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# A Study of unbalance in hydraulically driven fan systems

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# A Study of Unbalance in Hydraulically Driven Fan Systems

**by**

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**Abstract**

A study has been conducted to investigate unbalance in Valeo hydraulically driven fan systems (HDFS). The principles of balancing have been modeled and applied to HDFS assemblies. The process from the initial build of the part during the molding process to the final completed assembly has been evaluated to determine how to best decrease unbalance in a manufacturing environment. The areas that were deemed to need significant improvement are the couple unbalance specification and the act of inserting balls into the fan groove to correct for unbalance. A new specification of 48 kg-mm$^2$ was recommended and has been introduced to help expedite production cycle times, and a recommendation of a laser system to remove material from the outside of the ring has been made also been made. Preliminary studies have shown that the implementation of a laser balance system could yield very positive results with respect to repeatability and decreased cycle time. Improvement of this process has showed the potential to increase the profitability of Valeo HDFS assemblies in the current automotive market.

## Acknowledgements

I would like to thank God, my family, the personnel at Valeo Inc who include Dick Ransom, Greg Tenbus, Paul VanDeursen, Ned Storm, Renate Doeve, Tom Eisele, Jim Perdue, Jerry Perkins, Larry Cheney and Randy Agness, and the personnel at RIT who include Dr. Boedo, Dr. Robinson and Dr. Kochersberger, for all the help with respect to the development of this thesis.

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# Chapter 1

# Valeo Hydraulically Driven Fan Systems (HDFS)

## 1.1 Introduction to HDFS

At the Valeo Electrical Systems facility, in Rochester, NY, a division has been created to manufacture hydraulically driven fan systems (HDFS). This facility provides a fan system that replaces conventional electrical cooling systems that are used in Jeep Grand Cherokees and planned for future Dodge Vipers. An HDFS assembly employs a hydraulic motor that uses the excess hydraulic pressure from the steering assembly on a vehicle. This excess pressure is then forced through the motor causing a shaft to spin. A fan is then mounted to the shaft, and the fan is used to move air into the radiator. The speed of the fan is regulated by a pressure control valve and is correlated to the speed of the vehicle.

The main reason for the desire to use a hydraulic fan system in a vehicle is to improve on the efficiency of the cooling system. A hydraulic motor can output up to 10 times as much horsepower when compared with conventional 12-volt electrical cooling motor. Ultimately, this means that using a hydraulic motor will decrease the electrical load on the alternator and increase the amount of airflow through the radiator because of its ability to rotate a larger fan at higher speeds.

The market potential for this type of system is one of high value. As vehicles are becoming larger and more powerful, the need for better cooling systems are required. The increased market for trucks and SUVs have created the demand for a new type of cooling system. Valeo feels that that the HDFS program has the highest potential for future marketability and profitability.

### 1.2 Scope of Work

The scope of this thesis is to study the current balancing process used with HDFS fan assemblies and to investigate ways to improve the process. Valeo has specifications for unbalance so that vibration, and motor wear will be decreased over the life cycle of the product. The current specification for static unbalance is 0.04 kg-mm and for couple unbalance 12 kg-mm$^2$. This thesis will investigate the processes that can cause unbalance and determine if these specifications are appropriate for a manufacturing environment.

Current cycle times range from 140 seconds to 200 seconds to properly balance an assembly. The goal will be to find ways to decrease this cycle time to under 100 seconds per unit. Laser removal technologies will be investigated to determine if there is a better and more efficient way to correct for residual unbalance than the current process of inserting chrome balls into a groove along the hub of the fan.

### 1.3 Rationale for Well Balanced Assemblies

The question arises of why HDFS assemblies need to be balanced is a commonly asked question. The answer is relatively simple - a well-balanced assembly is generally a better assembly to have in your vehicle. The first thing that balance correction does is reduce vibration of the entire assembly. If an assembly has a high amount of vibration, residual stresses will be created on the mounting devices on the cooling systems. This may cause failure or damage to the equipment around the fan assembly. The operator in the vehicle will also feel residual vibration. The more vibration felt by the driver the more likely he or she will become tired and fatigued over long trips. This makes the vehicle less marketable because of its decrease in ride quality.

The second residual consequence of fan unbalance is the extra noise that is created by the assembly. This noise may cause annoyance and or fatigue in the operator of the vehicle. The amount of structural stress caused by residual unbalance on the hydraulic motor may cause leakage and early failure.

The last major benefit of having a well-balanced assembly is the increase in personal safety. Forces caused by unbalance can cause a fan, or motor failure causing a person working on the product to be injured. HDFS assemblies have been designed with a stress factor of safety of approximately 1.75 to 2. This does leave plenty of room for variation with respect to unbalance, but a unit with very high unbalance is more likely to fail under normal operating conditions.

As one can see it does make sense to balance to a desired specification. However there has been a conflict within Valeo to the actual specification. The manufacturing environment feels that a couple specification of 12 $kg\text{-}mm^2$ is unreasonably low, and it is difficult to implement and costly to manufacture. Similar systems employed on the Jeep Grand Cherokee Diesel and the Dodge Viper hydraulic fan systems are balanced to a couple specification of 48 $kg\text{-}mm^2$ that is more reasonable in a production environment. Studies from July 2000 to April 2001 have concluded that a specification change from 12 $kg\text{-}mm^2$ to 48 $kg\text{-}mm^2$ is not unreasonable and the implementation of this change into Jeep Grand Cherokee hydraulic fan assemblies is expected within the near future.

# Chapter 2

## Principles of Dynamic Balancing

Nearly all rotating machines have some type of machinery vibration caused by unbalance. To minimize vibration, noise, and bearing wear of a rotating body, the centrifugal forces need to be reduced by aligning one of the principal inertia axes with the geometric axis of rotation. This can be done through the addition or subtraction of material of the rotating body. According to the International Standards Organization (ISO) unbalance is defined as, "That condition which exists in a rotor when vibratory force or motion is imparted to its bearing as a result of centrifugal forces."

### 2.1 Problem Formulation

A HDFS assembly can be represented by a shaft rotating between two bearings while having an overhung rotor on to one end of the shaft as shown in Figure 2.1. The X, Y, Z axes are attached to the shaft-rotor assembly and rotate relative to a fixed inertial frame, $\hat{X}, \hat{Y}, \hat{Z}$ at an angular velocity $\vec{\omega} = \omega\vec{k}$ . At the instant shown, the inertial and rotating reference frames are assumed coincident.

Manufacturing imperfections result in a measured mass of M which lies at a distance of $R_{cm}$ from the shaft axis of rotation. Any type of rotor-shaft imperfection will thus produce inertia components $I_{xx}$, $I_{yy}$, $I_{zz}$, and product of inertia components $I_{xy}$, $I_{xz}$, and $I_{yz}$ which are measured relative to the rotating X, Y, Z system.

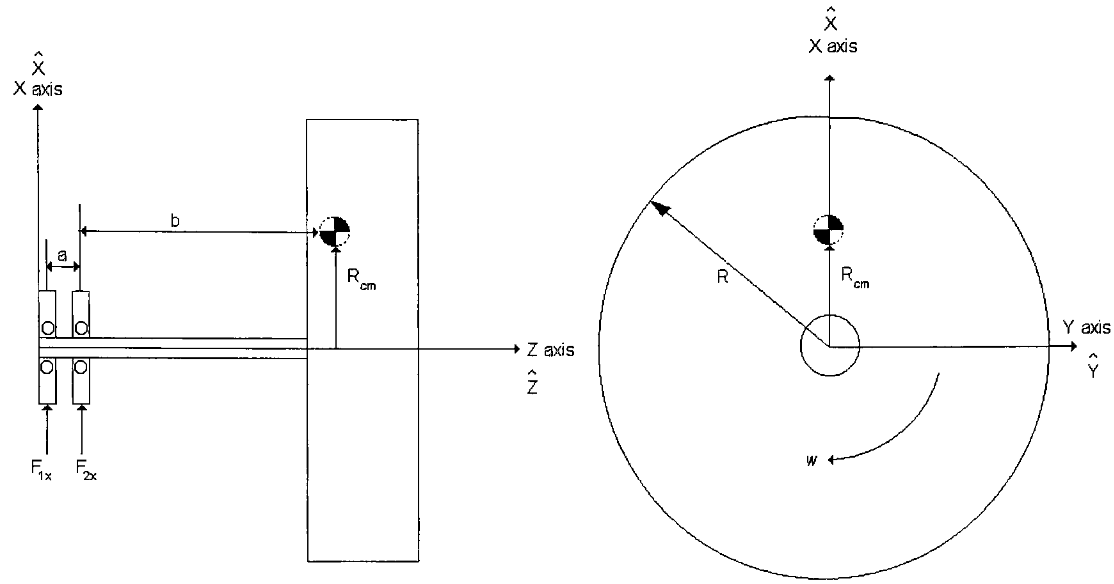



Figure 2.1

Assume that X, Y, Z axes are oriented so that the center of mass lies in the X-Z plane as shown in Figure 2.1. Dynamic equilibrium requires that (Bedford, 1999)

$$\sum \vec{F} = M\vec{a} = M(a_x\vec{i} + a_y\vec{j} + a_z\vec{k}) \tag{2.1}$$

$$\sum M = \vec{\omega} \times \vec{H} = \omega\vec{k} \times (H_x\vec{i} + H_y\vec{j} + H_z\vec{k}) \tag{2.2}$$

where $\vec{a}$ and $\vec{H}$ are acceleration and angular momentum vectors, respectively. In component form vector equations 2.1 and 2.2 become

$$\sum F_x = F_{1x} + F_{2x} = Ma_x = -MR_{cm}\omega^2 \tag{2.3a}$$

$$\sum F_y = F_{1y} + F_{2y} = Ma_y = 0 \tag{2.3b}$$

$$\sum F_z = F_{1z} + F_{2z} = Ma_z = 0 \tag{2.3c}$$

$$\sum M_x = -F_{2y}a = -\omega H_y \tag{2.4a}$$

$$\sum M_y = F_{2x}a = \omega H_x \tag{2.4b}$$

$$\sum M_z = 0 \tag{2.4c}$$

One must use the moments of inertia ($I_{xx}$, $I_{yy}$, and $I_{zz}$) and the products of inertia coefficients ($I_{xy}$, $I_{yz}$, and $I_{xz}$) to calculate $\vec{H}$ as follows:

$$\begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{2.5}$$

Since there is no rotational motion about the X and Y axes, $\omega_z = \omega$ and the values for $\omega_x$ and $\omega_y$ are equal to 0, resulting in

$$\begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \omega \end{bmatrix} \tag{2.6}$$

Or simplifying further

$$H_x = -I_{xz}\omega \tag{2.7a}$$

$$H_y = -I_{yz}\omega \tag{2.7b}$$

The resulting unbalance forces that are transmitted from the bearings to the sleeves are given by

$$F_{2x} = \frac{-I_{xz}\omega^2}{a} \tag{2.8a}$$

$$F_{2y} = \frac{I_{yz}\omega^2}{a} \tag{2.8b}$$

$$F_{1x} = MR_{cm}\omega^2 + \frac{I_{xz}\omega^2}{a} \tag{2.8c}$$

$$F_{2x} = \frac{-I_{yz}\omega^2}{a} \tag{2.8d}$$

Static or force unbalance is where all residual unbalance is assumed to lie in one plane. It can be detected by placing the rotor on knife-edges and allowing the "heavy spot" to fall to the bottom. A rotor will be considered statically balanced, i.e., $R_{cm}$=0, if when placed on knife-edges it does not rotate regardless of the position it is placed. Static unbalance can be corrected by simply adding or removing material from one plane. This is the simplest of all types of unbalance.

When $R_{cm}$=0, equations 2.8(a) to 2.8(d) describe what is typically known as quasi-static unbalance. Quasi-static unbalance is the combination of a static and couple unbalance. A minimum of two planes must be used to correct for this type of unbalance. This situation occurs when the amplitude of vibration is higher at one end of the rotor than the other. Fans used in HDFS are balanced by using the quasi-static unbalance measurement and balanced in two planes.

Unbalance is generally distributed throughout the rotating body, but can be represented by a dynamic unbalance described by two unbalance vectors in two specified planes, or a static unbalance and a couple unbalance described by three unbalance vectors in three specified planes. The measurement system that is used by Valeo is one of a single static unbalance and a couple unbalance. HDFS fans are modeled as 2 thin discs, each having a heavy spot at a given magnitude and location in the corresponding discs planes. The magnitude and location of this heavy spot is measured by a balancing machine and then converted to a static and couple unbalance. The mathematics behind this conversion is shown in detail in section 2.9.

## 2.2 Causes of Unbalance

This particular section discusses the most common causes of unbalance. Although all these causes do not pertain to the fans used by Valeo's HDFS assembly system, they are discussed for completeness.

### 2.2.1 *Corrosion and Wear*

Wear and corrosion along the surface of a fan will cause unbalance over time. The need to periodically rebalance a fan or rotor is needed because of wear to the surface of the part.

### 2.2.2 *Deposit build-up*

Build-up of deposits on the surface of a rotor or fan can cause a gradual increase in unbalance over time. This gradual increase in time can become a serious problem if portions of the deposits break away and cause a very rapid increase in vibration of the rotating member.

### 2.2.3 *Distortion*

A well-balanced part may undergo some stress relief or thermal distortion from the time of manufacture to assembly. This change may cause a high residual unbalance.

### 2.2.4 *Blow holes in cast parts*

Many components in rotating machinery are cast. A perfectly cast part can be designed to have very low unbalance, but if a void in the material occurs during the processing of the part a large residual unbalance may occur.

### 2.2.5 *Eccentricity*

If the geometric centerline, the axis of rotation that is determined by the rotational bearing surface or the mounting surface, does not coincide with the true rotating centerline, an unbalance will result. This can also be looked at as an "off center" rotating part.

### 2.2.6 *Addition of keys and keyways*

The lack of industry wide standards regarding the addition of keys in component building can cause a large amount of unbalance in a completed assembly. Many manufacturers balance their product to either a full, half or no key at all. Often an assembly is built where one component is balanced with no key and the corresponding motor is balanced with a full key. When the components are subsequently assembled using a key, a large residual unbalance will occur in the final assembly.

### 2.2.7 *Clearance tolerances*

A very common source of unbalance is the "stack up tolerances" caused by the assembly process. If each component is at the limits of its specifications, and then assembled, the entire unit may have significant residual unbalance.

Before balancing techniques are investigated, the vibration of the rotating body needs to be the result of an unbalance on the rotor. Vibration can have several different root causes, and unfortunately balancing cannot eliminate them all. Appendix A which was taken from the Entek IRD dynamic balancing book discusses some of these possibilities. These other causes for vibration can be the misalignment of couplings or bearings, bent shafts, bad bearings, eccentric journals, bad gears, mechanical looseness, and bad drive belts. These are just a couple of the causes for vibration, which do not include unbalance. The chart in Appendix A shows at what frequency and phase vibration amplitudes need to be measured to gather an accurate reason to the cause of vibration.

## 2.3 Units of Unbalance

"Unbalance" is typically defined by a mass at a given radius within a correction plane from which the actual unbalance force can be found by multiplying the "unbalance" by the square of the shaft speed ($\omega$, rad/s$^2$). The common units for weight are grams (g), ounces (oz) and kilograms (kg). Common units for distance, which are used to measure the radius are inches (in), millimeters (mm), centimeters (cm) or meters (m). Valeo uses the units of kg-mm to measure static unbalance. To obtain the couple unbalance measurement, the distance between the two planes must also be known. This number is in the same units of measurement and used to calculate the couple unbalance. The units that Valeo uses for couple unbalance are kg-mm$^2$. All fan assemblies are balanced at 1100 RPM so shaft speed can be dropped in the measurement of unbalance.

### 2.4 Single and Multi-Plane Balancing

As mentioned in section 2.1, balancing in one plane is simply finding the "heavy" spot and the angular location; in principle, the objective is to make $R_{cm} = 0$. Once the location and magnitude of the unbalance is found, material must be added 180° out of phase with the original unbalance or subtracted from the angular location of the heavy spot. The amplitude of the vibration is measured to determine the magnitude of the unbalance. The greater the amplitude means the greater the force, which ultimately means the greater the unbalance. If the vibration amplitude is almost negligible then the unit is considered a well-balanced unit. The relationship between the unbalance and the amplitude of the vibration are proportional. Therefore if a known unbalance is measured and a vibration amplitude is measured, all following measurements of vibration amplitude can be calculated to unbalance.

Not all balancing applications can be corrected in one plane alone. Typically, single plane balancing works well when the cross-product inertia terms are expected to be small. The relationship between the diameter and the length of the shaft determines the amount of planes that should be used in balancing. As the length to diameter ratio becomes smaller, single plane balancing alone becomes more acceptable. Appendix B has a chart that shows the relationship between diameter and length with respect to balancing in one, two or multiple planes.

However, as Appendix B shows, for HDFS, the operating speed is above 1000 RPM and the length to diameter ratio is less than 0.5. The chart suggest that two planes should be used for balancing and that is what is used in practice.

### 2.5 Cross-Talk Effects

When a rotor is balanced in two planes, attention must be paid to a condition called "cross-talk", also known as "cross-effect" or "correction plane interference". This is simply the effect of added weight in one plane having an effect on the other balancing plane. Unfortunately, there are ways to reduce cross-talk but no way to completely eliminate it. In HDFS assemblies, inserting large chrome balls into the top correction plane creates a significant amount of unbalance in the lower plane. This is caused by a deflection in the fan. In order to reduce this the walls of the groove need to be able to flex freely without distorting the fan. If material were to be removed from the fan instead of adding mass, cross-talk would still exist, but the effect of it would be significantly less then when mass was added. The amount of cross-talk would be significantly less because there would not be distortion caused by press-fitting a ball into a groove.

### 2.5.1 *Balancing Overhung Fan Systems*

The fan assembly, which is manufactured by Valeo, is very similar to the overhung rotor shown in Figure 2.1. The definition of an overhung rotor is that it has its balancing correction planes outside the support bearings. Figure 2.2 shows a model of the HDFS assembly, where the motor is represented by two bearings. An overhung rotor configuration is most common in fan systems, blowers and pumps. The largest concern is the effect of cross talk when balancing in one plane in these types of systems.

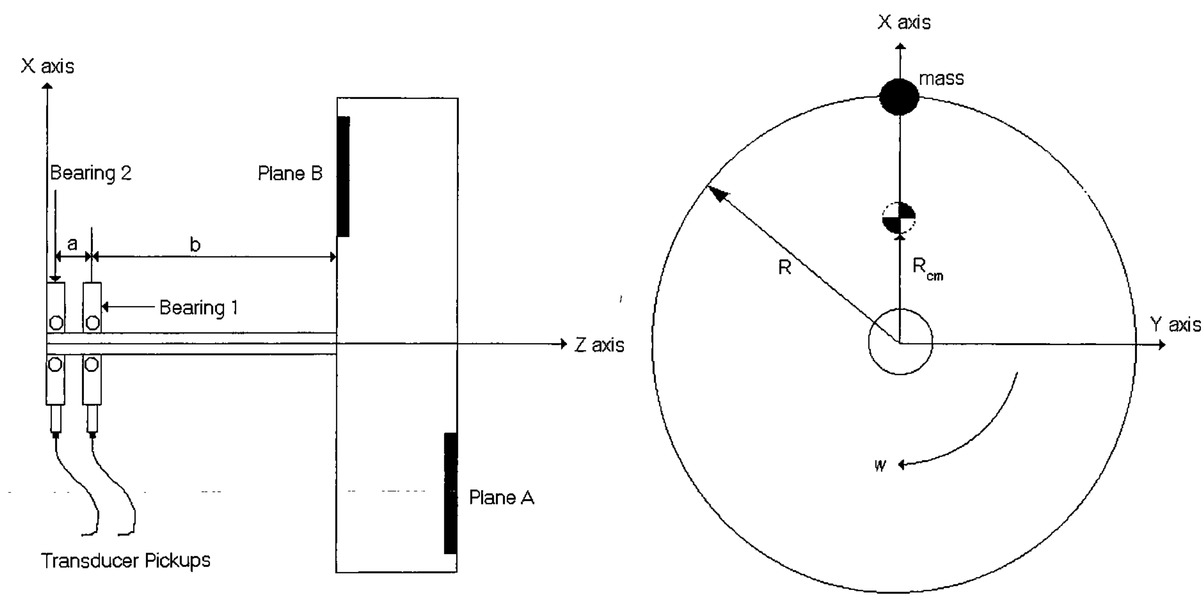



Figure 2.2

To balance in two planes, one must use the Static-Couple Derivation technique. A measurement of vibration must be taken at the locations of the force transducers. Since a bearing is at a distance of "b" away from plane B, correction weights should be added in plane B to correct for the static unbalance measured in bearing #1. Bearing #1 is assumed to sense and respond to the static unbalance of the system. If a single weight is used in plane B, the cross talk effect will read residual unbalance at the location of Bearing #2. To correct for this without affecting the original static unbalance correction a correction weight in the form of a couple must be used in both plane A and plane B. The location of the correction weights will be 180° out of phase with each other.

### 2.6 Distortion and Deflection Effects

The mathematical description in section 2.1 assumed that the rotors were rigid. Rotors that are flexible have the ability to change their mass distribution depending on speed and temperature. For HDFS assemblies, operation at higher speeds will yield a slight amount of deflection in the fan. If an assembly is balanced at a lower speed, there is the possibility that a different unbalance condition may occur at the higher speeds. To ensure proper balancing a rotor needs to be trimmed at its operating speed.

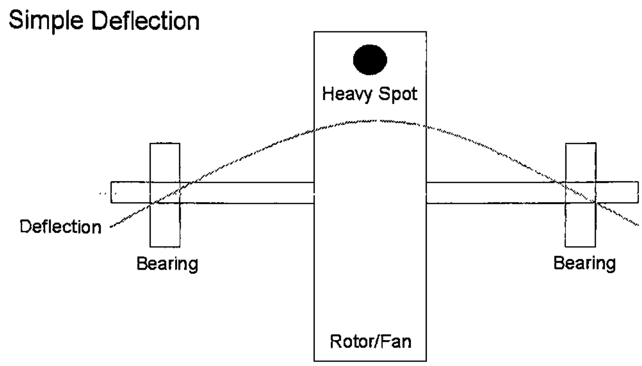



Figure 2.3

The rotation of the rotor causes a centrifugal force and the shaft at which it rotates on will begin to deflect. Because the deflection rotates with the shaft it will be seen as vibration. If a rotor is statically balanced but has a couple unbalance, the shaft can be deflected in more than one way. Figure 2.4 shows the deflection placed on a system that has a couple unbalance but is statically balanced.

