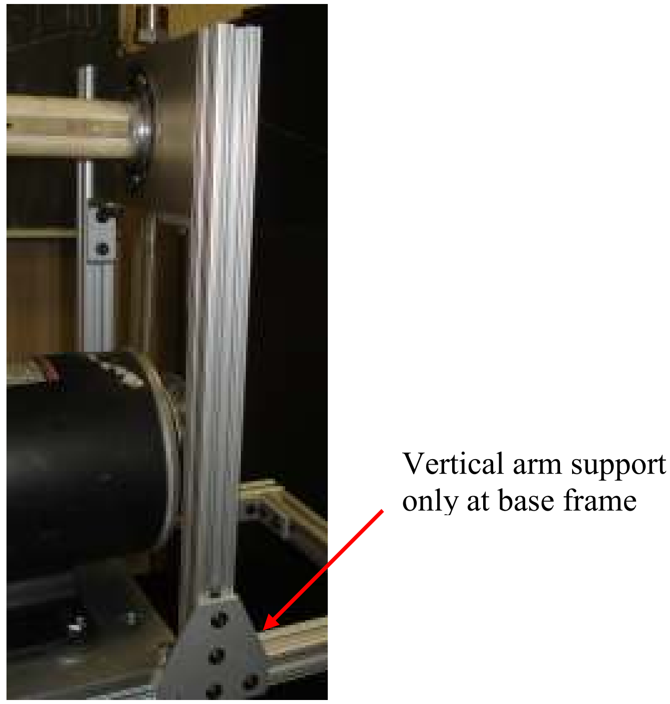

Figure 12-3 – Picture of vertical arm used on the bearing-plate side of machine.

Motor vibration may be problematic for data analysis, since noise contributions make isolating the shaft vibration signal more difficult. This also applies to any vibration propagation that may occur on the table the machine sits on. Vibration damping material was used at the bolt interface for the motor, however, a full "floating bolt" design (where the bolt is never in direct contact with the vibration source) was not achieved. It would be beneficial to add damping material underneath the bolt heads (since they currently have full contact with the motor) and possibly at the corners of the base frame. See figure below.

Figure 12-4 – Picture of bolt interface showing incomplete "floating bolt" design

12.2 Electrical

The motor purchased for the machine does not run very well at low speed (1-2 Hz). Its motion is erratic at times, slowing down randomly, then resuming normal operation. A motor more suited to low frequency ranges would be an improvement.

A National Instruments DAQ would be easier to work with than the Measurement Computing Corp (MCC) model used for this project. LabView is already setup to work with NI DAQ's, so the process is plug and play (near guarantee on functionality).

12.3 Software

Since the interface between the MCC DAQ and LabView was not functioning, no real data was taken -- thus, demonstration of the balance detection method developed by the team was not possible. However, whether or not theMCC DAQ is to be used in the future, a functioning interface must be developed to connect the DAQ to the analysis software. Once this is done, the acquisition and analysis may be completed.

Some additional features may be desired by CERN from the analysis software. Report generation with calculated values and a polar graph of the imbalance vectors would be very useful. Also, a graph which overlays radial displacement from both planes over each other, showing their respective magnitudes and phases in the time domain, could help CERN interpret rotation modes.

13 Conclusion

The completed machine is capable of safely mounting the shaft and rotating it to a desired speed. It can accept both length shafts (1.2m and 0.75m) by repositioning the motor and bearing-plate subassembly, and is designed to accept rotary and acceleration sensors to take readings appropriate for balance detection. To this extent, product specifications were met.

The software performs all required mathematical functions needed for vibration analysis. The outputs on the front panel of the LabView program shows relevant information and analytically-derived graphs useful for vibration characterization.

Ultimately, the project was not a complete success, however, many things were accomplished. Through ideation and analysis, concepts were generated, and developed for balance detection. A final design was chosen, and construction was successfully completed. Collaboration with the Romanian team produced software that performs all required analytical functions correctly. However, there were problems with linking the acquisition equipment to LabView, and thus, vibration analysis on the shaft could not be performed.

14 Acknowledgements

Dan Baxter, Senior Engineer, FSU Physics Lab – Machining

Kevin Garvey, Graduate Student – LabView help and electronics troubleshooting

Dr. Pat Hollis, Associate Professor – Vibration analysis and mechanical design advice

Jason Isaacs, PhD student – Electronics help

Dr. Alexandru Morega – Electronics advice and general counsel

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16 Glossary

80/20 - An "industrial erector set" made of t-slotted extruded aluminum by 80/20 Inc. It is a common system of materials and joiners used in engineering design for such purposes as machine and perimeter guarding custom work stations and any kind of quick assembly application.

Balance tolerance – A quantity that denotes the acceptable imbalance level of a rotating component. Its units are *mass* x *distance*, which represents the moment of mass by which a component may be imbalanced.

CEMB (Construzioni Elettro Meccaniche ing. Buzzi & C. Spa) - CEMB is dedicated to the supply of balancing equipment, vibration technology and associated services.

CERN (Counsel European Organization for Nuclear Research) - International scientific organization established for collaborative research into sub nuclear physics. Headquartered in Geneva, CERN includes extensive facilities at sites on both sides of the Swiss-French border. The world's largest particle physics laboratory.

Couple imbalance - The mass center is on the shaft axis, however, the mass axis is offset by some angle from the shaft axis.

Dynamic imbalance - The mass axis is at an angle with the shaft axis, however, the mass center is no longer on the shaft axis. This is the most common type of imbalance seen in rotating components.

Eccentricity - The maximum displacement of the mass center from the geometric axis.

Fast Fourier Transform (FFT) - is an efficient algorithm to compute the discrete Fourier transform (DFT) and its inverse. FFTs are of great importance to a wide variety of applications, from digital signal processing to solving partial differential equations to algorithms for quickly multiplying large integers

Large Hadron Collider (LHC) – World's largest particle Collider.

LVDT (Linear variable differential transformer) - A type of electrical transformer used for measuring linear displacement. The transformer has three solenoid coils placed end-to-end around a tube.

N402 - An imbalance detection device used in field testing applications, manufactured by CEMB.

RCU (Rotating Coils Unit) – Magnetic measurement device used to calibrate dipole and quadrupole magnets used in the Large Hadron Collider.

Static imbalance - This occurs when the mass axis is displaced from the shaft axis, but still parallel to it. The mass center is no longer on the shaft axis in this case.

TRU - (Twin Rotating Unit) – The motor unit that drives the RCU.

VFD - (Variable Frequency Drive) - A system for controlling the rotational speed of an electric motor.

Z50 - The Z50 is the smallest horizontal balancing machine CEMB manufactures that meets the requirements of the project.