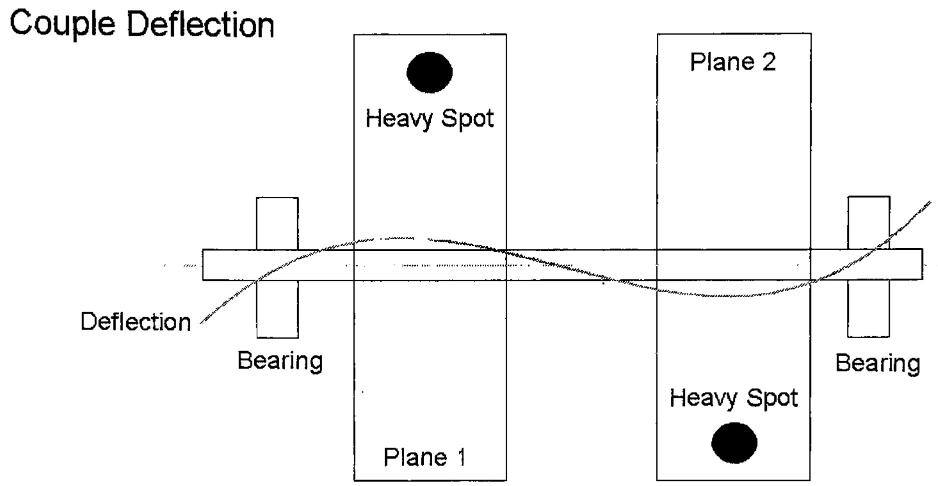



Figure 2.4

Distortion caused by rotation speed in the fan can have a significant impact on the bearing wear and the overall wear of the motor. Unbalance measurements are taken at 1100 rpm which provides valid results within the operating range of the assembly. If the assembly is run consistently at its maximum speed of 4400 rpm, there is a slight concern of bearing wear caused by the amount of vibration caused by what little residual unbalance remains after production balancing.

## 2.7 Introduction to Balance Machines

A balance machine is a relatively simple machine that uses either one or more transducers to measure the vibration caused by the rotating member. In HDFS fan assemblies, the manufacturing balancing machines are considered to be a hard bearing balancing machine. The reason for this is that its operating speed is well below the natural frequency of the assembly. If the operating speed were above the natural frequency a soft bearing system would be utilized.

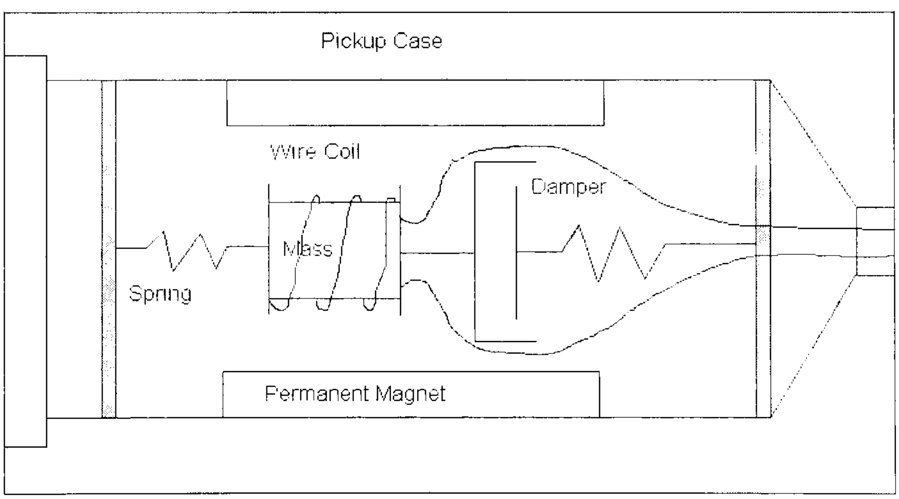
There are four types of centrifugal balancing systems that are commercially built. The first three classes are of the soft bearing type. The first class shows unbalance as the amount of displacement and/or velocity of vibration at its bearings. The second type are a calibratable balancing machine which requires a balanced prototype but has the ability to measure in more than one plane. The third is similar to the second type but does not require a balanced prototype to calibrate the machine. The fourth type is the type of system that is used by the HDFS manufacturing facility. It is a permanently calibrated balancing machine. This type of balancing machine is used to balance a large amount of assemblies without having to be recalibrated after each unit. Class IV balancing machines are, of the hard bearing type, and usually has a computer integrated into the entire balancing system.

## 2.8 Vibration Measurement Devices

In order to measure vibration in a mechanical system, a device called a transducer must be used to collect the measurements. There are different types of transducers that can be used in vibration measurement, and many different methods to apply the measurement techniques.

### 2.8.1 Velocity Pickups

One of the more common types of transducers is called a velocity pickup. The basis of the name comes from the fact that the output voltage is proportional to the velocity of the vibrating part. A velocity pickup is known as a seismic-velocity pickup transducer.




Velocity Vibration Pickup

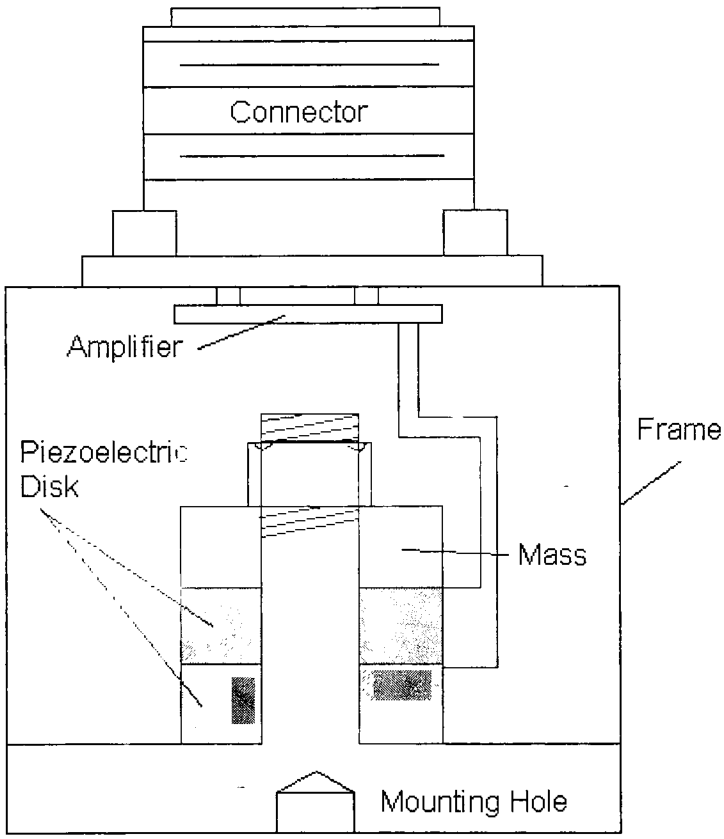
Figure 2.5

This type of transducer consists of a coil of fine wire supported by springs of low stiffness. The suspended coil has a strong magnetic field around it caused by a permanent magnet on the outside housing of the pickup. The velocity pickup is then mounted to the surface of the vibrating part, or a fixture holding the part, and the permanent magnet follows the motion of the vibration. As the permanent magnet is vibrating with the part or fixture, the wire coil remains stationary in space. Voltage is induced by the change in the relative position of the magnet and the wire coil. This voltage created is proportional to the amount of vibration, hence, the larger the vibration the larger the voltage outputted by the velocity pickup.

The sensitivity of a velocity pickup is greatly reduced as the frequency range decreases. As the frequency of vibration drops below 700 cycles per minute (CPM), the sensitivity of the velocity pickup is drastically decreased. This would lead one to have to select another type of transducer to take accurate measurements on a vibrating object. Strong magnetic fields can also cause readings that are not accurate. Therefore, a second type of transducer is desired. This type of transducer would be an accelerometer pickup.

### 2.8.2 Accelerometer Pickups

An accelerometer pickup is very similar to the operation of a velocity pickup. As its name states, an accelerometer pickup produces a output voltage that is proportional to the vibration acceleration of the part being measured. Accelerometers are very sensitive to vibration at high frequencies. This is proved because acceleration is a function of displacement and frequency squared. The difference between a vibration pickup and an acceleration pickup is that an accelerometer uses a "piezoelectric" material instead of a coil of wire. The "piezoelectric" material will produce a charge when it is compressed. It is compressed by a force which is a function of acceleration by Newton's second law (F=ma). (Entek, 1996)




Accelerometer Pickup

Figure 2.6

The output of accelerometers is usually very small so there is a need for amplification before a useable signal is obtained. Once the signal is amplified, there are significant benefits over a velocity pickup. These are the elimination of cable length problems and cable interchangeability.

## 2.9 Mathematics of Balancing

Unbalance is measured on HDFS assemblies in two planes. Each of these planes is individually balanced using a Static-Couple derivation. The vibration in each plane is measured by a transducer and yields a magnitude, and a photo eye determines the location. From these two unbalance readings the static and couple unbalance readings are calculated. The following pages show the mathematics behind calculating two plane readings into a static and couple unbalance. Figure 2.7 shows the location of the two balance planes located on HDFS assemblies. The unbalance mass is the magnitude of the plane unbalance and the angle measurement is taken from the zero position, 12 o'clock, and the distance between the planes is d.

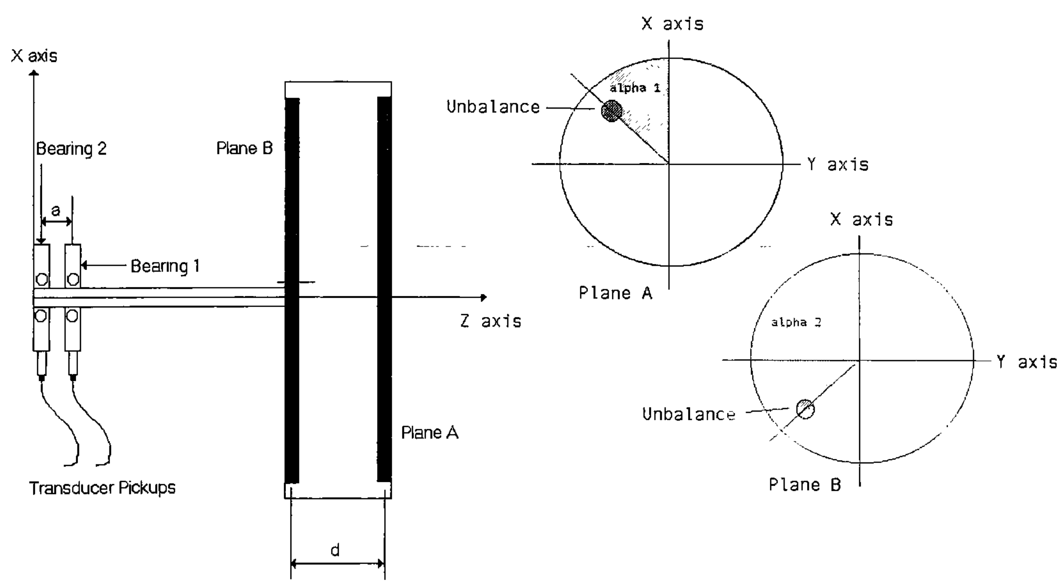



Figure 2.7

At a given speed, the photo eye and the transducer measure the following:

$P_1$ = Plane 1 magnitude unbalance (N)

$P_2$ = Plane 2 magnitude unbalance (N)

$\alpha_1$ = angle location in plane 1 (deg)

$\alpha_2$ = angle location in plane 2 (deg)

$d$ = plane separation (m)

The static unbalance magnitude and location are determined from

$$P_1 \cos\alpha_1 + P_2 \cos\alpha_2 = P_{Fx}$$
$$P_1 \sin\alpha_1 + P_2 \sin\alpha_2 = P_{Fy}$$
$$P_F = \sqrt{P_{Fx}^{\ 2} + P_{Fy}^{\ 2}} \qquad (2.9a\text{-}d)$$
$$\alpha_F = Tan^{-1}\frac{P_{Fy}}{P_{Fx}}$$

The couple unbalance magnitude and location are determined from

$$P_1 \cos\alpha_1 - P_2 \cos\alpha_2 = P_{Fxc}$$
$$P_1 \sin\alpha_1 - P_2 \sin\alpha_2 = P_{Fyc}$$
$$P_F = \sqrt{P_{Fxc}^{\ 2} + P_{Fyc}^{\ 2}}\,\frac{d}{2} \qquad (2.10a\text{-}d)$$
$$\alpha_F = Tan^{-1}\frac{P_{Fyc}}{P_{Fxc}} + 180°$$

## 2.10 Methods for Balancing

Technology today allows for many different methods to reduce unbalance in a rotating member. The material and application of the rotor or fan will usually determine the type of correction technique required to reduce unbalance. HDFS fans were designed to have weight added to the circumference of the hub by having two grooves in each of the two balancing planes. Figure 2.8 shows the hub of the fan and one can see where the large and small grooves are for chrome balls to be inserted. Chrome balls are press-fit into the groove to correct for unbalance. These grooves are located on the circumference of the hub which has a significantly less of an impact on unbalance correction based on weight added. If mass is added or removed from the blade end circumference, there will be a much greater impact on unbalance with less weight.

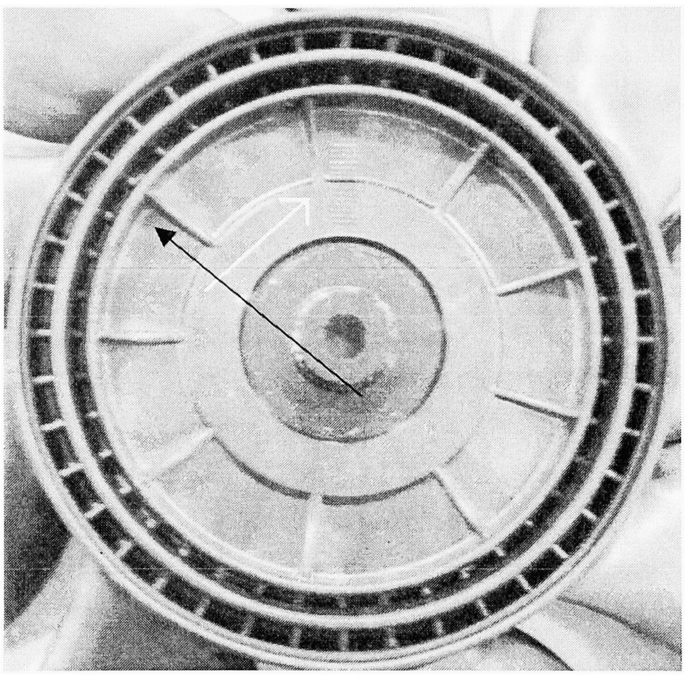


Figure 2.8

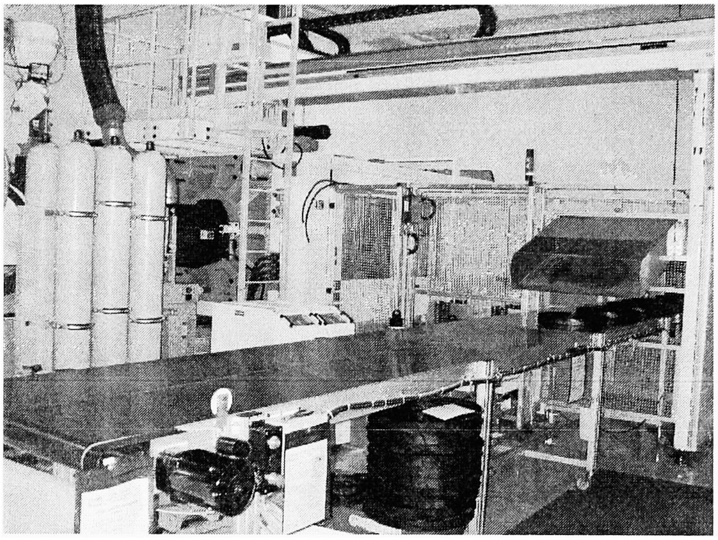
To correct for unbalance one simply has to add or subtract weight from a given area. One needs to add weight at the light spot or subtract weight from the heavy spot. Drilling, milling and lasers are methods to remove material while chrome balls, paste, lead tape, welding, and the addition of wax are used to add material. For HDFS assemblies, a permanent solution is needed because these units are expected to hold their unbalance specifications throughout the life of the entire vehicle. Paste, lead tape and wax are usually used for temporary balancing applications. Welding is usually used on turbine applications where strength is of the essence. Drilling and milling are used on high-speed rotor and armature applications where high precision is required. This leaves two methods, one of inserting chrome balls using a press-fit or a laser application where material is removed from the inside of the fan at rotating speeds. Chapter 4 will discuss conventional methods of balancing, while Chapter 5 will outline the benefits of a proposed laser balancing machine.

# Chapter 3

## Balancing with Respect to Molding

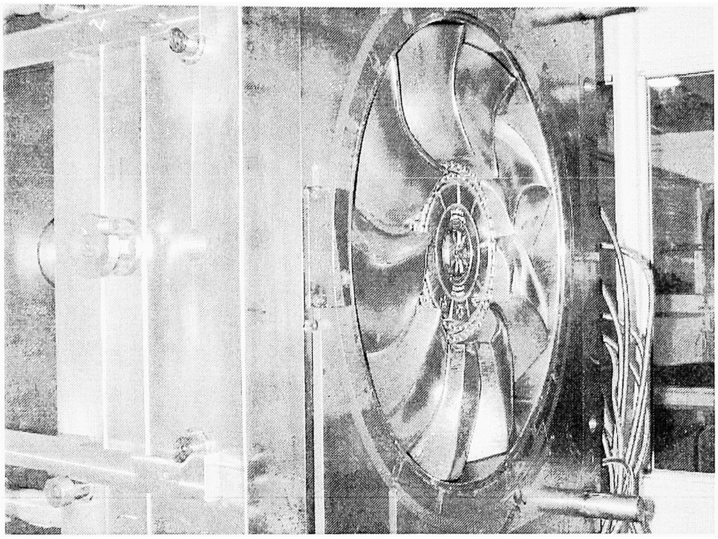
### 3.1 Introduction

When correcting for unbalance in the final assembly, one must first track the unbalance back to its origin. This would lead one to the molding process from which the fans are made. The ability to adjust for both static and couple unbalance must be accounted for. Some other significant issues that can be addressed are residual stress and run-out, injection pressure, mold temperature, and skin thickness.



To correct for static unbalance the mold uses "slides". These "slides" can move into or away from the mold so mass can be added or subtracted from the circumference. Couple unbalance can be corrected by adjustment of two "wobble" screws. Along the center of the mold there is the possibility to rock slightly the center hub to correct for the tilt of the fan. Two wobble screws control the "movable wobble". The stationary or follower wobble conforms to the position of the movable wobble when the mold closes. The ability to adjust these slides and wobble allow the molding coordinator to accurately adjust these settings to build parts with a lower unbalance.

In the evaluation of molded parts over the duration of this study, it has not been uncommon for molded fans to have a large range of residual unbalance. The couple



deviation of the fans has been as high as 20 $kg\text{-}mm^2$, while static deviation has a typical range of approximately .04 kg-mm. When molding fans, it is unusual to have consistently low statically and couple unbalanced parts. If the static unbalance is low (<.05 kg-mm), then the fan couple is usually above 35 $kg\text{-}mm^2$. If the couple is low (<20 $kg\text{-}mm^2$) the static unbalance is usually above .07 kg-mm.

Currently Valeo does not have any other molding processes that use inserts around which to mold their fans. HDFS fans are also the largest (20.5 inches in diameter) made for the automotive industry by Valeo. Their size and the fact that there can be induced unbalance caused by the insert make HDFS fans consistently difficult to make.

### 3.2 The Steel Inserts

Welding a machined hub to a stamped plate creates a steel insert around which the fan is molded. The main concerns that have arisen from this process are:

1) residual stresses on the center bore of the hub caused by the welding process
2) run-out of the insert causing high run-out of the entire fan
3) the accuracy of which datum is being held to mold the fan around
4) the effect of the steel insert on the plastic fan

The data collected during this study suggest that the temperature of the mold can have a significant impact on the ability to balance completed assemblies. The temperature is critical because HDFS is using a "press fit" or "interference fit" for inserting ball bearings into four (4) fan grooves. Studies have shown that the cooler the mold temperature, the more difficult the assembly balancers have in correcting unbalance. There is also only a small window to work in with respect to temperature. If the temperature of the mold becomes too high, then the ball bearings are at a risk of becoming loose in operation. Loose bearings are not acceptable in a vehicle set to go to market.

### 3.3 Skin Thickness

A hypothesis on why temperature is so crucial to the molding process is the relationship between skin thickness and hub temperature. When the hub temperature of the mold is lower, the resin will "freeze" quicker and induce "shock" into the plastic. This causes a "skin" along the outside of the groove where the material is harder, because it froze first when the resin was injected into the mold. When this occurs, the material will be harder on the outside of the fan groove, which in return makes inserting balls into the groove more difficult. The cooler the mold hub is with relationship to the resin the thicker the “skin” will be.

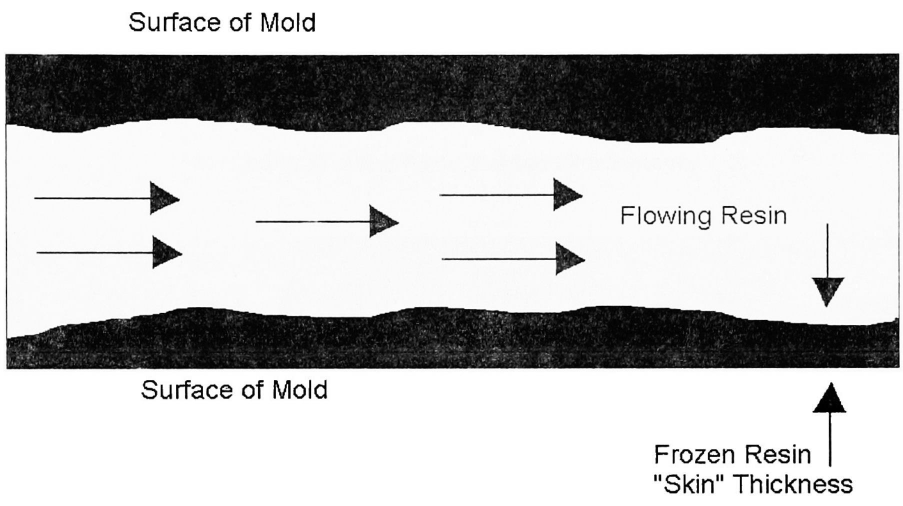



Figure 3.1

If the hub’s temperature is too high, the skin is not thick enough, and plastic deformation occurs when the ball bearings are press fit into the groove. If this occurs then the assemblies are in danger of having loose ball bearings.

A study was conducted in October 2000 to determine if the hypothesis of “skin” thickness could be proven. It was noticed that when the fan mold was received back on

10/19/00 from a routine cleaning, the percentage of correctable parts in the assembly cells decreased from an average of 96% to 89%. This percentage drop was accounted for by the inability to insert balls into the fan groove without deflection of the fan. On 11/06/00 the temperature of the hub was increased from 55°F to 60°F. The corresponding results were an increase in assembly cell percentage to 96%. Figure 3.2 shows the daily percentage of good parts yielded on the assembly balancers. From this data, it is evident that the slight increase in hub temperature had a significant impact on the ability to balance good units.

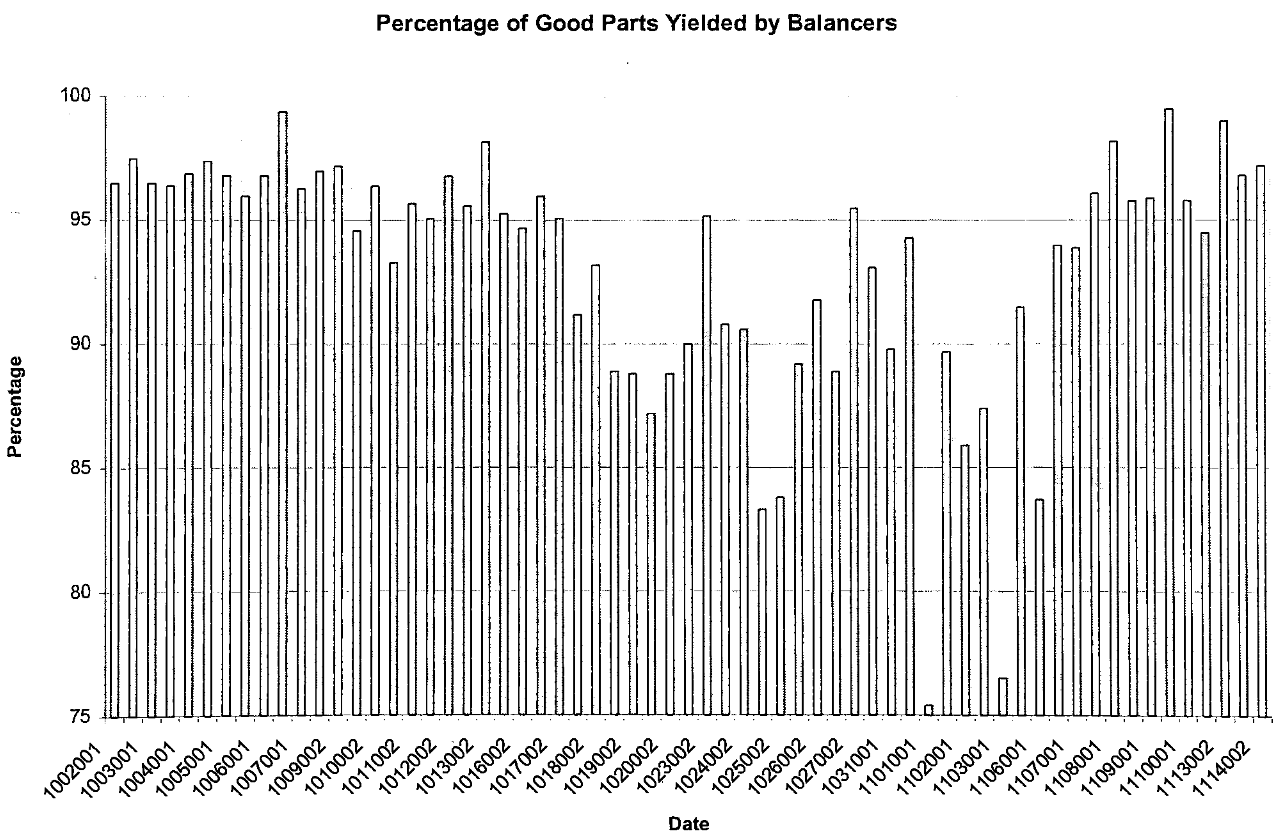



Figure 3.2

### 3.4 Wobble Position

The adjustable wobble should fit snuggly into the nest in which it sits. The base of the wobble has a slight radius which allows it to move smoothly against the nest and allows for adjustment as shown in Figure 3.3. The wobble and the corresponding nest need to be mated so their radiuses match closely and allow for no "play" in the precision of the mold. If a gap is located between the wobble and the nest, there will be discrepancies in the couple unbalance of the molded parts. If the radii of the wobble and nest do not match, the travel of the adjustable wobble will be limited and the ability to mold precise parts will be dramatically reduced. If a gap is located between the wobble and the nest, the location of the unbalance may become inconsistent due to the injection pressure moving the adjustable wobble against the nest and resting on a different location each molded cycle. The injection of the resin forces the adjustable wobble back until it locates in the nest causing the wobble to be out of position.

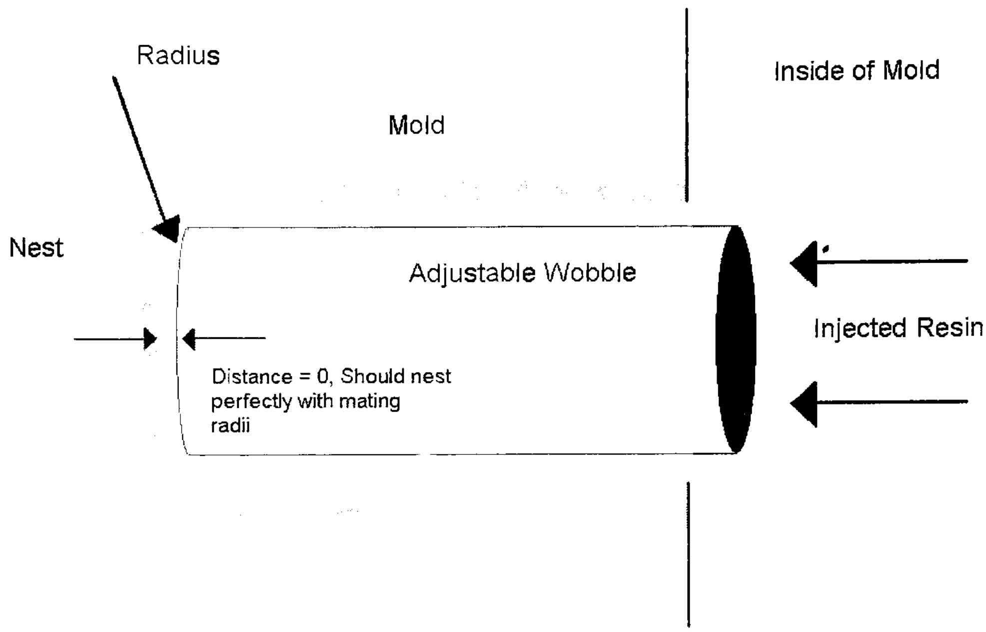



Figure 3.3

The adjustable wobble is controlled by two screws, one in the horizontal direction and one in the vertical directions as shown in Figure 3.12. The design supports 24 revolutions of movement each which allows for approximately .003"/revoltion movement. Unfortunately the design only allows for 5 to 6 revolutions before the wobble moves against the wall of the nest. To allow for a greater amount of movement the distance between the adjustable wobble and the side wall of the nest needs to be increased from about .016" to .030". This will allow for a must larger travel and hence a better opportunity to correct for residual couple unbalance in molded fans.

### 3.5 Static Balance Correction of Fan Molds

As described in Chapter 2, static unbalance is where all unbalanced masses lie in a single plane resulting in an unbalance of a single radial force. Static unbalance can also be noted as the vector sum of all the unbalance located in all the balancing planes. Slides located on the fan mold allow for the addition or subtraction of material in order to correct static unbalance.

(a). Slide One (1) is located at 60°

(b). Slide Two (2) is located at 180°

(c). Slide Three (3) is located at 300°

Figure 3.4 shows the location of the slides within the actual fan mold.

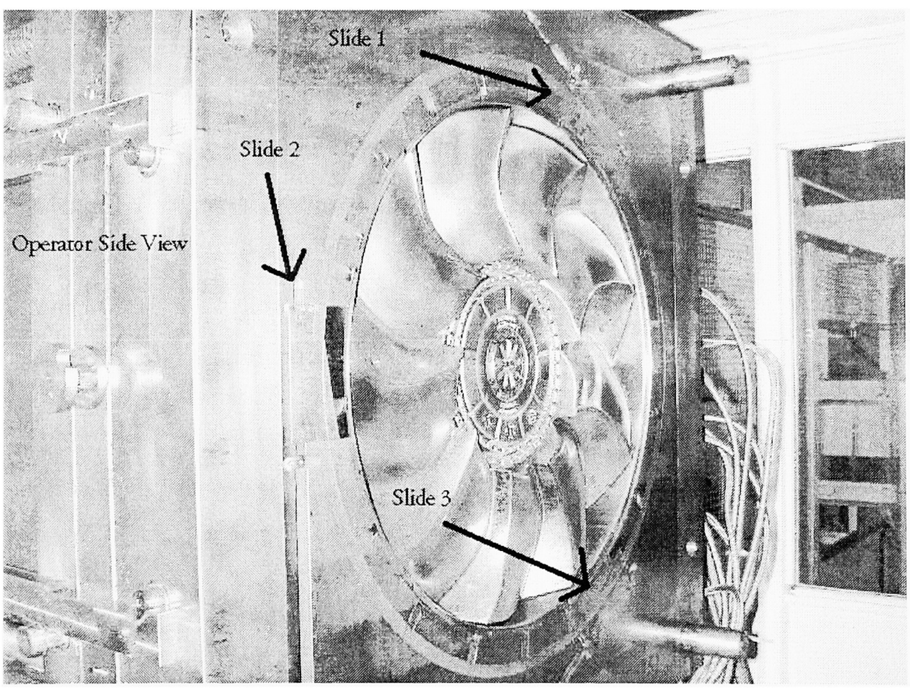



Figure 3.4

The location of zero (0°) degrees, and hence the reference point for the fan is located where the raised groove is located on the hub of the fan. See Figure 3.5.

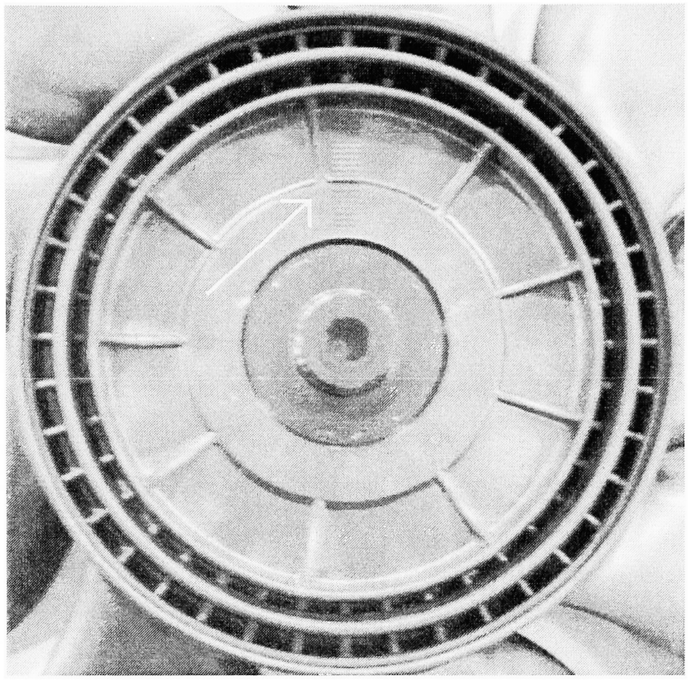


Figure 3.5

The yellow arrow denotes the location of zero degrees (0°) as located on the fan as reference.

The Audit-balance machine measures the magnitude and location of a static unbalance as a single radial force.

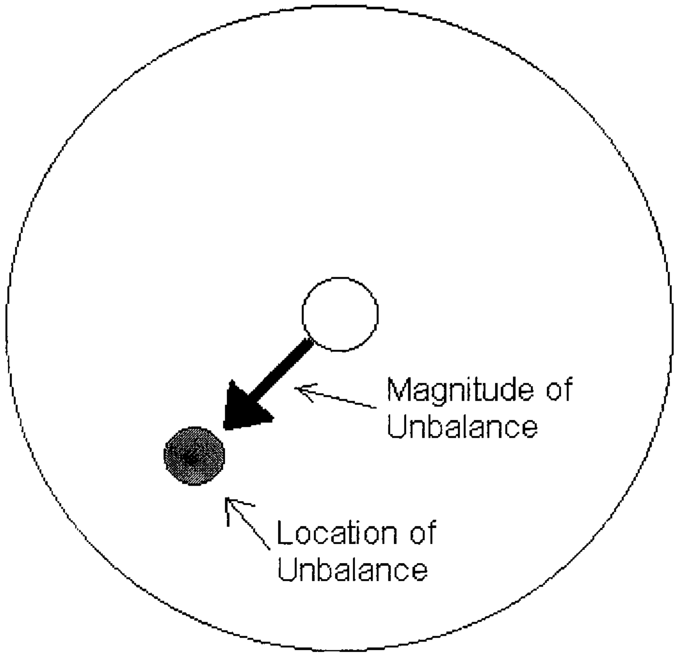



Figure 3.6

The simplest way to correct this type of unbalance would be to add weight 180° out of phase or subtract weight at the same angle of the unbalance. See Figure 3.7.

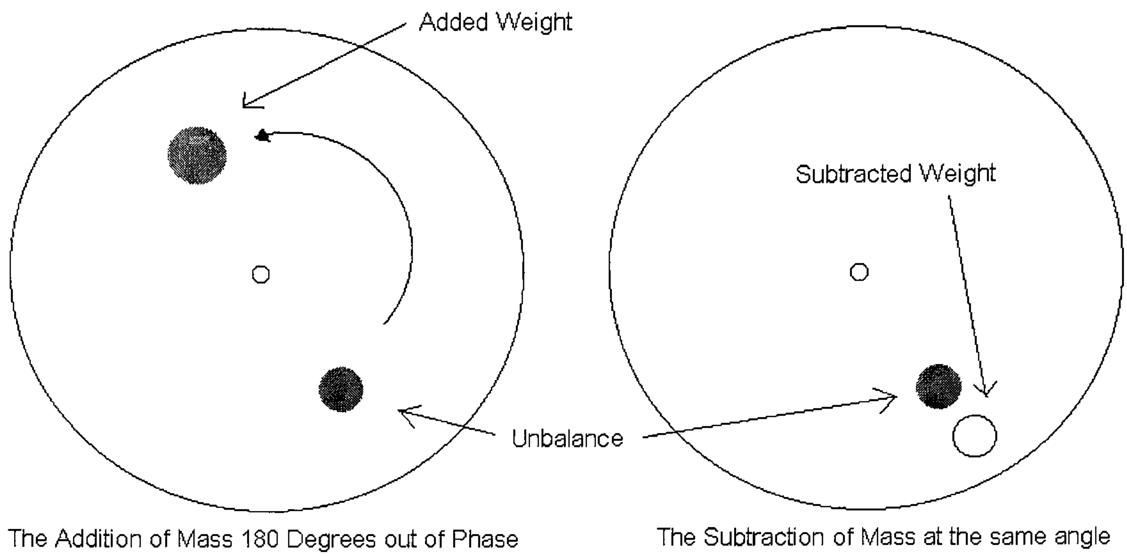



Figure 3.7

### 3.5.1 *Location of Slide Adjustments*

In order to adjust the mold to correct for static unbalance, the three slides need to be moved to add or subtract the appropriate amount of material from the outer surface of the fan. See Figure 3.8 for location of slide adjustments.

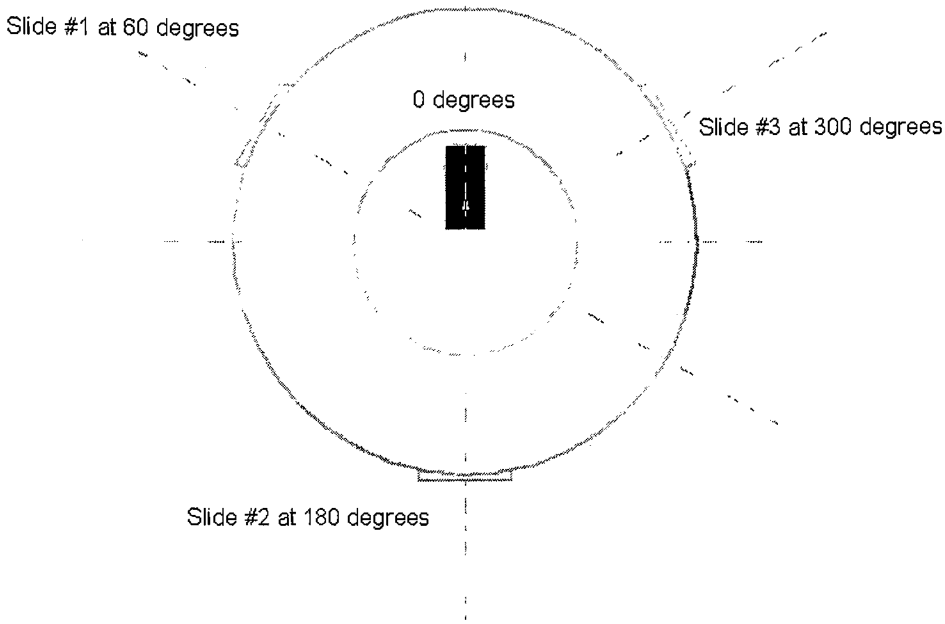



Figure 3.8

An adjustment to a slide is done by tightening or loosening a screw that controls the placement of the slide block. The following adjustments will correspond to the slides.

- Slide #1
  - Clockwise rotation – add material to outer surface of fan
  - Counter-clockwise rotation – subtract material from outer surface of fan
- Slide #2
  - Clockwise rotation – add material to outer surface of fan
  - Counter-clockwise rotation – subtract material from outer surface of fan
- Slide #3
  - Clockwise rotation – subtract material from outer surface of fan

- Counter-clockwise rotation – add material to outer surface of fan

### 3.5.2 *Example of Sample Static Correction: Example #1*

Figure 3.9 shows the unbalance that may be located in a fan. The numbers obtained for the unbalance of this sample piece were obtained from actual unbalance numbers found in a production environment. The unbalance is located at 210° and has a magnitude of 0.1910 kg-mm.

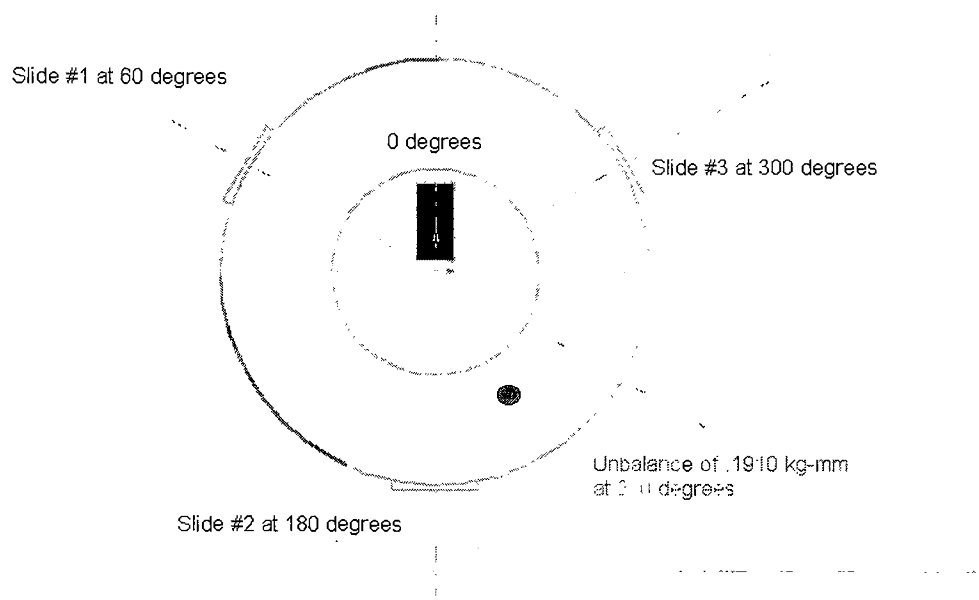



Figure 3.9

For this particular adjustment two (2) slides will need to be adjusted in order to correct the unbalance. The reason is that the unbalance does not lie at the 60°, 180° or 300° locations on the fan. If the unbalance lies within 15° of these locations or at exactly 180° out of phase only one slide needs to be adjusted.

There are two options that can be used with this example. One is to remove material from 210° or add material at 30°.

To remove material at 210°

- Slide #3 needs material subtracted
- Slide #2 needs material subtracted

- To add material at 30°

  Slide #2 needs material subtracted

  Slide #1 needs material added

### 3.5.3 *Example of Sample Static Correction: Example #2*

Figure 3.10 shows the unbalance that may be located in a fan. The numbers obtained for the unbalance of this sample piece were obtained from actual unbalance numbers found in a production environment. The unbalance is located at 0° and has a magnitude of 0.1500 kg-mm.

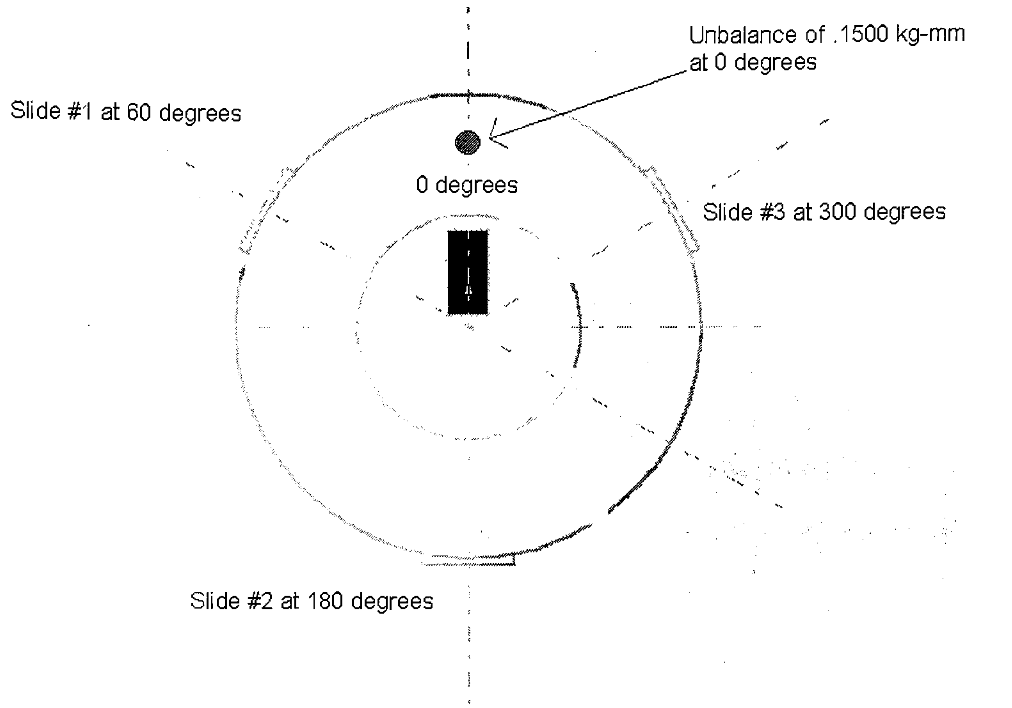



Figure 3.10

For this particular adjustment either one (1) or two (2) slides can be adjusted to correct the unbalance. The reason for this is that the unbalance is located 180° out of phase with one of the slides. For this particular example it is located 180° out of phase with slide number 2.

There are two options that can be used with this example. One is to remove material from 0° or add material at 180°.

- To add material at 180°
  - Slide #2 needs material added

- To remove material at 0°
  - Slide #3 needs material subtracted
  - Slide #2 needs material subtracted

### 3.6 Couple Balance Correction in Fan Molds

As described in chapter 2, a couple unbalance is simply two parallel equal forces acting in opposite directions, but not in the same plane. For molding couple unbalance can be simplified even more by stating that it is the "tilt" of the molded fan. If a fan is molded so its central principal axis and its shaft axis do not align, a residual couple unbalance will occur. This was described in detail in Chapter 2. To correct for this the mold has two "wobble" adjustments that can be made to compensate for "tilt" in any location of the fan.

The location of the couple unbalance can be perceived as the "high" point on the fan. To correct for this unbalance the fan mold needs to be adjusted to lower this high point. This will be explained further later in this chapter.

#### 3.6.1 *Location of Wobble Adjustments*

The fan position in the mold has the ability to rotate a few degrees on both its X and Y axis. The side and bottom wobble adjustments control this motion, and can lock the position. See Figure 3.11 for location of wobble adjustments.

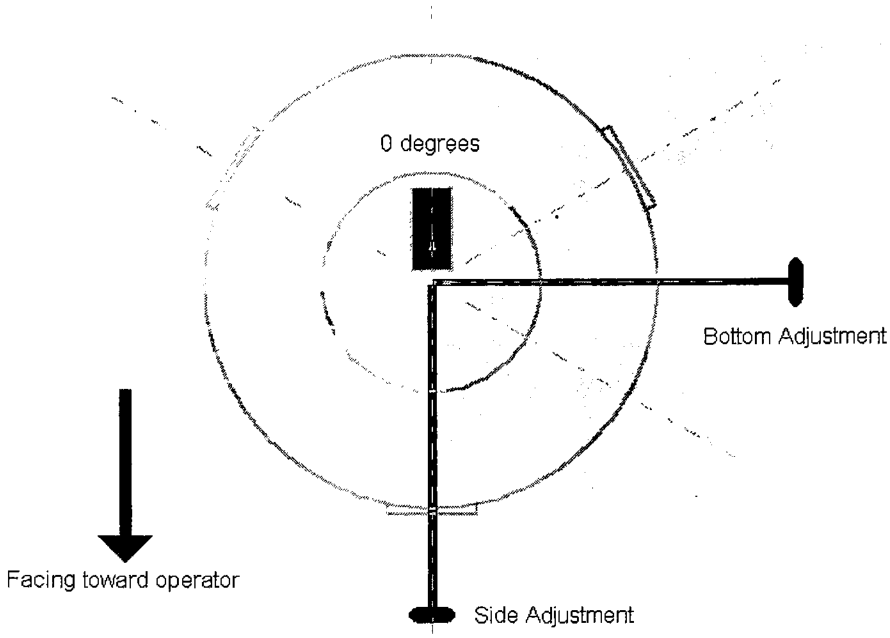



Figure 3.11

The wobble will move as follows:

- The bottom adjustment will move the bottom of the hub away from the mold and towards the stationary wobble
- The bottom adjustment will move the top of the hub into the mold and away from the stationary wobble
- The side adjustment will move the operators side of the hub away from the mold and towards the stationary wobble

The side adjustment will move the hub, at zero degrees into the mold and away from the stationary wobble. The side wobble (located at 180°) adjustment creates a moment about the y-axis. The bottom wobble (located at 270°) adjustment creates a moment about the x-axis. Figure 3.12 shows the location of the X and Y axis, and the locations of the Side and Bottom wobble adjustments.

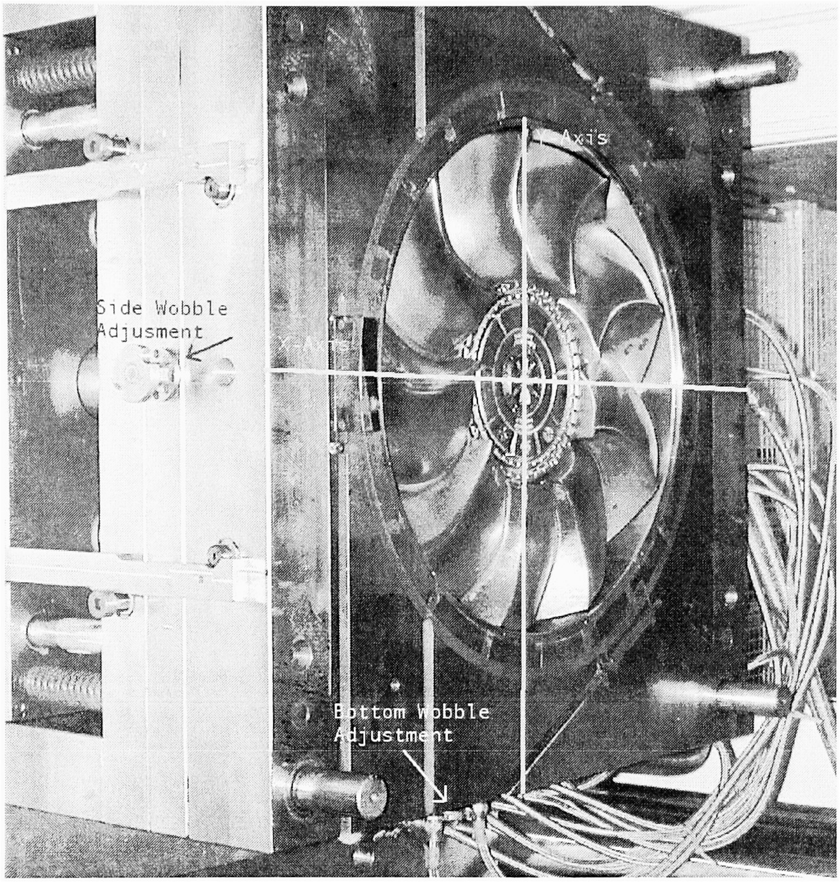



Figure 3.12

The Audit-balance machine measures the magnitude and location of a couple unbalance. The location is where the "high" point is on the fan. From this reading one can adjust the appropriate "wobble" to lower the "high" point of the unbalance. It is not unusual to have to move both "wobbles" to compensate for "high" points not located on either the X or Y axis. Figure 3.13 shows a sample of where a couple unbalance could be located.

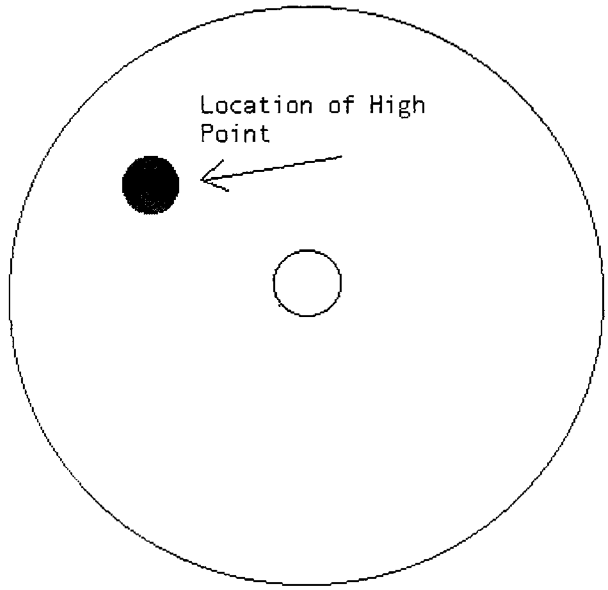



Figure 3.13

The simplest way to correct this type of unbalance would be loosen or tighten the corresponding wobble adjustments to “lower” the high spot in the fan.

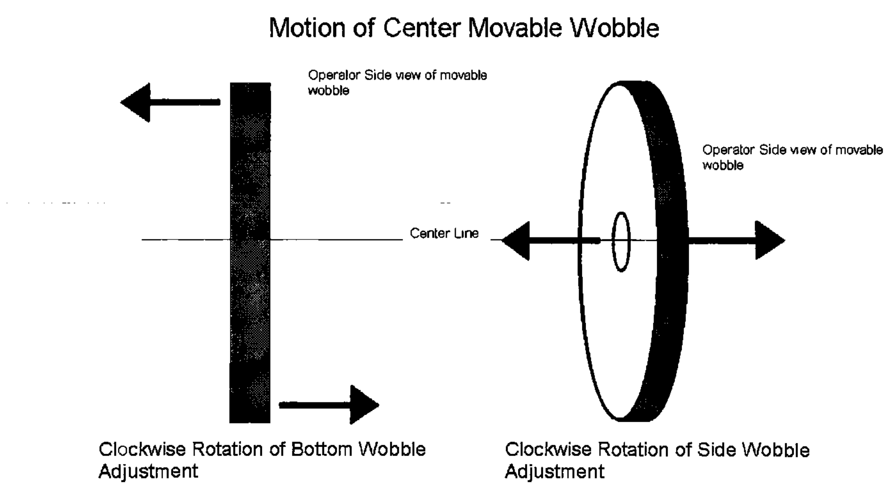



Figure 3.14

The method of wobble adjustment can be described as follows:

(a) If location is from 350 to10 degrees on the fan

Clockwise rotation on side wobble

(b) If location is from 11 to 79 degrees on fan

- Clockwise rotation on side wobble
- Clockwise rotation on bottom wobble

(c) If location is from 80 to 100 degrees on fan

- Clockwise rotation on bottom wobble

(d) If location is from 110 to 169 degrees on fan

- Clockwise rotation on bottom wobble
- Counter-clockwise rotation on side wobble

(e) If location is from 170 to 190 degrees on fan

Counter-clockwise rotation on side wobble

(f) If location is from 191 to 259 degrees on fan

Counter-clockwise rotation on side wobble

- Counter-clockwise rotation on bottom wobble

(g) If location is from 260 to 280 degrees on fan

Counter-clockwise rotation on bottom wobble

(h) If location is from 281 to 349 degrees on fan

- Counter-clockwise rotation on bottom wobble

Clockwise rotation on side wobble

### 3.6.2 *Example of Sample Couple Correction*

Figure 3.65 shows the unbalance that may be located in a fan. The numbers obtained for the unbalance of this sample piece were obtained from actual unbalance numbers found in a production environment. The unbalance is located at 50° and has a magnitude of .48 kg-mm$^2$.

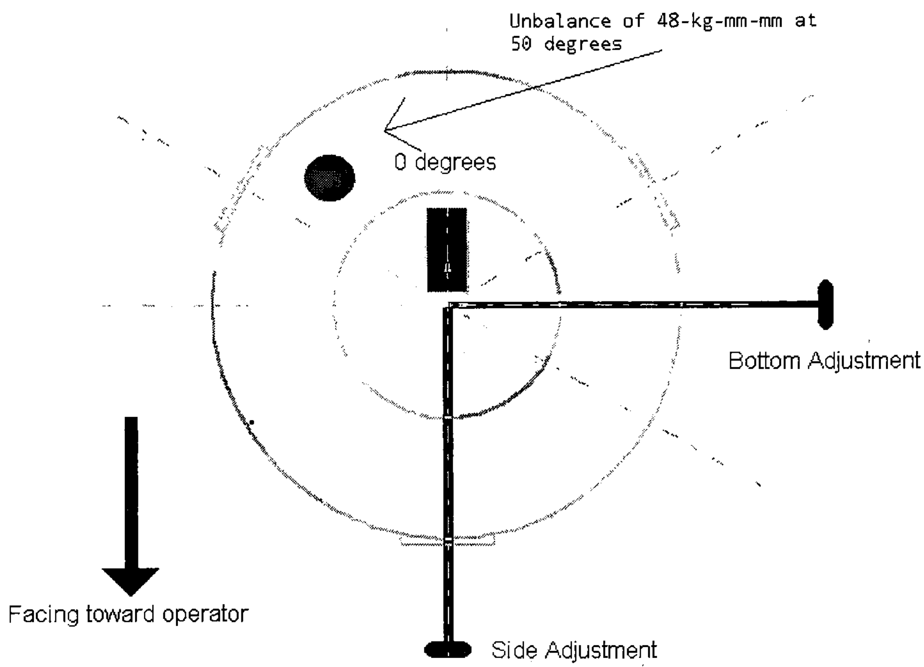



Figure 3.15

For this particular adjustment both wobble adjustments will need to be adjusted in order to correct the unbalance. The reason for this is the unbalance does not lie at the 0°, 90°, 180° or 270° locations on the fan. If the unbalance lies within 10° of these locations only one wobble adjustment needs to be adjusted.

The appropriate movement of the wobble adjustments for this unbalance would be:

(i) Clockwise rotation on the side wobble

(j) Clockwise rotation on the bottom wobble

Because this is located almost exactly between the X and Y axis the side and bottom wobble adjustments will have about the same amount of turns.

# Chapter 4

## The Current HDFS Balancing Process

Current HDFS production techniques have been implemented since January 2000. After a year of production, the area of balancing has shown the need for improvement. Although the current process is effective in correcting unbalance in approximately 95% of the assemblies attempted, there is a desire to decrease cycle time and move to a 99% correction rate.

### 4.1 Introduction

Once the fan is mounted onto the shaft of the motor and connected to the shroud, the completed assembly is ready to be balanced in the production-balancing machine. The balance machines used by Valeo are currently manufactured by Balance Technology Inc. (BTI) of Ann Arbor, MI. This machine was designed by a cooperative effort between Valeo and BTI. BTI is responsible for the design of the vibration measurement and the equipment used to balance the assemblies. Valeo is responsible for the transport system and the hydraulic system used to power the motor.

In the assembly process that Valeo uses, chrome balls are inserted into grooves along the hub of the fan. The hub contains 4 grooves, 2 in each plane. Each plane contains a groove for a large and small chrome ball. The large chrome balls are used to decrease the couple unbalance and the small balls are used to correct for the static unbalance. With both static and couple unbalance vectors known, either unbalance can be corrected for without the concern of affecting the other. Therefore the order in which the static or couple unbalance is corrected for does not matter. In a theoretical environment where "cross-talk" (section 2.5) does not exist, both static and couple corrections can be carried out simultaneously.

Assemblies are loaded on to a sled, which is hydraulically powered and delivers the assembly to the balancing "nest". The nest is the area in which the assembly is balanced. The inlet and outlet ports and pressure control valve (PCV) are connected to, and hydraulic oil is pushed into the motor. The label that was put on the unit during the assembly is read for traceability and the fan is rotated. The speed of the fan is controlled by a signal that controls the voltage sent to the PCV. The computer controls the signal and rotates the fan at a speed of 1100 rpm. Once a speed of 1100 rpm is obtained the unbalance readings are read and recorded into the computers ROM. The rotation of the speed is stopped and a stepper motor connects to the surface of the fan and orients it to be balanced. If an unbalance exists, either large or small chrome balls are inserted into the ball grooves located along the circumference of the fan hub. The balance machine has the ability to have four cycles of balance pass correction. There are two large ball passes and two small ball passes. The majority of balancing cycles use one large ball pass and one small ball pass. About 25% of the balanced units use three passes. After the unit is balanced to specification, all data is recorded into the ROM of the computer and the assembly is deemed as a good part. The hydraulic oil is then evacuated from the motor, removed from the nest, and placed on a conveyor. The current balancing time is approximately 145, seconds and the reject rate is approximately 5%.

The goal of Valeo is to develop a balancing system in which fans can be balanced in about 60 to 90 seconds. The implementation of a specification change for couple unbalance would dramatically increase the productivity of the HDFS facility. It is recommended that a specification change of 48 kg-mm$^2$ be implemented for couple unbalance. It has been determined that this specification change will not have any effect on the vibration of the vehicle. Studies are being conducted by Chrysler to determine if this specification change will shorten the life of the motor. A study was conducted to show the effects of a specification change on the cycle times of units being manufactured. Appendix G shows that a specification change will save almost 50 seconds on average for each assembly, bringing the average to approximately 99 seconds. However, the implementation of a laser balancing system (Chapter 5) could decrease the cycle time to as low as 75 seconds. This will lead Valeo to double their productivity over the current system so that the amount of units made currently on two shifts could be done in one.

### 4.2 Unbalance Caused By Assembly

One of the main concerns that has arose throughout the research into building better balanced assemblies is the amount of unbalance caused by the assembly process itself. Molded fans are press-fit onto the shaft of the motor, using between 5500N to 13,000N of force. The fact that the fan is pressed onto a shaft can create a change in the couple unbalance of the fan. If it is pressed onto the shaft with a slight tilt, the angle and the magnitude of the couple unbalance will change, while the force unbalance will be left relatively unchanged.

An initial study was conducted in which 128 molded fans were measured and the data was collected. These fans then were split into two groups of 64, to be processed in the two assembly cells. Cell 1 yielded results that approximately 5 kg-mm$^2$ of induced couple unbalance was added to the fan as it was press fit onto the shaft of the motor. The data showed also that approximately 95% of all units would be within a couple unbalance of 20 kg-mm$^2$ of the original fan unbalance. This data was obtained by calculating the standard deviation of the population in parts to determine what the range of the assembled parts would be. Cell 2 yielded results that approximately an 8 kg-mm$^2$ decrease in couple unbalance and that approximately 95% of all units would be within a couple unbalance of 20 kg-mm$^2$ of the original fan unbalance. Both cells had negligible effect on force unbalance from fans alone to assembly. This study showed that as a general population the amount of unbalance induced through the assembly process is negligible, when the population is large. Data was collected during this study to determine what the final balanced assembly readings were. Cell 1 balanced to a force unbalance of 0.0176 kg-mm and a couple unbalance of 5.06 kg-mm$^2$. Cell 2 balanced to a force unbalance of 0.0155 kg-mm$^2$ and a couple unbalance of 4.51 kg-mm$^2$. Appendix C shows the results of the data collected from the study which demonstrated that as a population unbalance was not significantly changed in the assembly process. Figure 4.1, which is based on the data in Appendix C, shows the change in static unbalance caused by assembly in cell 1 during the study. The graph shows that the change in static unbalance from fan alone to assembly is minimal.

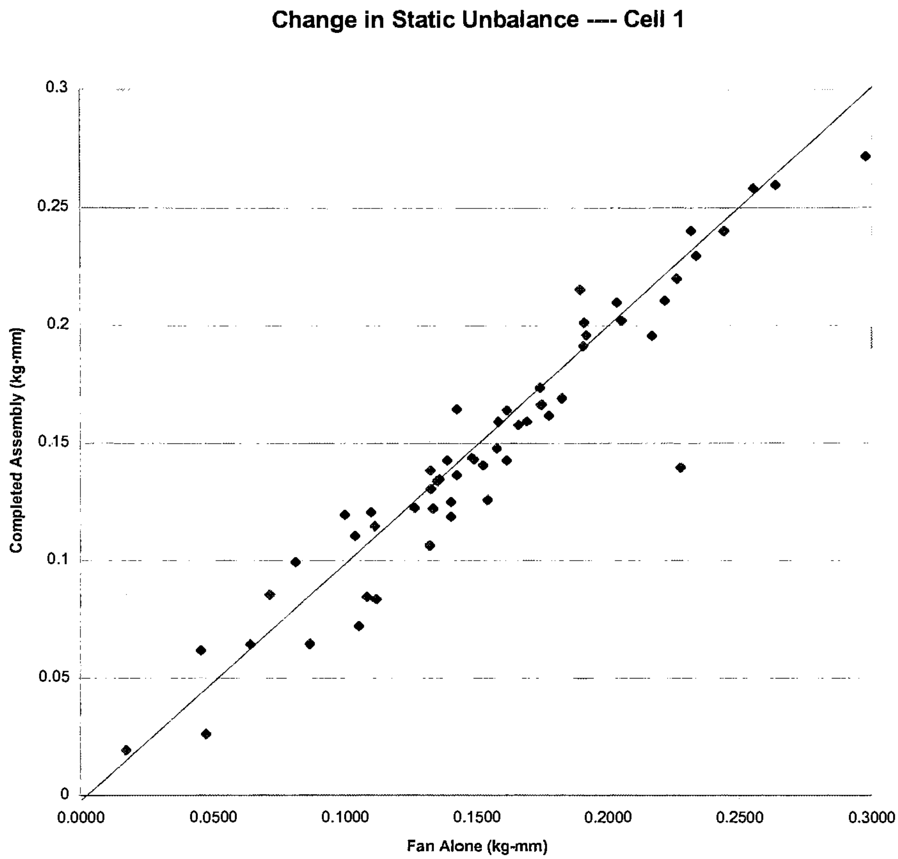



Figure 4.1

Figure 4.2 also based on the data in Appendix C, shows the change in couple unbalance created by assembly on cell 1. The general population averages to be about the same as the incoming fans alone but there still remains a large deviation between the two. From this data it can be concluded that only couple unbalance is changed during the process of assembling fans on to the shaft of the motor.

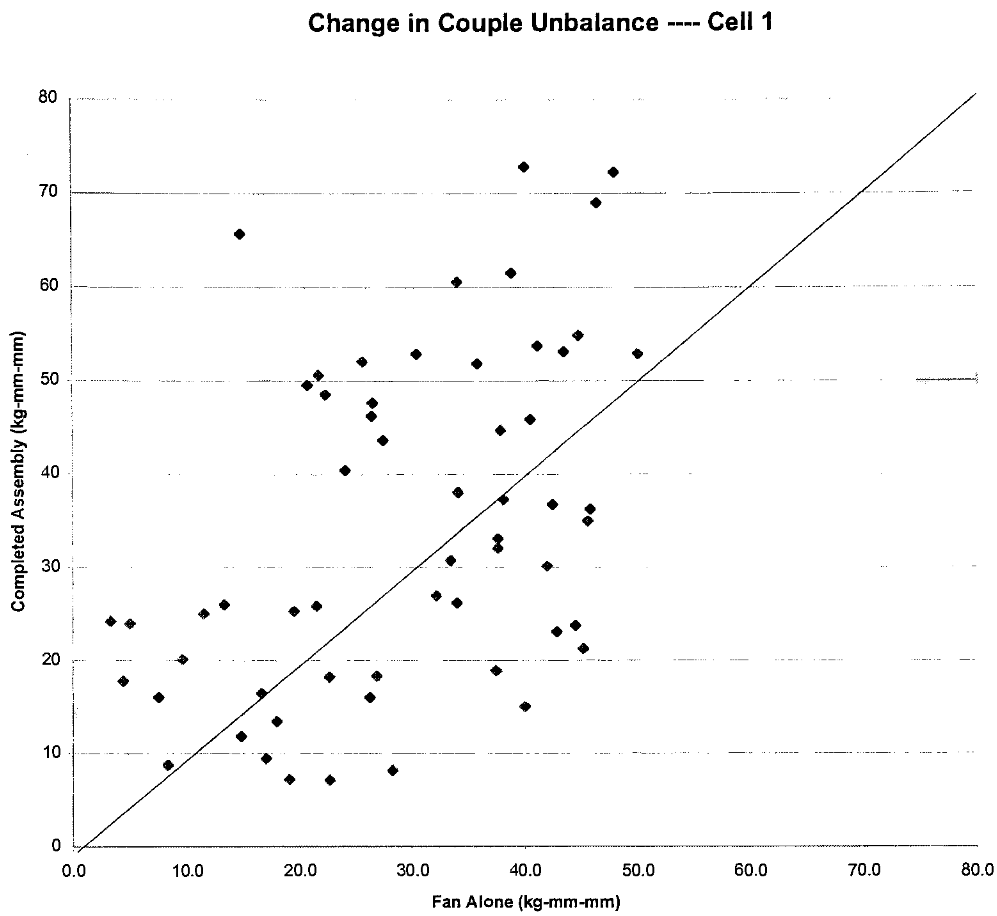



Figure 4.2

The results for cell 2 were very similar to that of cell 1. Appendix C shows the data for cell 2. From this initial test it can be concluded that static unbalance remains constant during the unbalance process while couple unbalance can change, but as a general population does not have a significant increase or decrease in couple unbalance.

A secondary study was conducted by using another 64 assemblies 10 months later to determine if the process had changed due to tool wear or other variables. This study showed that the distribution of unbalance was approximately the same as the initial study but the population as a whole has shifted to where almost 30 kg-mm$^2$ of couple unbalance was being induced into the assembly as the fan is press-fit on to the shaft. This would lead one to believe that fixturing is showing signs of wear, or that assembly parts are not being held to specification. Appendix D shows the data for the secondary study. To correct for this problem, investigation of tooling wear and shaft tolerances would be an appropriate next step. Figure 4.3 based on the data in Appendix D, shows the static unbalance of the fan alone compared to the static unbalance of the completed assembly does not change by a substantial amount.

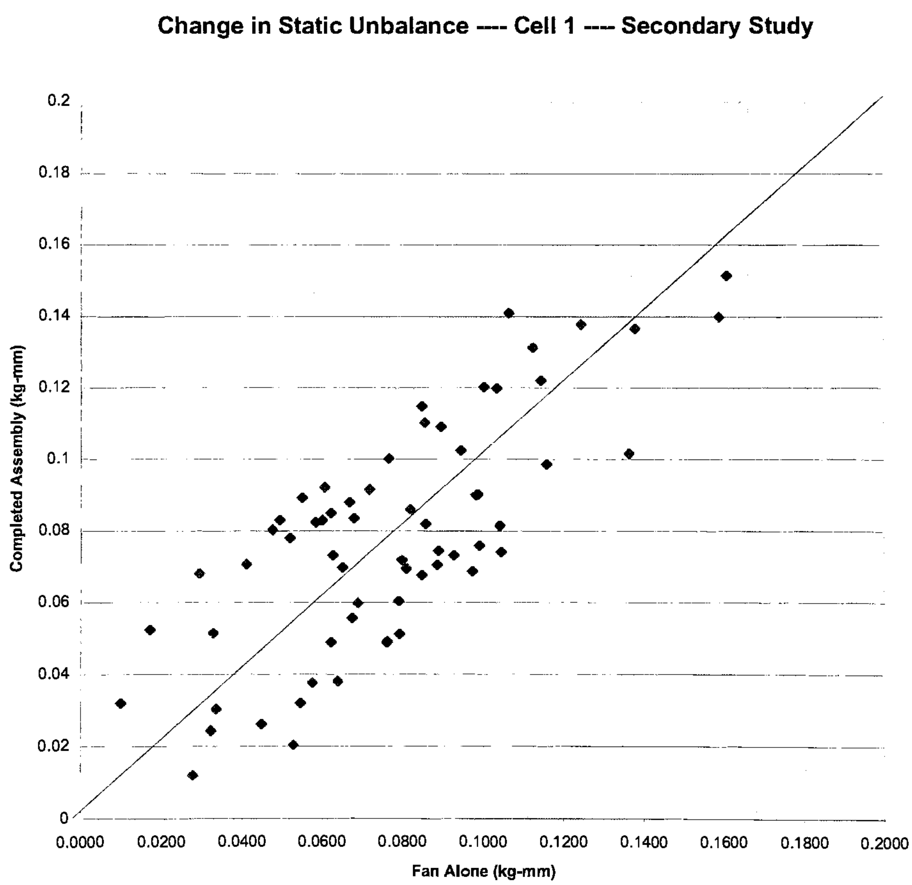



Figure 4.3

Figure 4.4 also based on Appendix D, shows an increase in the amount of couple unbalance caused by assembly. Both the initial and secondary studies were conducted in the same manor. A change in the process is not evident but must exist to explain the differences in the data that was obtained. Appendix D shows the complete data obtained during the secondary study. At this time tooling wear appears to be the root cause of this major change.

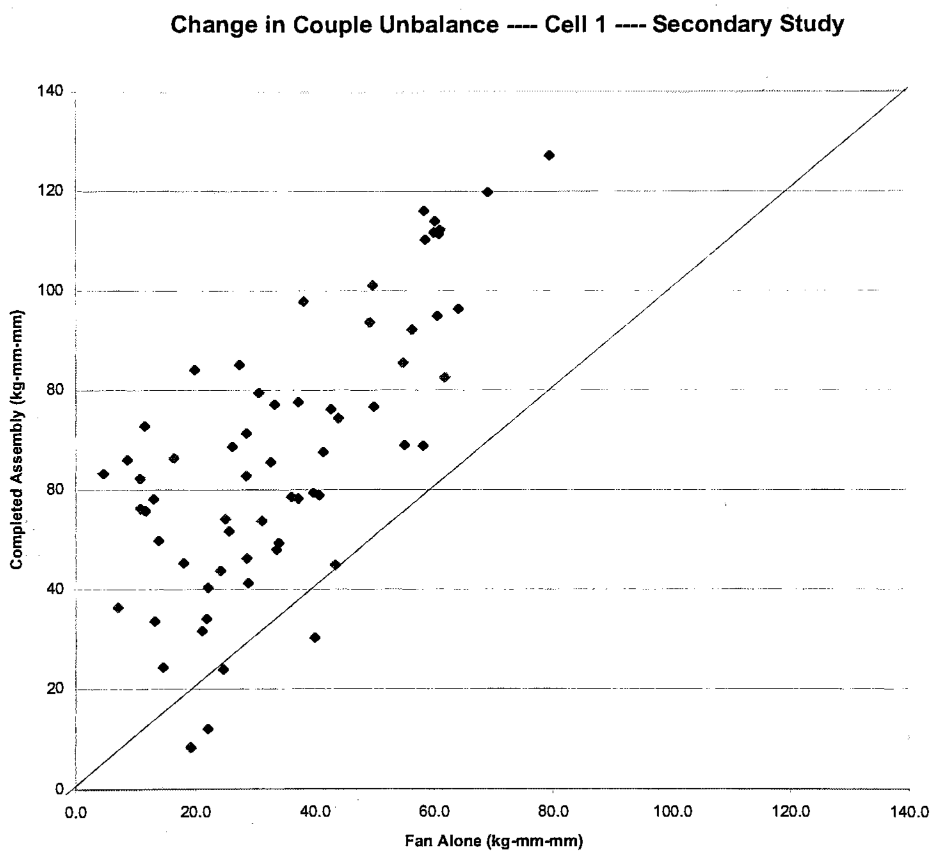



Figure 4.4

### 4.3 Algorithm Test Program

Cycle times to balance assemblies are a critical piece of the manufacturing puzzle. The faster units are balanced, the more productive the cell will become. Small balls are used to correct for static unbalance. The algorithm used by Balance Technology Inc. (BTI), does not perform to the standards in which Valeo desires. The goal of this short study is to prove and show that assemblies can be made to current specifications in a more efficient manor than that of what the balance machines are currently capable of. Assemblies will be chosen at random and placed into the balance machine to record initial unbalance. These values will be recorded each time the assembly enters the system. The first study will entail the manual balancing of placing chrome ball bearings into the groove. The least amount of balls will be used to determine what the most efficient method for balancing is. After the assembly's balance is within the desired specification, the placement of the balls will be marked with a yellow marker. At this time all balls will be removed and the part will be re-measured for initial unbalanced. The BTI algorithm will then balance the assembly, and the amount of balls, along with their placement will be recorded. The amount of balls used will be compared to the amount used by the manual method. It is anticipated that we will see from about 3 times the number of balls used upwards as much as 10 times as many. The mass of the manual balancing will also be compared to the mass of the algorithm balancing.

The study was conducted by using 3 sample units. The initial unbalance was recorded and then they were manually corrected. An average of 5 balls was used to correct the assemblies within specification. The average amount of mass per unit was 10.9g added. For the BTI algorithm an average of 15.7 balls were used and a mass of 31.9 grams. This shows that the amount of balls and weight of the overall assembly can be greatly reduced. A decrease of 10 balls per assembly will yield savings of about $0.50/unit. The hypothesis on why the BTI algorithm is using so many more balls to correct for unbalance is that it is using a vector formula to match the static unbalance to 0.005 kg-mm. If the code is modified to determine the method to use the least possible amount of balls to bring the static unbalance to under 0.04 kg-mm, the decrease in overall ball usage will be seen. Each ball takes about 2 seconds to cycle into the groove. A decrease in 10 balls per unit will shave approximately 20 seconds off the cycle time of the unit. The extra cycle time would show an increase in production of about 10% to 15% over the entire day. Appendix E shows the data collected during the study.

### 4.4 Fan Design Flaws Which Affect Unbalance

The design of the fan leads to a problem with the ability to balance using the top large ball groove. The fan blades connect to the top large ball groove. When a ball is inserted in an area where the blade connects to the hub, the fan is deformed and moves mass into the low balancing plane. Figure 4.5 shows the deflection cause by inserting balls into the groove.

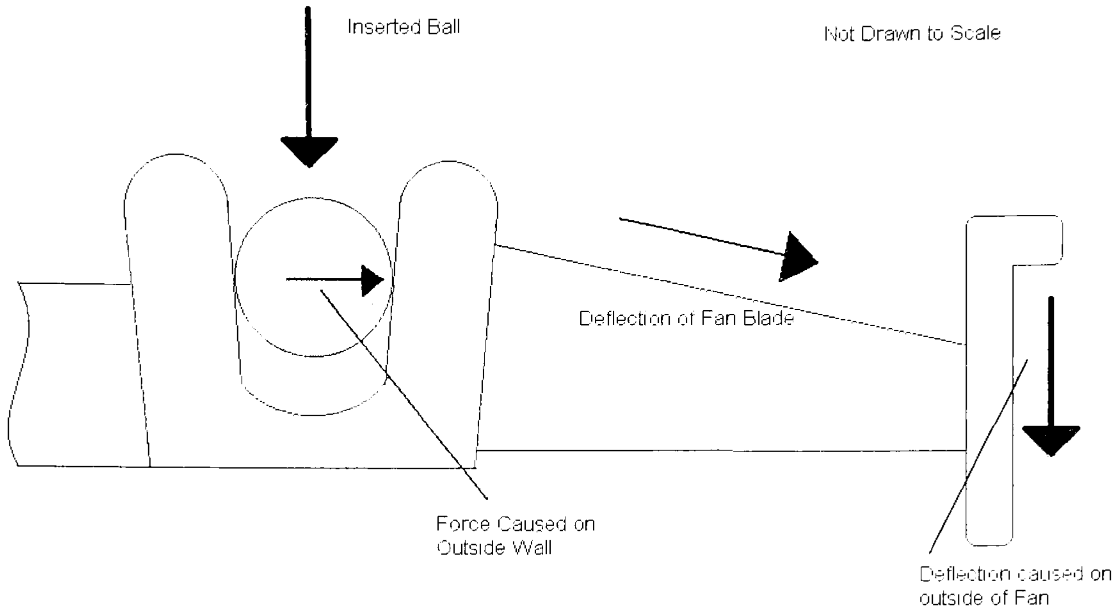



Figure 4.5

This will cause the balance machines to have longer cycle times due to the fact that the unbalance is changing due to deformation of the fan. A study was conducted to determine where large balls could be inserted into the top fan groove and not have a significant impact on the unbalance in the lower plane. The shade areas in figure 4.6 shows where a large ball can be inserted and cause less than 10% cross-talk.

**Locations where large balls can be placed without deformation of fan**

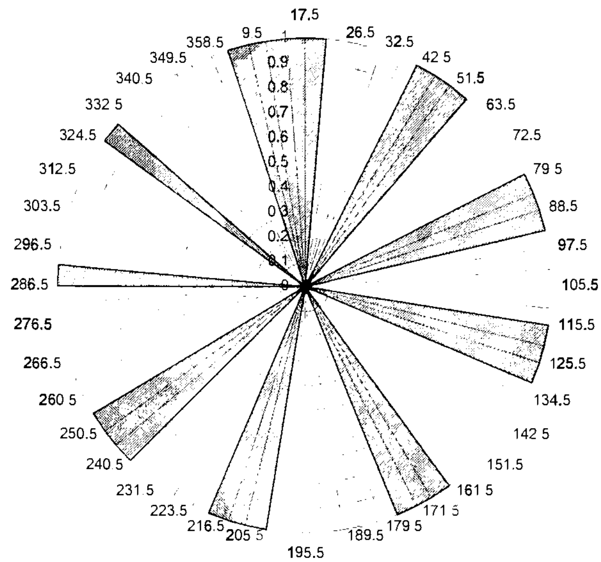



Figure 4.6

The solution proposed was to move the wall of the large ball groove above the location of where the fan blade and the hub meet. This would increase the effective balancing area from about 40% of the groove to 100%. If this is done then the amount of cross-talk caused by fan deformation will be minimized and the effectiveness of the balance machines will be increased. The HDFS for the 2002 Dodge Viper has accounted for this change and has had a very positive effect on the ability to accurately and quickly balance assemblies.

A modification to the HDFS balancing machine program has been included but not yet implemented to use “exclusion” zones. These zones will be marked so that the balance machine will not insert balls into the areas that are know to cause deflection and cross-talk in the fan. This program modification has the potential to decrease the amount of large chrome balls used in correcting for couple unbalance. At this time however, a study has not been conducted to determine the total benefit of implementing this program.

# Chapter 5

# Proposed HDFS Laser Balancing Process

## 5.1 Introduction

One of the most effective ways of correcting unbalance is to remove material from the heavy spot of the rotating member. A technology which was developed in 1983 and eventually patented in 1988 is a microprocessor laser control system for multi-plane balancing of rotors. This system emits a laser pulse to remove material from a rotating element, controlled by a computer. This technology allows the part to be checked at operating speeds for unbalance. If a rotor is unbalanced, excess material can be removed by using a laser, without affecting the operation of the unit. Conventional rotor balancing methods were very labor intensive and tedious. It is normally done on a trial and error method, which the rotor needs to be dismounted, machined to remove excess material, remounted and tested. A laser system eliminates the total need for dismounting and secondary testing of units. For HDFS assemblies, the current process cycles the units to 1100 rpm to measure for unbalance, and then stops the motor so the fan unit can be balanced. Theoretically, a laser system can correct unbalance at operating speeds, without having to stop the fan's rotation.

## 5.2 How Laser Balancing Works

The development of a laser balancing system is very similar to that of a conventional balancing machine. Most balancing machines use accelerometers or force transducers to measure the amount of vibration caused by the rotating member. This data is transferred into a computer and stored in memory, converted to the desired units, and used for tracking and comparison. The computer in return sends a message to a control interface module which controls where weight is added or subtracted. The user has the ability to input desired characteristics through a keyboard, and can watch through a visual representation shown on a display unit. Balancing machines use a tachometer to measure the speed of the rotor, so precise measurements can be made. The tachometer is connected to the control interface module, which is responsible for the speed of the drive motor. In the case of HDSF assemblies, it is the amount of current pushed through the pressure control valve (PCV) which controls the amount of hydraulic fluid flowing through the motor.

The main difference in a laser-balancing machine is the fact that the rotor will never stop rotating during the entire balancing process. This means that cycle times will decrease because there is not the time-consuming accelerating and deceleration of the fan system. The control interface module will send a signal to the energy source which will "power" the laser head. A laser control circuit will move the laser in parallel with the axis of rotation so more than one plane can be corrected in. Measurements from the tachometer then will allow for the energy source to "pulse" laser shots and vaporize material from the desired area. At 1100 RPM, one pulse per revolution would yield a pulse every 0.054 seconds. This would yield 18.3 pulses per second. The amount of time the laser would be on during the pulse would be about 0.015 seconds if material were to be removed in one-inch increments. This process generates a gas, which needs to be removed from the balancing environment, so the addition of ventilation hoods will be needed.

The choice of the laser is very important in the overall process. Unfortunately, the funding for research into which types of lasers would be appropriate at this time have not been allocated. From previous experience from Foster Miller Inc., it appears that the best laser to be used would be a $CO_2$ laser. Their internal studies have shown effective removal rates from a black plastic similar to that used to mold our fans. Integration of a laser system into Valeo's current manufacturing process has been deemed to be possible from a manufacturing standpoint. Further research needs to be conducted on material removal rates. If a laser system is integrated into HDFS assembly balancing cells, much of the development of the transport system, hydraulics and measurement systems can be reused. This will save in both development cost and time, if a laser system is implemented.

### 5.3 Overall Effects of Laser Balancing

The main goal of the addition of a laser balancing system is to correct for static unbalance and remove the need for the use of the small chrome balls for balancing. Provided that the specification is increased from 12 kg-mm$^2$ to 48 kg-mm$^2$ for couple unbalance the use of large balls will be dramatically decreased. This specification change may have little to no effect on the amount of small balls used because they have traditionally been used to correct for static unbalance. A laser system would be an appropriate choice to remove the excess material because the mass usually needed to correct for static unbalance is minimal. This could possibly save upwards of 25 to 30 seconds of cycle time per unit by simply removing the need for the addition of small balls.

Laser balancing systems have been used over a variety of different applications, ranging from dental turbine rotors, gyroscope rotors, electric motor armature, gas turbine engine parts, and turbomolecular pumps. The implementation of a laser system into the HDFS manufacturing cells appears to be an appropriate natural progression in the overall improvement in assembly cost and time.

### 5.4 Concerns of Laser Balancing

The two major concerns that have arose in the studies of whether laser correction of unbalance is feasible is the safety of the entire process, and if the removal of the material will cause a degradation in the life of the fan system. To ensure that the manufacturing environment is safe, a chamber will need to be constructed to house the laser and the balancing nest. This will protect operators from being directly exposed to the laser. This chamber will need to be ventilated to remove the vapor of the lased material to the atmosphere. This will require a ventilation system to circulate air throughout the chamber. Although this does not need to be airtight, this system need to be able to remove upwards of 98% of all lased material vapor.

The second main concern is whether removing material from the outside surface of the fan will cause premature failure. To develop a study to determine if this will become a problem, 3 fan units were balanced by using a material removal process. These fans were balanced by milling material off the inside of the outer circumference ring. The fans were balanced to specification, and then burst tested. The comparison of this test to the history of burst test failures determined if laser balancing is a possible avenue to take. The test showed that removing material from that area will provided little to no effect on the overall life of the fan. Previous burst test have shown failure where the fan blade connects to the hub, and not along the outside surface. For our study there was not a significant impact on the removal of material to balance on the outside ring. The fan burst were well within the specification of the fan unit, and is then deemed as a feasible process to go into production. Appendix H shows the values obtained for the three samples burst tested.

One issue of concern, which should not be forgotten , is if the amount of material to be lased can be removed faster than the current process. Based on preliminary numbers and prior experience of Foster Miller, approximately 0.05 grams of material can be removed from the surface of the fan per second. This calculation was obtained from data collected on a 1500-Watt laser system. If a larger laser system was utilized, a faster removal rate could be obtained. From the calculations shown in Appendix H, one can see that on average changing to a laser system will save a minimum of about 10 seconds. The major time savings will be shown on the non-cycling of the ramp up and ramp down of the fan from its measurement speed of 1100 rpm. For the laser balance test program it was assumed that a depth of 1/32 of an inch of material will be lased. The width of a laser is approximately 0.01 inches and can remove material at a rate of 70 inches per minute by utilizing a 500 watt $CO_2$ laser. The proposed system used for this experimental system, is a 1500 watt laser that could remove 210 inches per minute at a depth of 1/32 of an inch and a width of 0.01 inches. This would yield a mass removal of 0.049 grams per second. This value was determined by finding the volume of the plastic removed per second and multiplying it by the density of the material.

The significant decrease in cycle time will be the fact that material will be removed from the outside of the fan which allows for less mass to be removed with comparable correction to added weight at the grooves located in the hub. There will be a decrease of 12 seconds for each time that a measurement is needed on the fan for unbalance. Laser balancing completely removes the need to stop the fan in order to perform correction.

**5.5 Anticipated Cost Savings**

The majority of cost savings of introducing a laser balance system into HDFS would be found in the increase of production and the decrease of cycle time. Cost savings will also be evident in the removal of using small balls to correct for unbalance. Each small ball costs approximately \$0.02, which means that there will be a savings of approximately \$0.20 for each unit that is lased. It is estimated that the introduction will bring a minimum of a 15 to 25 second per cycle decrease in cycle times. In an operating day that consist of 820 running minutes and an average cycle time of 140 seconds, a laser system could balance between 10% to 25% more parts. This will all be done without the addition of extra operators to run the equipment. It is also plausible that output would decrease from a 5% reject rate to less than 1%. Each rejected assembly cost Valeo over $120.00 in labor and material cost. The decrease in rejects could save Valeo thousands in scrap a day. The bottom line is that a laser balance system could save $100 a day in small ball usage, $1500 a day in reduced scrap and increase production so up to 50 more units can be made a day using the same about of operators. This means that $6500 a day increase for Valeo over current production schedules. A yearly increase of $1.6 million in cash flow could result from changing to a laser system to reduce static unbalance. These numbers were calculated from a 500 part per day production schedule.

# Chapter 6

## Summary and Conclusions

### 6.1 Transition from 12 kg-mm$^2$ to 48 kg-mm$^2$

The transition to a couple specification of 48 kg-mm$^2$ will yield a cycle time for production in the area of about 105 seconds per unit. This is a decrease in cycle time of about 40 seconds over the current production cycle times. Currently two operators are used in a cell, to build assemblies. At this time it appears that the operators can handle the increase production caused by the 40 seconds improvement in balancer cycle time. One problem that may hinder balanced assembly production is if cycle times for balancing assembles decreases to approximately 75 seconds. If this occurs an additional person will need to be added to complete the hose, wire harness, etc installation. At this time it is expected that operation will continue as it does today, with increased output caused by the change in the couple unbalance specification. Appendix G shows the data collected from a study to determine how much improvement could be achieved by changing to a 48 kg-mm$^2$ specification for couple unbalance. This data shows a cycle time that averages approximately 100 seconds.

### 6.2 Transition from Balance Balls to Laser Removal

The transition from using small chrome balls to a laser to remove material will require development of a plan to incorporate a laser system into the current machinery. This will require the addition of a ventilation system to remove the gases caused by lased material. Housing will also be needed to protect the operators from the laser. This is something that can be done by building on to the current system. The combination of a 48 kg-mm$^2$ couple specification and the use of a laser will remove the need for small chrome balls. Cycle times will decrease from an average of 100 seconds by using the 48 kg-mm$^2$ specification alone to approximately 80 to 90 seconds on average per unit. The largest increase in productivity will come when all incoming assemblies have an initial unbalance of 48 kg-mm$^2$. If this occurs then the use of large balls will become obsolete. One significant benefit of a laser system is that that static unbalance can be decreased to 10% of the specification if desired. A laser system will allow for complete and accurate control of static unbalance in assemblies. The addition of a laser system may cause the need for an extra operator in the cell to account for the increase in balanced assemblies. Appendix H shows a study that calculates the time savings of the implementation of a laser balance system.

### 6.3 Conclusions

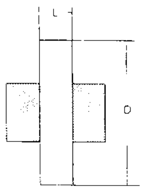
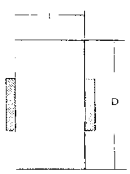
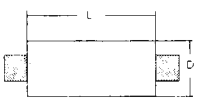
The initial intent of HDFS was to build completed assemblies at a cycle time of 60 to 90 seconds. The implementation of the new 48 kg-mm$^2$ couple specification and a laser balancing system to correct static unbalance will allow HDFS to work within these desired cycle times. Issues that are addressed in Chapter 3 and 4 should be considered in future designs of both equipment and parts. Molding is a significant player in unbalance and constant modification and changes need to be implemented to the molds slides and wobble positions to accommodate for slight changes in material, ambient temperature and other outside parameters. Although studies indicate that as a whole the act of assembly does not cause significant changes in unbalance there is room for additional studies to determine the changes caused to the fan by press-fitting it onto the shaft of the motor.

Future designs of equipment to balance HDFS assembles in production should consider using a laser balancing system. As the fan diameter decreases, couple unbalance will be less evident and static unbalance will become more critical. At this time if Dodge Viper fan assemblies go into production, a laser balance system will be the best avenue in static unbalance correction.

## Appendix A:
## Vibration Identification Chart

| Cause | Amplitude | Frequency | Phase | Remarks |
|---|---|---|---|---|
| Unbalance | Proportional to unbalance, Largest in radial direction | 1 x RPM | Single Reference, Mark-stable repeatable | Most common cause of vibration |
| Misalignment Couplings or Bearings and Bent Shaft | Large in axial Direction. 50% or more of radial vibration | 1 x RPM, usual 2 & 3 x RPM sometimes | Single, Double or Triple | Best found by appearance of large axial vibration |
| Bad Bearings, Anti-friction type | Unsteady-use velocity, acceleration and spike energy measurements | Very high, Several times RPM | Erratic-Multiple Marks | Bearing responsible most likely the one nearest point of largest high frequency vibration |
| Eccentric Journals | Usually not large | 1 x RPM | Single Mark | Motor- disappears when power is turned off |
| Bad Gears or Gear Noise | Low-Use Velocity, Acceleration and Spike Energy Measurements | Very High, Gear Teeth times RPM | Erratic-Multiple Marks | Velocity, Acceleration and Spike Energy measurements recommended |
| Mechanical Looseness | Sometimes Erratic | 2 x RPM | Two Reference Marks, Slightly Erratic | Usually accompanied by unbalance and or Misalignment |
| Bad Drive Belts | Erratic or Pulsing | 1, 2, 3 &4 x RPM of Belts | One or Two depending on Frequency, Usually Unsteady | Strobe Light best tool to freeze faulty belt |
| Electrical | Disappears when power is turned off | 1 x RPM or 1 or 2 x synchronous frequency | Single or Rotating Double Mark | If vibration amplitude drops off instantly when power is turned off cause is electrical |
| Aerodynamic or Hydraulic Forces | Can be large in the axial direction | 1 x RPM or number of blades on fan or impeller x RPM | Multiple Marks | Rase as a cause of trouble except in cases of resonance |
| Reciprocating Forces | Higher in line with motion | 1, 2 & higher orders x RPM | Multiple Marks | Inherent in reciprocating machines |

## Appendix B:
## Relationship Between Rotor Length and Diameter

| | | Balance Correction | | |
|---|---|---|---|---|
| | L/D Ratio exclusive of Shaft | Single Plane | Two Plane | Multi-Plane |
|  | Less than 0.5 | 0-1000 RPM | Above 1000 RPM | N/A |
|  | More than 0.5 but less than 2 | 0-150 RPM | 150-2000 RPM or above 70% of 1st critical | Above 2000 RPM or above 70% of 1st critical |
|  | More than 2 | 0-100 RPM | Above 100 RPM to 70% of 1st critical | Above 70% of 1st critical |

# Appendix C:
# Unbalance Caused by Assembly Initial Study

| Summary of Results Cell 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fan Assembly Alone | | | | Fan and Shroud Assembly | | | |
| | Force | | Couple | | Force | | Couple | |
| | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle |
| Average | 0.1542 | 155.9 | 29.1224 | 228.8 | 0.1487 | 150.1 | 34.3991 | 231.0 |
| Std Dev | 0.0570 | 82.1 | 12.8134 | 112.8 | 0.0562 | 84.4 | 17.9998 | 83.7 |

| | Calculation of Errors | | | |
|---|---|---|---|---|
| | Force | | Couple | |
| | Magnitude | Angle | Magnitude | Angle |
| Average | -0.0055 | -5.8 | 5.3 | 2.2 |
| Std Dev | 0.0176 | 17.2 | 16.5 | 98.4 |

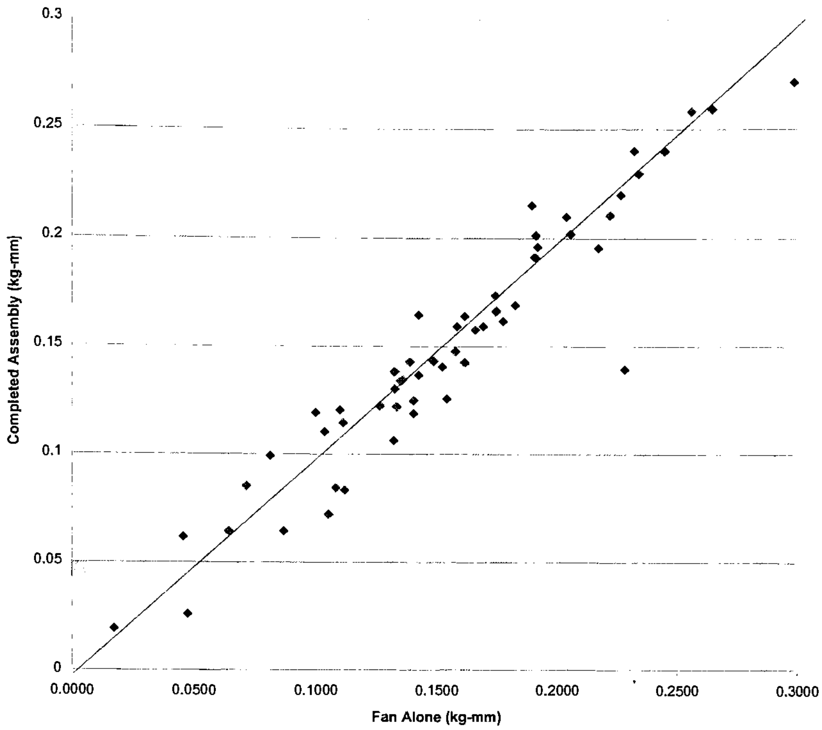
## Actual Study Data, Collected on 6/6/00, Cell 1

Rack "A" 6/6/00 — Testing was completed on cell #1

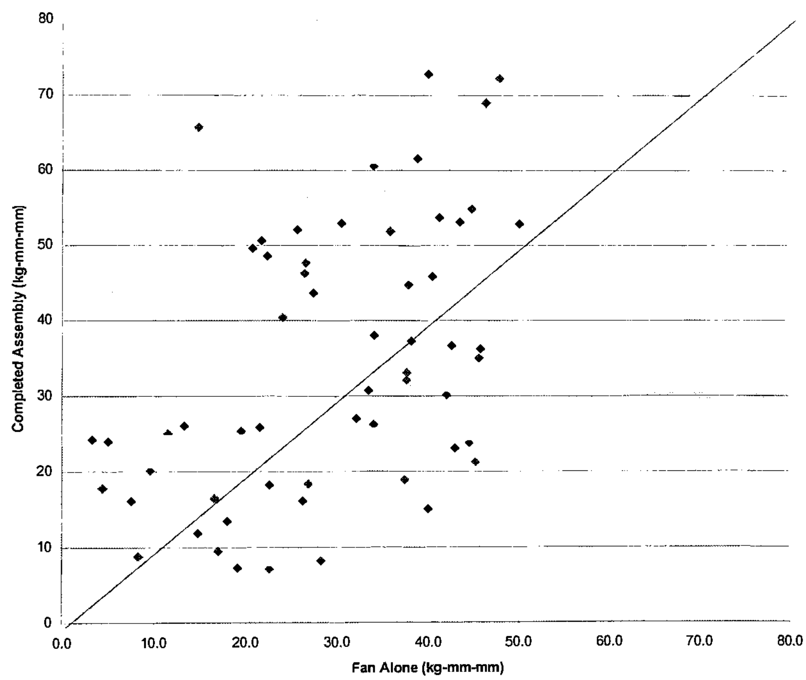
| Number | | | Fan Assembly Alone | | | | Fan and Shroud Assembly | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Force | | Couple | | Force | | Couple | |
| | | | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle |
| 1 | A | 57 | 0.1402 | 69.0 | 17.0 | 341.9 | 0.1249 | 60 | 9.48 | 263 |
| 2 | A | 8 | 0.1082 | 80.3 | 26.2 | 301.2 | 0.0845 | 70 | 16.06 | 234 |
| 3 | A | 52 | 0.1324 | 245.4 | 42.5 | 20.0 | 0.1384 | 250 | 36.7 | 21 |
| 4 | A | 53 | 0.2334 | 214.1 | 16.6 | 35.7 | 0.2297 | 213 | 16.44 | 44 |
| 5 | A | 54 | 0.1916 | 183.3 | 37.4 | 278.7 | 0.1959 | 187 | 18.92 | 282 |
| 6 | A | 55 | 0.1523 | 177.1 | 45.2 | 309.4 | 0.1406 | 186 | 21.28 | 303 |
| 7 | A | 56 | 0.0998 | 165.1 | 37.8 | 292.6 | 0.1194 | 181 | 44.76 | 309 |
| 8 | A | 47 | 0.2216 | 179.9 | 47.9 | 316.3 | 0.2106 | 180 | 72.27 | 268 |
| 9 | A | 48 | 0.2277 | 199.7 | 34.0 | 324.1 | 0.1396 | 195 | 60.6 | 285 |
| 10 | A | 49 | 0.1909 | 199.2 | 14.8 | 224.1 | 0.2013 | 199 | 11.85 | 17 |
| 11 | A | 50 | 0.1540 | 218.3 | 21.5 | 10.0 | 0.1258 | 220 | 25.86 | 214 |
| 12 | A | 51 | 0.1333 | 95.7 | 41.2 | 228.2 | 0.1222 | 94 | 53.74 | 218 |
| 13 | A | | 0.0454 | 240.9 | 22.6 | 357.1 | 0.0617 | 262 | 7.12 | 354 |
| 14 | A | 43 | 0.0641 | 245.5 | 13.3 | 318.6 | 0.0643 | 254 | 26.02 | 228 |
| 15 | A | 44 | 0.2033 | 267.9 | 34.0 | 37.4 | 0.2099 | 267 | 26.23 | 0 |
| 16 | A | 45 | 0.1742 | 230.9 | 24.0 | 277.6 | 0.1736 | 233 | 40.42 | 234 |
| 17 | A | 68 | 0.1349 | 228.9 | 46.4 | 218.3 | 0.1341 | 223 | 68.98 | 224 |
| 18 | A | 62 | 0.1112 | 223.9 | 32.1 | 329.7 | 0.1147 | 226 | 26.98 | 276 |
| 19 | A | 38 | 0.1614 | 225.2 | 27.4 | 329.0 | 0.164 | 222 | 43.66 | 274 |
| 20 | A | | 0.1748 | 73.1 | 4.4 | 21.4 | 0.1665 | 66 | 17.79 | 222 |
| 21 | A | 12 | 0.1321 | 287.0 | 37.6 | 149.1 | 0.1065 | 278 | 33.1 | 208 |
| 22 | A | 64 | 0.1893 | 263.2 | 45.6 | 333.1 | 0.2153 | 261 | 34.99 | 325 |
| 23 | A | 59 | 0.1035 | 260.2 | 35.8 | 240.9 | 0.1105 | 259 | 51.87 | 217 |
| 24 | A | 11 | 0.1099 | 255.2 | 19.5 | 343.0 | 0.1206 | 251 | 25.34 | 320 |
| 25 | A | 5 | 0.2168 | 74.0 | 8.3 | 33.7 | 0.1956 | 67 | 8.76 | 247 |
| 26 | A | 65 | 0.1052 | 86.5 | 40.0 | 332.9 | 0.0722 | 102 | 72.81 | 335 |
| 27 | A | 60 | 0.1118 | 82.9 | 42.9 | 307.3 | 0.0835 | 70 | 23.06 | 273 |
| 28 | A | 7 | 0.2980 | 86.3 | 49.6 | 247.4 | | | | |
| 29 | A | 6 | 0.2441 | 65.8 | 21.7 | 211.7 | 0.2401 | 60 | 50.65 | 200 |
| 30 | A | 66 | 0.1642 | 58.4 | 32.5 | 319.1 | | | | |
| 31 | A | 61 | 0.1746 | 98.7 | 3.3 | 193.2 | 0.1663 | 92 | 24.21 | 222 |
| 32 | A | 46 | 0.0170 | 45.1 | 45.8 | 21.2 | 0.0192 | 0 | 36.25 | 335 |
| 33 | A | 22 | 0.1356 | 34.9 | 25.6 | 334.8 | 0.1346 | 31 | 52.08 | 261 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 34 | A | 23 | 0.2638 | 94.7 | 43.5 | 128.0 | 0.2594 | 86 | 53.13 | 147 |
| 35 | A | 24 | 0.1824 | 118.4 | 11.5 | 273.1 | 0.1691 | 113 | 25.04 | 215 |
| 36 | A | 25 | 0.0867 | 60.4 | 18.0 | 304.8 | 0.0645 | 45 | 13.46 | 269 |
| 37 | A | 26 | 0.1402 | 83.4 | 34.1 | 307.2 | 0.1189 | 77 | 38.05 | 265 |
| 38 | A | 16 | 0.1000 | 202.4 | 38.1 | 213.1 | 0.1194 | 201 | 37.28 | 215 |
| 39 | A | 18 | 0.1325 | 140.4 | 26.5 | 247.2 | 0.1305 | 136 | 47.7 | 233 |
| 40 | A | 36 | 0.1580 | 83.0 | 9.6 | 69.5 | 0.1591 | 71 | 20.14 | 134 |
| 41 | A | 67 | 0.1693 | 65.3 | 40.0 | 349.0 | 0.1593 | 54 | 15.02 | 311 |
| 42 | A | 62 | 0.1776 | 57.3 | 26.8 | 344.9 | 0.1617 | 46 | 18.35 | 353 |
| 43 | A | 37 | 0.1614 | 91.4 | 33.4 | 303.5 | 0.1427 | 86 | 30.74 | 261 |
| 44 | A | 38 | 0.0473 | 186.8 | 22.3 | 297.5 | 0.0261 | 174 | 48.57 | 218 |
| 45 | A | 39 | 0.1783 | 90.0 | 25.7 | 301.7 | | | | |
| 46 | A | 40 | 0.0714 | 300.0 | 50.0 | 291.6 | 0.0854 | 186 | 52.9 | 271 |
| 47 | A | 41 | 0.2551 | 77.2 | 30.4 | 278.8 | 0.2582 | 72 | 52.92 | 240 |
| 48 | A | 32 | 0.0811 | 158.2 | 38.8 | 193.5 | 0.0992 | 165 | 61.57 | 283 |
| 49 | A | 14 | 0.1423 | 78.9 | 14.8 | 287.8 | 0.1645 | 78 | 65.72 | 248 |
| 50 | A | 13 | 0.2052 | 48.6 | 44.8 | 256.5 | 0.2021 | 42 | 54.87 | 223 |
| 51 | A | 15 | 0.2317 | 52.7 | 7.5 | 332.3 | 0.2402 | 46 | 16.06 | 202 |
| 52 | A | 8 | 0.1488 | 83.5 | 44.5 | 33.4 | 0.1432 | 64 | 23.77 | 62 |
| 53 | A | 14 | 0.1659 | 95.0 | 22.6 | 304.7 | 0.1578 | 87 | 18.23 | 247 |
| 54 | A | 20 | 0.1028 | 210.4 | 44.6 | 280.1 | | | | |
| 55 | A | 19 | 0.2232 | 78.0 | 21.9 | 257.0 | | | | |
| 56 | A | 18 | 0.2007 | 276.0 | 40.1 | 267.4 | | | | |
| 57 | A | 33 | 0.1386 | 274.8 | 40.5 | 259.2 | 0.1428 | 267 | 45.9 | 243 |
| 58 | A | 34 | 0.1482 | 271.3 | 5.0 | 318.6 | 0.1436 | 270 | 23.95 | 195 |
| 59 | A | 35 | 0.1423 | 281.2 | 26.4 | 205.1 | 0.1365 | 282 | 46.29 | 196 |
| 60 | A | 27 | 0.2262 | 240.6 | 28.2 | 35.5 | 0.2199 | 240 | 8.17 | 37 |
| 61 | A | 28 | 0.1906 | 268.8 | 19.1 | 58.8 | 0.1913 | 266 | 7.24 | 324 |
| 62 | A | 29 | 0.1575 | 79.4 | 37.6 | 17.6 | 0.1478 | 73 | 32.08 | 331 |
| 63 | A | 30 | 0.2975 | 119.5 | 42.0 | 292.5 | 0.2716 | 118 | 30.14 | 275 |
| 64 | A | 31 | 0.1264 | 113.9 | 20.7 | 194.2 | 0.1226 | 103 | 49.58 | 185 |
| | | | | | | | | | | |
| Average | | | 0.1542 | 155.9310 | 29.1224 | 228.7948 | 0.1487 | 150 | 34.40 | 231 |
| Std Dev | | | 0.0570 | 82.0551 | 12.3134 | 112.8088 | 0.0562 | 84 | 18.00 | 84 |
| | | | | | | | | | | |

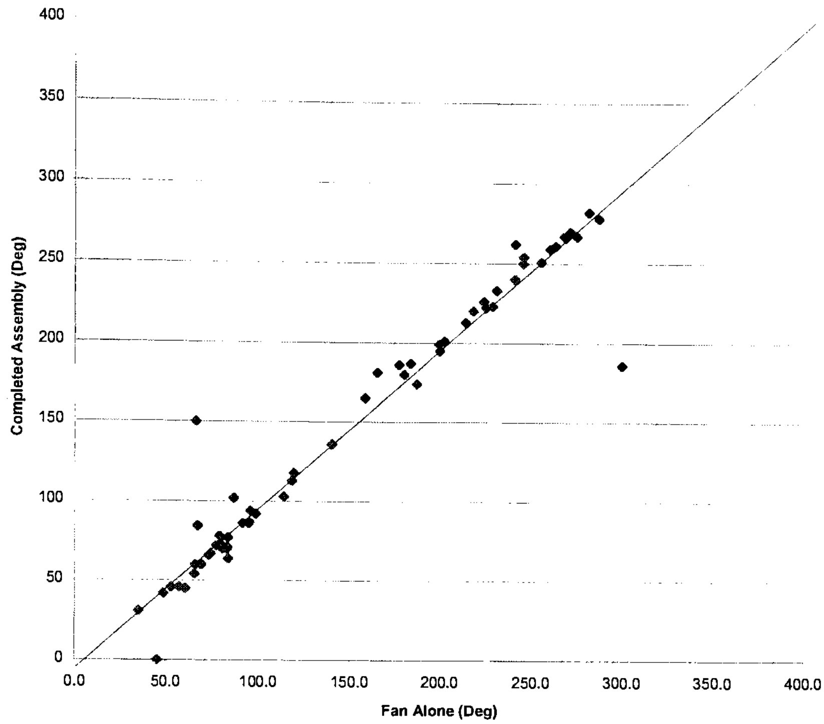
## Change in Static Unbalance ---- Cell 1



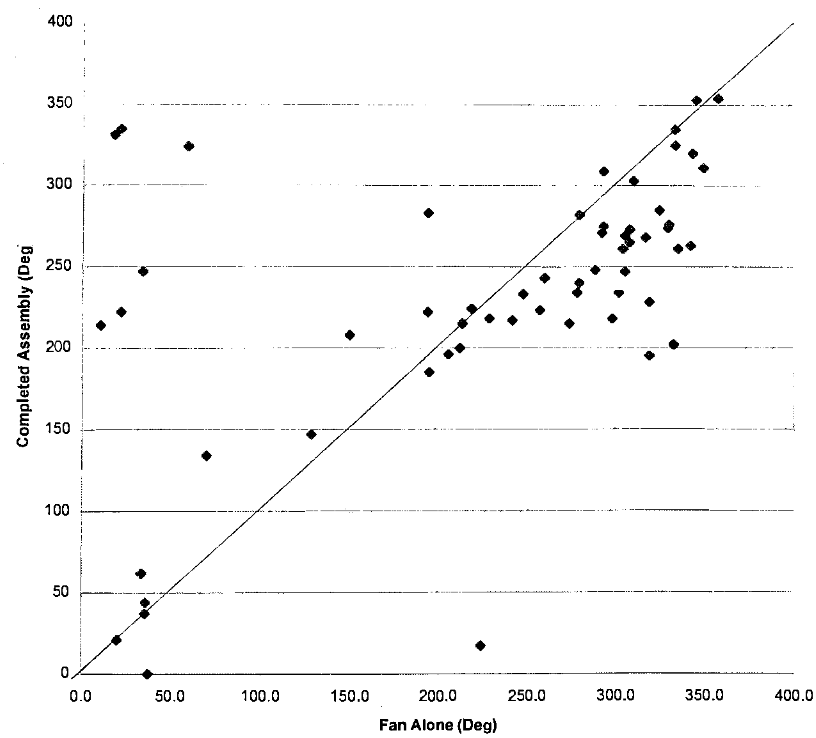

## Change in Couple Unbalance ---- Cell 1



## Change in Static Angle ---- Cell 1




## Change in Couple Angle ---- Cell 1



| Summary of Results Cell 2 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fan Assembly Alone | | | | Fan and Shroud Assembly | | | |
| | Force | | Couple | | Force | | Couple | |
| | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle |
| Average | 0.1350 | 110.3054 | 34.2625 | 211.9839 | 0.1283 | 108.6429 | 25.8839 | 205.7321 |
| Std Dev | 0.0659 | 38.7968 | 9.7852 | 134.4011 | 0.0779 | 52.0857 | 15.7209 | 100.8593 |
| | | | | | | | | |
| | Calculation of Errors | | | | | | | |
| | Force | | Couple | | | | | |
| | Magnitude | Angle | Magnitude | Angle | | | | |
| Average | -0.0067 | -1.6625 | -8.3786 | -6.2518 | | | | |
| Std Dev | 0.0342 | 43.0065 | 16.6151 | 122.8777 | | | | |

# Actual Study Data, Collected on 6/600, Cell 2

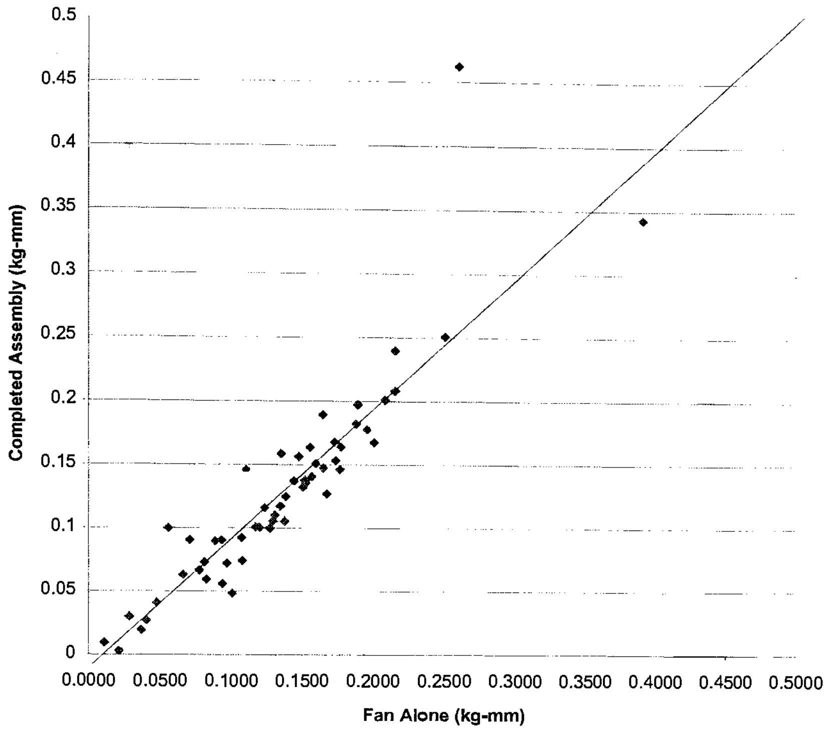
Rack "B" Testing was completed on cell #2

6/6/00

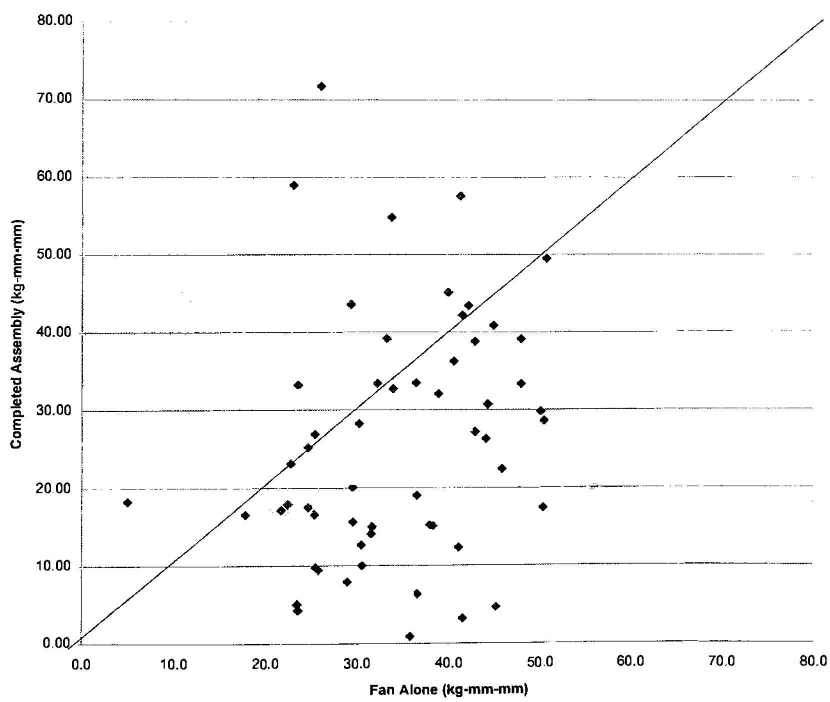
| | | | Fan Assembly Alone | | | | Fan and Shroud Assembly | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Force | | Couple | | Force | | Couple | |
| Number | | | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle |
| 1 | B | 75 | 0.1306 | 96.3 | 30.5 | 346.1 | 0.1104 | 78 | 10.02 | 174 |
| 2 | B | 73 | 0.1554 | 49.5 | 24.6 | 256.1 | 0.164 | 32 | 25.21 | 205 |
| 3 | B | 63 | 0.0930 | 89.5 | 31.6 | 1.2 | 0.0903 | 80 | 14.99 | 352 |
| 4 | B | 72 | 0.0820 | 103.8 | 21.7 | 93.0 | 0.0594 | 102 | 17.12 | 138 |
| 5 | B | 64 | 0.1766 | 128.6 | 50.3 | 302.8 | 0.1464 | 125 | 17.38 | 317 |
| 6 | B | 65 | 0.0703 | 153.2 | 30.4 | 191.2 | 0.0905 | 180 | 12.70 | 123 |
| 7 | B | 66 | 0.2150 | 107.5 | 42.1 | 281.0 | 0.2082 | 96 | 43.41 | 254 |
| 8 | B | 67 | 0.0658 | 79.2 | 31.5 | 74.2 | 0.0632 | 57 | 14.13 | 147 |
| 9 | B | 74 | 0.1346 | 124.0 | 29.3 | 209.1 | 0.1172 | 114 | 43.57 | 219 |
| 10 | B | 68 | 0.1199 | 133.2 | 17.8 | 269.3 | 0.1005 | 136 | 16.53 | 215 |
| 11 | B | | 0.2599 | 169.3 | 18.1 | 123.2 | | | | |
| 12 | B | 69 | 0.1376 | 178.4 | 41.0 | 22.4 | 0.1055 | 171 | 12.27 | 234 |
| 13 | B | 70 | 0.1566 | 169.5 | 41.4 | 353.4 | 0.1408 | 151 | 42.18 | 290 |
| 14 | B | 71 | 0.1595 | 135.9 | 25.4 | 320.4 | 0.1508 | 127 | 26.86 | 280 |
| 15 | B | 58 | 0.1648 | 118.9 | 23.4 | 20.0 | 0.1473 | 111 | 5.04 | 118 |
| 16 | B | | 0.1364 | 117.9 | 15.3 | 344.4 | | | | |
| 17 | B | 53 | 0.2082 | 106.6 | 44.8 | 294.3 | 0.2011 | 96 | 40.80 | 271 |
| 18 | B | 52 | 0.1517 | 128.1 | 22.7 | 295.6 | 0.1378 | 119 | 23.12 | 258 |
| 19 | B | 51 | 0.2005 | 112.2 | 29.5 | 296.1 | 0.1677 | 107 | 15.63 | 257 |
| 20 | B | 50 | 0.3901 | 102.8 | 42.8 | 28.5 | 0.3433 | 98 | 38.77 | 123 |
| 21 | B | 49 | 0.1439 | 95.9 | 50.0 | 341.6 | 0.1373 | 89 | 29.78 | 329 |
| 22 | B | 48 | 0.2149 | 136.7 | 50.7 | 273.5 | 0.2399 | 135 | 49.50 | 313 |
| 23 | B | 47 | 0.1272 | 130.9 | 40.5 | 272.1 | 0.0997 | 124 | 36.25 | 245 |
| 24 | B | 45 | 0.1641 | 205.6 | 33.7 | 354.7 | 0.1895 | 192 | 54.82 | 344 |
| 25 | B | 60 | 0.1384 | 123.4 | 23.5 | 301.2 | 0.1248 | 111 | 33.22 | 273 |
| 26 | B | 61 | 0.0770 | 72.2 | 25.7 | 315.4 | 0.0667 | 53 | 9.44 | 307 |
| 27 | B | | 0.0580 | 112.3 | 7.9 | 317.9 | | | | |
| 28 | B | | 0.1303 | 136.6 | 28.3 | 196.4 | | | | |
| 29 | B | 55 | 0.2500 | 126.3 | 32.2 | 67.6 | 0.2512 | 130 | 33.42 | 82 |
| 30 | B | 56 | 0.1772 | 120.0 | 30.2 | 0.2 | 0.1641 | 123 | 28.24 | 49 |
| 31 | B | | 0.0845 | 149.2 | 8.8 | 90.6 | | | | |
| 32 | B | 57 | 0.0112 | 138.2 | 29.5 | 57.8 | 0.0095 | 191 | 20.09 | 59 |
| 33 | B | 45 | 0.0967 | 79.2 | 5.0 | 349.4 | 0.0723 | 59 | 18.34 | 167 |
| 34 | B | 44 | 0.1292 | 136.5 | 45.1 | 303.3 | 0.1054 | 124 | 4.64 | 293 |
| 35 | B | 43 | 0.1522 | 126.0 | 25.4 | 46.6 | 0.1358 | 119 | 9.78 | 155 |
| 36 | B | 28 | 0.1954 | 96.6 | 24.6 | 320.0 | 0.1779 | 88 | 17.51 | 259 |
| 37 | B | 29 | 0.1672 | 113.1 | 42.8 | 287.5 | 0.1272 | 103 | 27.16 | 229 |
| 38 | B | 30 | 0.0556 | 120.4 | 26.0 | 318.9 | 0.0997 | 99 | 71.71 | 295 |
| 39 | B | 32 | 0.1727 | 97.4 | 33.9 | 325.9 | 0.1678 | 82 | 32.73 | 278 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 40 B | 38 | 0.0807 | 11.7 | 37.9 | 354.7 | 0.0731 | 80 | 15.22 | 255 |
| 41 B | 27 | 0.0404 | 58.7 | 33.2 | 56.4 | 0.0272 | 349 | 39.17 | 102 |
| 42 B | 17 | 0.0937 | 127.0 | 41.5 | 1.9 | 0.056 | 108 | 3.24 | 169 |
| 43 B | 18 | 0.1004 | 72.4 | 28.9 | 50.7 | 0.0487 | 65 | 7.96 | 60 |
| 44 B | 19 | 0.1171 | 183.6 | 38.3 | 55.1 | 0.1006 | 168 | 15.11 | 294 |
| 45 B | 20 | 0.1503 | 136.9 | 50.4 | 337.6 | 0.1321 | 126 | 28.56 | 321 |
| 46 B | 21 | 0.1306 | 92.5 | 23.5 | 312.0 | 0.11 | 78 | 4.28 | 265 |
| 47 B | 11 | 0.0369 | 63.1 | 47.8 | 29.7 | 0.0195 | 39 | 33.35 | 65 |
| 48 B | 12 | 0.1076 | 122.3 | 38.9 | 284.7 | 0.0746 | 108 | 32.04 | 251 |
| 49 B | 13 | 0.1474 | 164.6 | 39.9 | 323.0 | 0.1566 | 161 | 45.09 | 338 |
| 50 B | 14 | 0.1070 | 148.1 | 22.4 | 23.4 | 0.0922 | 149 | 17.92 | 87 |
| 51 B | 15 | 0.0476 | 71.6 | 25.3 | 355.0 | 0.041 | 69 | 16.55 | 8 |
| **52 B** | | **0.0274** | **196.6** | **42.5** | **81.0** | | | | |
| **53 B** | | **0.0646** | **318.9** | **44.7** | **18.3** | | | | |
| 54 B | 8 | 0.2594 | 91.3 | 35.7 | 20.0 | 0.4622 | 82 | 0.92 | 21 |
| **55 B** | | **0.0652** | **187.8** | **34.5** | **49.5** | | | | |
| 56 B | 10 | 0.0284 | 92.3 | 44.2 | 297.6 | 0.0301 | 43 | 30.69 | 280 |
| 57 B | 42 | 0.1889 | 102.6 | 23.0 | 260.2 | 0.1974 | 86 | 58.94 | 253 |
| 58 B | 41 | 0.1099 | 13.2 | 36.5 | 19.4 | 0.1459 | 9 | 6.36 | 260 |
| 59 B | 40 | 0.1352 | 45.6 | 36.4 | 311.0 | 0.1586 | 37 | 33.47 | 266 |
| 60 B | 39 | 0.1734 | 123.5 | 45.8 | 345.6 | 0.1536 | 117 | 22.38 | 337 |
| 61 B | 22 | 0.0213 | 46.2 | 41.2 | 39.4 | 0.0031 | 48 | 57.57 | 52 |
| 62 B | 23 | 0.1234 | 92.0 | 44.0 | 87.4 | 0.1161 | 81 | 26.26 | 156 |
| 63 B | 24 | 0.0883 | 132.7 | 47.8 | 356.9 | 0.0897 | 129 | 39.05 | 12 |
| 64 B | 26 | 0.1879 | 149.6 | 36.5 | 359.0 | 0.1822 | 150 | 19.01 | 17 |
| | | | | | | | | | |
| Average | | 0.1350 | 110.3 | 34.3 | 212.0 | 0.1283 | 109 | 25.88 | 206 |
| Std Dev | | 0.0659 | 38.3 | 9.8 | 134.4 | 0.0779 | 52 | 15.72 | 101 |

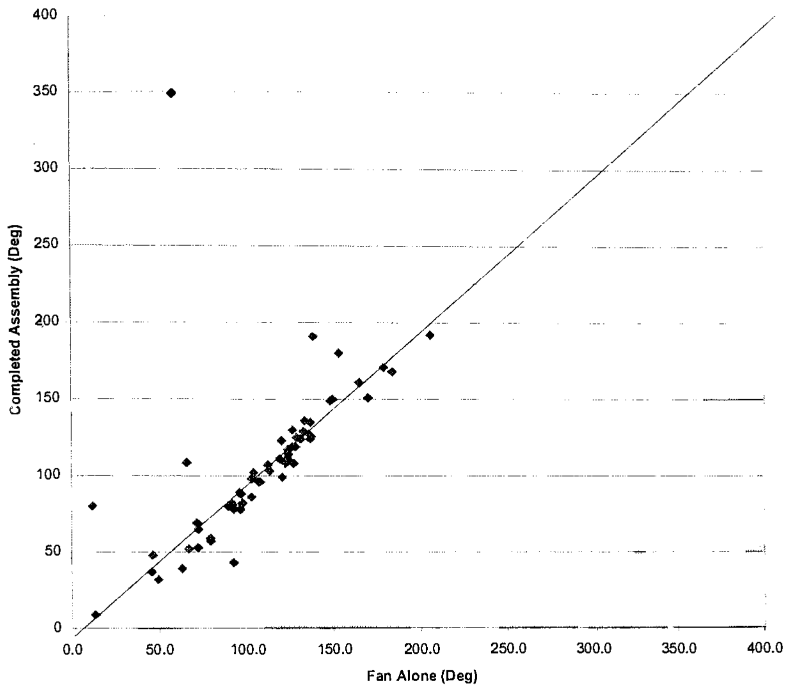
## Change in Static Unbalance ---- Cell 2



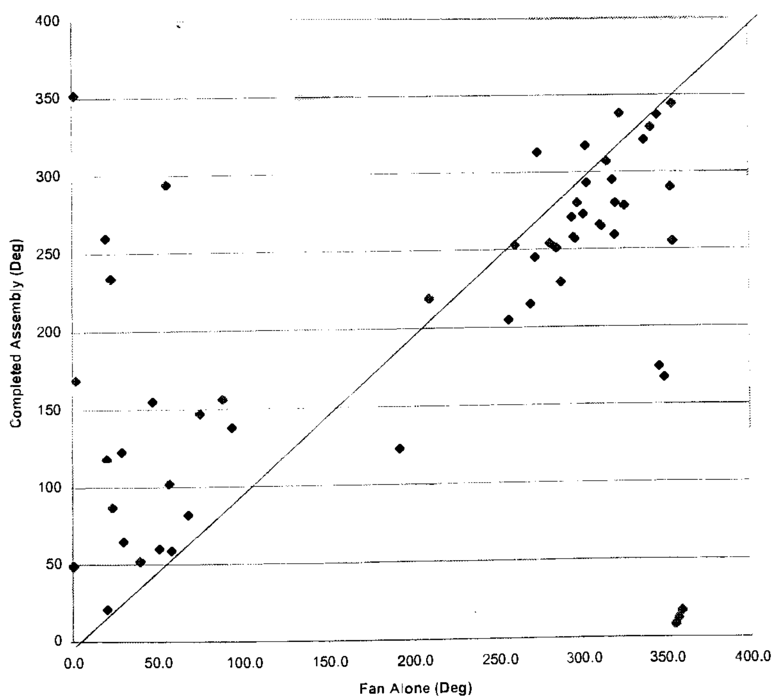

## Change in Couple Unbalance ---- Cell 2



## Change in Static Angle ---- Cell 2




## Change in Couple Angle ---- Cell 2



# Appendix D:
# Unbalance Caused by Assembly Secondary Study

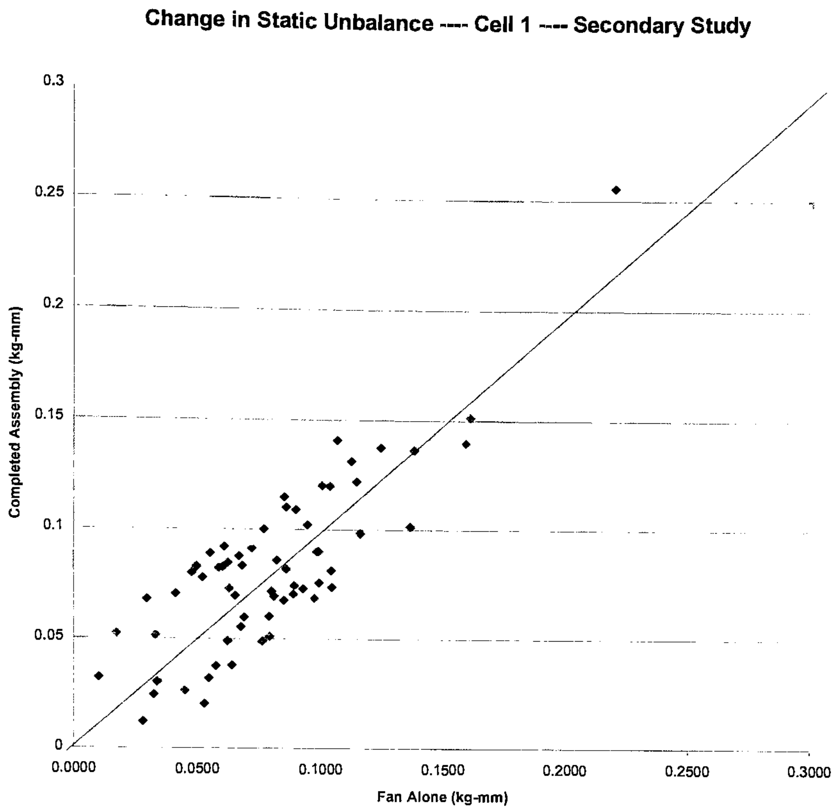
| Summary of Results Cell 1 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Fan Assembly Alone | | | | Fan and Shroud Assembly | | | |
| | Force | | Couple | | Force | | Couple | |
| | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle |
| Average | 0.0795 | 201.4 | 35.1813 | 123.9 | 0.0815 | 178.2 | 67.3567 | 151.4 |
| Std Dev | 0.0360 | 115.5 | 18.2388 | 71.2 | 0.0389 | 127.0 | 27.4113 | 37.9 |

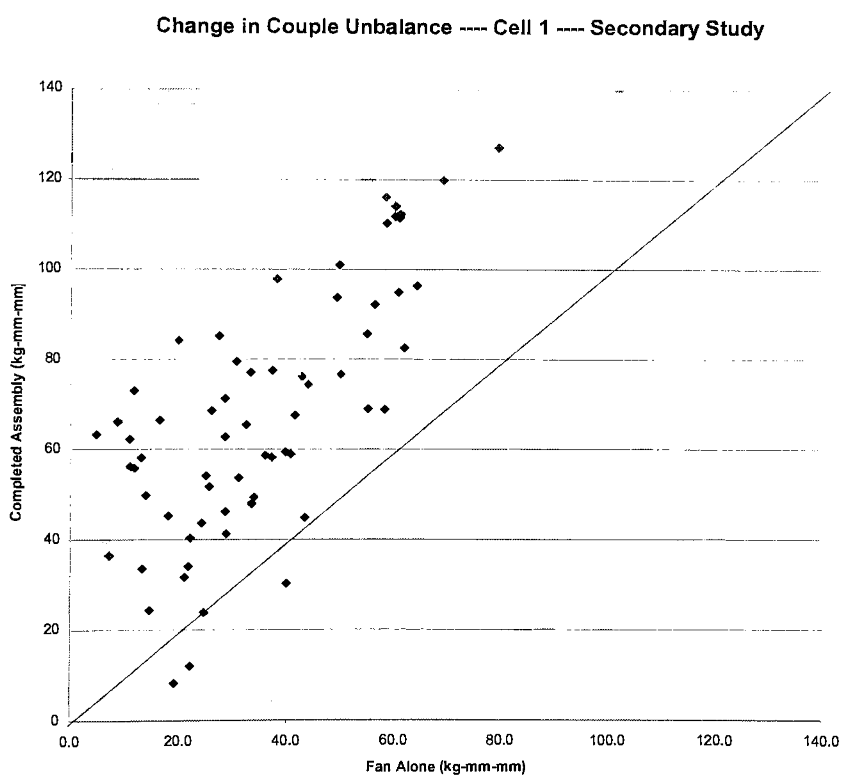
| | Calculation of Errors | | | |
|---|---|---|---|---|
| | Force | | Couple | |
| | Magnitude | Angle | Magnitude | Angle |
| Average | -0.0020 | 23.2 | -32.2 | -27.6 |
| Std Dev | 0.0222 | 107.7 | 18.9 | 48.8 |

Actual Study Data, Collected on 4/26/01, Cell 1

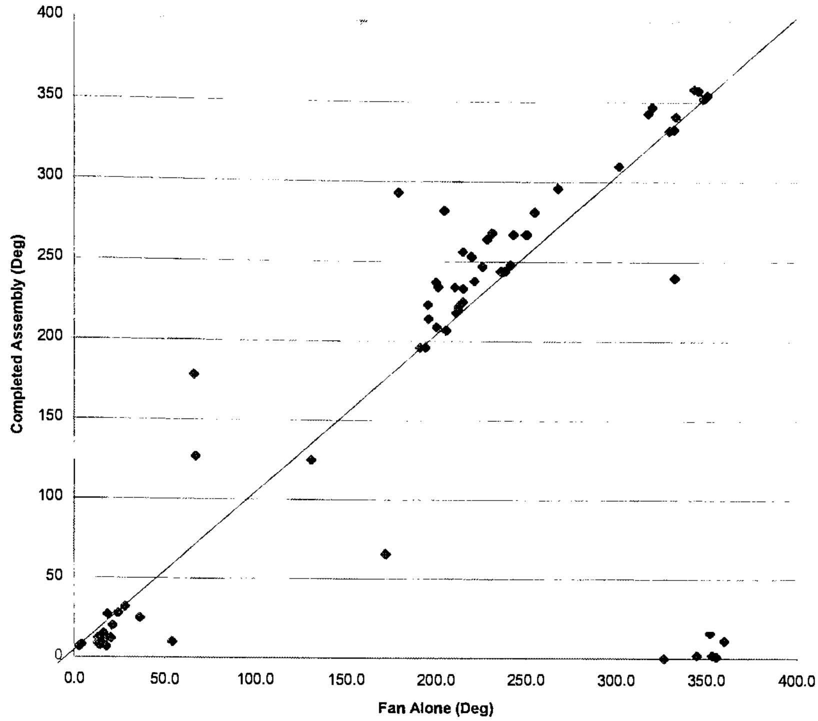
| Rack "A" | | | Testing was completed on cell #1 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4/2 6/0 1 | | | | | | | | | | |
| | | | Fan Assembly Alone | | | | Fan and Shroud Assembly | | | |
| | | | Force | | Couple | | Force | | Couple | |
| Number | | | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle | Magnitude | Angle |
| 1 | A | | 0.0944 | 2.8 | 55.2 | 139.2 | 0.1024 | 7 | 68.9 | 138 |
| 2 | A | | 0.0678 | 16.9 | 64.2 | 130.6 | 0.0835 | 12 | 96.4 | 128 |
| 3 | A | | 0.0668 | 36.2 | 28.5 | 199.2 | 0.088 | 25 | 62.8 | 184 |
| 4 | A | | 0.0847 | 225.3 | 40.0 | 55.5 | 0.0677 | 247 | 30.3 | 110 |
| 5 | A | | 0.1244 | 21.2 | 56.4 | 158.9 | 0.1378 | 20 | 92.2 | 164 |
| 6 | A | | 0.0990 | 212.0 | 28.8 | 56.4 | 0.0759 | 222 | 41.2 | 126 |
| 7 | A | | 0.1041 | 250.0 | 33.5 | 96.1 | 0.0814 | 267 | 47.9 | 165 |
| 8 | A | | 0.1378 | 237.8 | 21.1 | 84.6 | 0.1366 | 244 | 31.6 | 125 |
| 9 | A | | 0.0808 | 221.0 | 22.1 | 17.7 | 0.0695 | 238 | 12 | 166 |
| 10 | A | | 0.0327 | 54.0 | 13.0 | 98.3 | 0.0515 | 10 | 58.2 | 131 |
| 11 | A | | 0.0762 | 210.4 | 16.4 | 138.6 | 0.0492 | 218 | 66.4 | 164 |
| 12 | A | | 0.0600 | 17.8 | 11.7 | 22.6 | 0.0829 | 7 | 55.8 | 139 |
| 13 | A | | 0.0448 | 199.5 | 25.0 | 86.4 | 0.0263 | 237 | 54.1 | 125 |
| 14 | A | | 0.0621 | 230.8 | 42.7 | 84.5 | 0.049 | 268 | 76.2 | 128 |
| 15 | A | | 0.1143 | 18.5 | 58.2 | 164.0 | 0.1221 | 27 | 68.8 | 187 |
| 16 | A | | 0.1064 | 13.2 | 40.7 | 114.0 | 0.141 | 12 | 58.9 | 132 |
| 17 | A | | 0.0972 | 195.1 | 37.2 | 29.3 | 0.0688 | 223 | 58.2 | 99 |
| 18 | A | | 0.0639 | 178.6 | 10.9 | 92.1 | 0.0381 | 293 | 56.2 | 143 |
| 19 | A | | 0.1124 | 24.3 | 54.9 | 163.0 | 0.1313 | 28 | 85.6 | 169 |
| 20 | A | | 0.0895 | 28.0 | 33.2 | 165.0 | 0.1092 | 32 | 77.1 | 181 |
| 21 | A | | 0.0475 | 14.1 | 38.1 | 128.0 | 0.0803 | 8 | 97.9 | 135 |
| 22 | A | | 0.0761 | 205.2 | 14.6 | 4.2 | 0.0489 | 207 | 24.4 | 167 |
| 23 | A | | 0.0650 | 300.6 | 32.5 | 171.0 | 0.0697 | 310 | 65.5 | 179 |
| 24 | A | | 0.0790 | 199.8 | 21.8 | 52.3 | 0.0604 | 209 | 34.1 | 113 |
| 25 | A | | 0.0798 | 190.7 | 19.2 | 347.0 | 0.0718 | 196 | 8.33 | 348 |
| 26 | A | | 0.0410 | 349.1 | 30.6 | 168.0 | 0.0707 | 354 | 79.5 | 163 |
| 27 | A | | 0.0292 | 318.8 | 58.6 | 136.0 | 0.0681 | 347 | 110.3 | 140 |
| 28 | A | | 0.0099 | 344.3 | 7.1 | 232.0 | 0.0322 | 357 | 36.4 | 213 |
| 29 | A | | 0.1044 | 193.9 | 24.7 | 348.0 | 0.074 | 196 | 23.9 | 208 |
| 30 | A | | 0.0584 | 359.6 | 43.9 | 141.0 | 0.0824 | 11 | 74.4 | 161 |
| 31 | A | | 0.0855 | 16.4 | 58.4 | 136.0 | 0.1103 | 15 | 116.1 | 135 |
| 32 | A | | 0.1363 | 195.3 | 26.1 | 23.5 | 0.1017 | 214 | 68.6 | 116 |
| 33 | A | | 0.1610 | 235.6 | 43.4 | 67.0 | 0.1515 | 244 | 44.9 | 84 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 34 | A | | 0.0519 | 344.6 | 60.7 | 137.0 | 0.0781 | 2 | 94.9 | 166 |
| 35 | A | | 0.0335 | 130.5 | 28.6 | 243.0 | 0.0304 | 125 | 46.2 | 219 |
| 36 | A | | 0.0494 | 331.8 | 60.2 | 139.0 | 0.083 | 341 | 114.1 | 142 |
| 37 | A | | 0.0847 | 353.1 | 60.1 | 142.0 | 0.1148 | 2 | 111.8 | 150 |
| 38 | A | | 0.2197 | 328.4 | 27.4 | 78.9 | 0.2557 | 332 | 85.1 | 134 |
| 39 | A | | 0.0927 | 267.2 | 19.8 | 118.0 | 0.0732 | 296 | 84.2 | 191 |
| 40 | A | | 0.0890 | 254.1 | 61.1 | 111.0 | 0.0745 | 281 | 112.3 | 135 |
| 41 | A | | 0.0792 | 214.4 | 25.6 | 94.2 | 0.0512 | 225 | 51.7 | 157 |
| 42 | A | | 0.0528 | 200.7 | 4.6 | 317.0 | 0.0204 | 234 | 63.3 | 188 |
| 43 | A | | 0.0170 | 347.0 | 60.9 | 124.0 | 0.0523 | 352 | 111.5 | 125 |
| 44 | A | | 0.1158 | 211.8 | 10.8 | 155.0 | 0.0986 | 220 | 62.3 | 163 |
| 45 | A | | 0.0818 | 20.4 | 22.1 | 182.0 | 0.086 | 12 | 40.3 | 189 |
| 46 | A | | 0.0674 | 242.5 | 31.1 | 79.5 | 0.0557 | 267 | 53.7 | 138 |
| 47 | A | | 0.1590 | 331.7 | 41.4 | 97.7 | 0.1399 | 240 | 67.6 | 132 |
| 48 | A | | 0.1035 | 331.0 | 36.0 | 150.0 | 0.1199 | 333 | 58.6 | 135 |
| 49 | A | | 0.0606 | 13.0 | 49.3 | 172.0 | 0.0921 | 9 | 93.7 | 157 |
| 50 | A | | 0.0575 | 214.6 | 11.6 | 155.0 | 0.0377 | 256 | 72.9 | 169 |
| 51 | A | | 0.0321 | 204.1 | 18.0 | 25.7 | 0.0244 | 282 | 45.2 | 107 |
| 52 | A | | 0.0545 | 209.9 | 13.2 | 39.8 | 0.0321 | 234 | 33.6 | 141 |
| 53 | A | | 0.0621 | 316.7 | 37.2 | 124.0 | 0.0849 | 343 | 77.6 | 153 |
| 54 | A | | 0.0886 | 249.3 | 39.7 | 94.1 | 0.0706 | 267 | 59.4 | 121 |
| 55 | A | | 0.0766 | 342.0 | 50.0 | 129.0 | 0.1002 | 358 | 76.7 | 147 |
| 56 | A | | 0.0981 | 214.7 | 28.5 | 61.0 | 0.09 | 233 | 71.3 | 101 |
| 57 | A | | 0.0549 | 351.8 | 49.8 | 148.0 | 0.0892 | 16 | 101.1 | 168 |
| 58 | A | | 0.0688 | 219.5 | 33.9 | 44.4 | 0.0599 | 253 | 49.3 | 99 |
| 59 | A | | 0.0987 | 241.0 | 24.2 | 65.8 | 0.0902 | 248 | 43.7 | 114 |
| 60 | A | | 0.0627 | 326.5 | 69.2 | 163.0 | 0.0731 | 0 | 119.9 | 177 |
| 61 | A | | 0.0718 | 4.0 | 79.5 | 163.0 | 0.0915 | 8 | 127.2 | 155 |
| 62 | A | | 0.0857 | 228.0 | 8.6 | 32.9 | 0.082 | 264 | 66.1 | 142 |
| 63 | A | | 0.1002 | 355.3 | 61.9 | 158.0 | 0.1202 | 1 | 82.6 | 151 |
| 64 | A | | 0.0277 | 171.8 | 13.9 | 134.0 | 0.0121 | 66 | 49.8 | 160 |
| | | | | | | | | | | |
| Average | | | 0.0795 | 201.4 | 35.2 | 123.9 | 0.0815 | 178.2 | 67.4 | 151.4 |
| Std Dev | | | 0.0360 | 115.5 | 18.2 | 71.2 | 0.0389 | 127.0 | 27.4 | 37.9 |

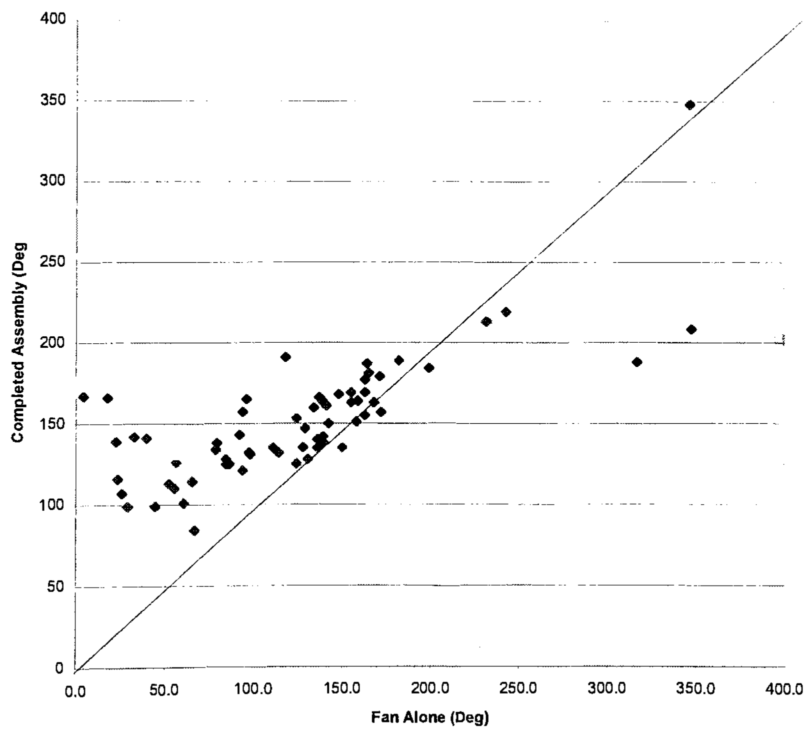

Change in Static Unbalance ---- Cell 1 ---- Secondary Study
Completed Assembly (kg-mm)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.0000
0.0500
0.1000
0.1500
0.2000
0.2500
0.3000
Fan Alone (kg-mm)


Change in Couple Unbalance ---- Cell 1 ---- Secondary Study
Completed Assembly (kg-mm-mm)
140
120
100
80
60
40
20
0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
Fan Alone (kg-mm-mm)

## Change in Static Angle ---- Cell 1 ---- Secondary Study




## Change in Couple Angle ---- Cell 1 ---- Secondary Study



# Appendix E:
# Algorithm Test Program

Algorithm Test Program

| | |
|---|---|
| Sample Size | 3 |

| | Initial Unbalance Readings of Samples | | | | Manually Corrected | | | |
|---|---|---|---|---|---|---|---|---|
| Sample # | Force | Force Angle | Couple | Couple Angle | Force | Force Angle | Couple | Couple Angle |
| 1 | 0.1512 | 212 | 9.68 | 172 | 0.0229 | 97 | 10.97 | 149 |
| 2 | 0.1064 | 184 | 11.71 | 194 | 0.0325 | 111 | 10.51 | 191 |
| 3 | 0.047 | 264 | 32.29 | 196 | 0.0396 | 196 | 11.9 | 265 |

| | Balancer Corrected | | | |
|---|---|---|---|---|
| Sample # | Force | Force Angle | Couple | Couple Angle |
| 1 | 0.0361 | 247 | 2.65 | 149 |
| 2 | 0.0393 | 303 | 5.91 | 228 |
| 3 | 0.031 | 183 | 7.29 | 265 |

Amount of Balls Used

| | Manually Corrected | | | Balancer Corrected | | |
|---|---|---|---|---|---|---|
| **Test** | **Large** | **Small** | **Total** | **Large** | **Small** | **Total** |
| 1 | 0 | 3 | 3 | 4 | 14 | 18 |
| 2 | 0 | 2 | 2 | 4 | 16 | 20 |
| 3 | 6 | 4 | 10 | 9 | 0 | 9 |
| **Average** | 2 | 3 | 5 | 5.7 | 10 | 15.7 |

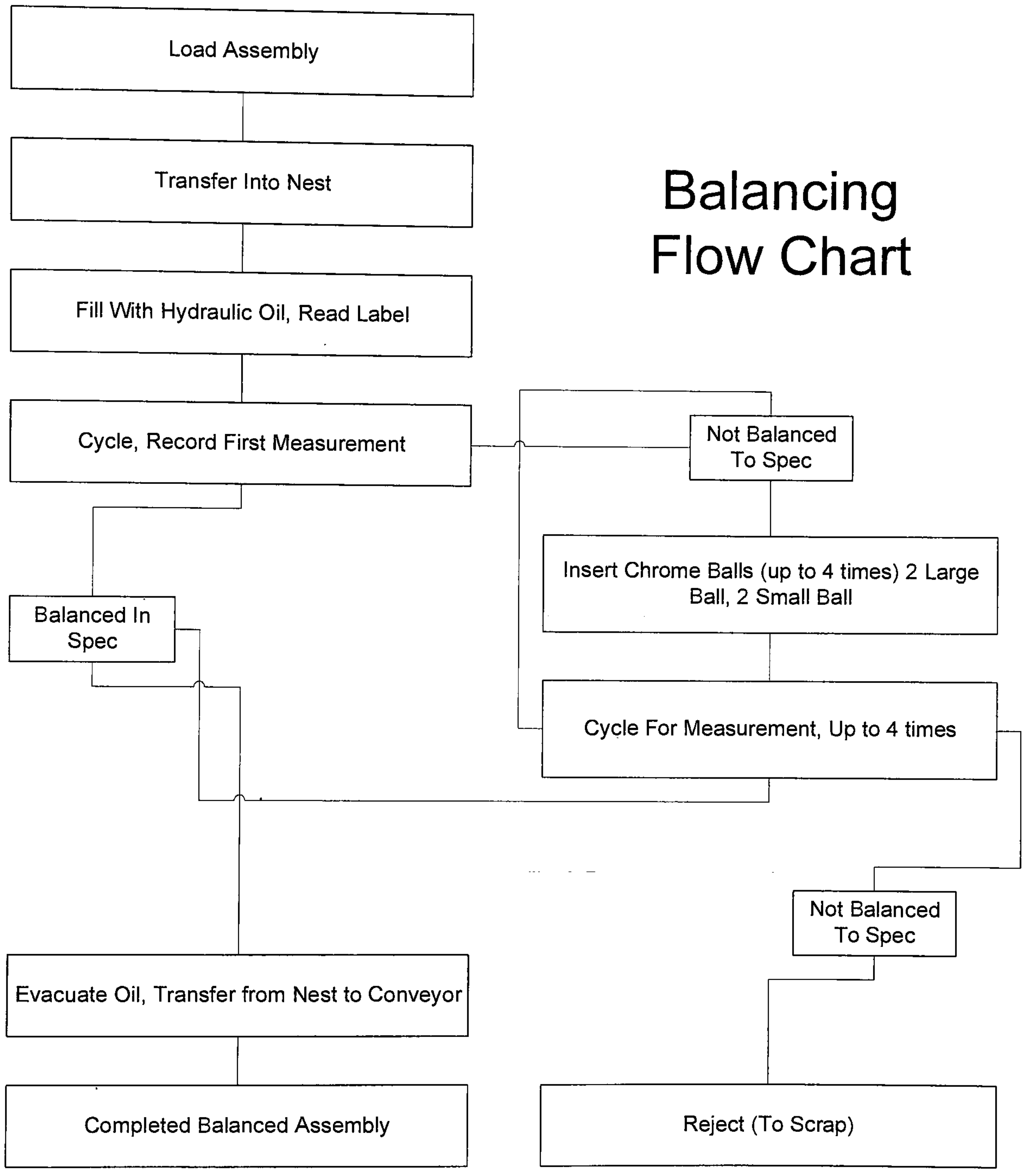
Mass Added

| | | |
|---|---|---|
| Weight of Large Ball | 4.431 | g |
| Weight of Small Ball | 0.683 | g |

| | Manually Corrected | | | Balancer Corrected | | |
|---|---|---|---|---|---|---|
| **Sample #** | **Large** | **Small** | **Total** | **Large** | **Small** | **Total** |
| 1 | 0 | 2.049 | 2.049 | 17.724 | 9.562 | 27.286 |
| 2 | 0 | 1.366 | 1.366 | 17.724 | 10.928 | 28.652 |
| 3 | 26.586 | 2.732 | 29.318 | 39.879 | 0 | 39.879 |
| **Average** | 8.862 | 2.049 | 10.911 | 25.1 | 7 | 31.9 |

This Data shows on average that the balancer uses about 10 more balls per assembly and 20 more grams of added weight to correct for the same unbalance.

## Appendix F:
## Balancer Flow Chart



# Appendix G:
# Balancing Cycle Times Study

| Balanced To: (kg-mm$^2$) Time (s) | | | | |
|---|---|---|---|---|
| Sample # | 48 | 36 | 24 | 12 |
| 1 | 102 | 134 | 200 | 163 |
| 2 | 75 | 142 | 133 | 132 |
| 3 | 96 | 232 | 219 | 164 |
| 4 | 69 | 16 | 173 | 114 |
| 5 | 132 | 72 | 48 | 111 |
| 6 | 41 | 241 | 107 | 184 |
| 7 | 76 | 154 | 139 | 168 |
| 8 | 140 | 83 | 195 | 155 |
| 9 | 135 | 209 | | 112 |
| 10 | 74 | 100 | 171 | 144 |
| 11 | 68 | 130 | 140 | 168 |
| 12 | 124 | 77 | 122 | 111 |
| 13 | 94 | 165 | 168 | 145 |
| 14 | 103 | 45 | 154 | 127 |
| 15 | 74 | 69 | 121 | 126 |
| 16 | 78 | 129 | 166 | 162 |
| 17 | 123 | 180 | 148 | 218 |
| 18 | 83 | | 147 | 146 |
| 19 | 46 | 70 | 42 | 145 |
| 20 | 146 | 69 | 113 | 127 |
| 21 | 84 | 121 | 79 | 243 |
| 22 | 78 | 195 | 44 | 122 |
| 23 | 107 | 157 | 103 | 119 |
| 24 | 175 | 133 | 126 | 112 |
| 25 | 160 | 102 | 172 | 147 |
| | | | | |
| Average | 99.3 | 126.0 | 134.6 | 146.6 |
| Stdev | 34.5 | 58.7 | 47.6 | 33.1 |

# Appendix H:
# Output of Potential Laser System

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Laser Balance Test Program | | | | | 04/0301 | | | |
| | | | | | | | | |
| Sample Size | | 3 | | | | | | |
| | | | | | | | | |
| | **Initial** | | | | **Final** | | | |
| **Test #** | **Force** | **Force Angle** | **Couple** | **Couple Angle** | **Force** | **Force Angle** | **Couple** | **Couple Angle** |
| 1 | 0.0834 | 341.4 | 19.6 | 126 | 0.0134 | 28.9 | 25.8 | 137 |
| 2 | 0.1112 | 334 | 9.5 | 80.3 | 0.014 | 165 | 15.1 | 99 |
| 3 | 0.1027 | 347.6 | 19.3 | 111.1 | 0.0349 | 356 | 20.6 | 131 |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | Distance from Center | 250 | mm | |
| | **Difference** | | | | | | | |
| **Test** | **Force** | **Force Angle** | **Couple** | **Couple Angle** | **Material Removed (grams)** | | **Burst Speed (rpm)** | |
| 1 | 0.0700 | 313 | -6.2 | -11 | 0.2800 | | 8100 | |
| 2 | 0.0972 | 169 | -5.6 | -19 | 0.3888 | | 8500 | |
| 3 | 0.0678 | -8 | -1.3 | -20 | 0.2712 | | 8000 | |
| | | | | | | | | |
| **Average** | 0.078333333 | 157.7 | -4.366666667 | -16.5 | 0.3133 | | 8200 | |
| | | | | | | | | |
| | | | | | | | | |
| **Test** | **Material Removed (g)** | **Corrected Unbalance (kg-mm)** | **Material To Be Added** | **Min Balls Required** | **Laser Time (seconds)** | **Balancer Time (seconds)** | | |
| 1 | 0.2800 | 0.0700 | 0.8537 | 2 | 6 | 17 | | |
| 2 | 0.3888 | 0.0972 | 1.1854 | 2 | 8 | 17 | | |
| 3 | 0.2712 | 0.0678 | 0.8268 | 2 | 5 | 17 | | |
| | | | | | | | | |
| | | | | | | | | |
| **Average** | 0.3133 | 0.0783 | 0.9553 | 2 | 6 | 17 | | |
| | | | | | | | | |
| | | | **Balancer** | | **Laser System** | | **Plastic Properties** | |
| | | | 12 | Measure (sec) | 1500 | Power (watts) | 1.38 | spec grav |
| | | | 2.5 | Insert Ball (sec) | 0.063 | depth (in) | 1 | $g/cm^3$ $h_20$ |
| | | | | | 1.167 | length (in/s) | 1.38 | $g/cm^3$ |
| | | | | | 0.010 | width (in) | | |
| | | | | | 0.002 | $in^3/s$ | | |
| | | | | | 0.036 | $cm^3/s$ | | |
| | | | | | | | | |
| | | | | | 0.049 | grams/s | | |

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