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**TITLE: Method and Apparatus for Analyzing Rotor Balance**



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**FIELD OF THE INVENTION**

The present invention relates generally to the field of dynamic balancing machines.

5 More particularly, the present invention relates to a noise tolerant balance analyzer with improved cycle time.

**BACKGROUND OF THE INVENTION**

A wide variety of machines use rotating shafts to carry loads and to transmit power. A rotating  
10 shaft supported by coaxial bearings, together with any attached mass, is called a rotor.

A dynamic force will occur if a rotor's center of mass is not located along its axis of rotation. This dynamic force can cause excessive lateral deflection, which reduces gear performance and bearing life. This dynamic force can also cause vibrations, which can lead to objectionable noise levels and can interfere with the operation of neighboring equipment. In addition, this dynamic force can increase the  
15 internal stresses acting on the rotor and on the bearings.

The magnitude of the dynamic force is:

$$\text{Force} = (\text{mass}) \times (\text{eccentricity}) \times (\text{angular speed})^2$$

where eccentricity is the distance between the center of mass and the axis of rotation. This force can be very significant in high speed machinery because it is proportional to the square of the rotor's  
20 rotational speed. The effect of this force will also be magnified if the shaft operates near its critical speed.

One method of reducing the dynamic force is to "balance" the shaft. Two major balancing methods currently exist. The first, called static balancing, is generally used for relatively short, low speed rotors. Static balance is obtained by adding and subtracting balancing weights until the rotor does not have any tendency to rotate around its horizontal axis when started from any initial position. Static balancing is simple, but cannot detect equal and opposite imbalances located at different points along the shaft. The second method, called dynamic balancing, can detect this condition. Dynamic balancing is generally accomplished by sensing the forces acting on the test subject when it is rotating at high speed. Weights are then added to or subtracted from the rotor at a definite radius in two different planes. These planes can be located anywhere, but are usually located near the ends of the rotor.

Conventional dynamic balancing machines rely on the phase lock loop ("PLL") method of detecting perturbations in the output of two radial force transducers to identify balance problems in rotatory machinery. One of the problems with this method is the time required to "lock on" to the balance signal after the transducer signals have settled. This interval is typically around three seconds. PLL machines also require an additional three seconds to collect a single data set after achieving a "lock on" condition. These two intervals increase the cycle time required to perform the balancing operation on a part during production mode, as measured from the start of one part to the start of the next part ("TAKT"). TAKT is significant because it affects the number of products that can be produced by a particular manufacturing line. Low TAKT is desired because a manufacturer can produce more goods on existing machinery.

External Noise ("EN") can affect the accuracy of the dynamic balancing procedure. EN is a vibration that comes from sources other than the rotor under test, such as personnel or objects moving

near the fixture, adjacent tools in the assembly line, or air disturbances from air handling or audio equipment. EN may also result from electrical interaction between the testing device and other nearby electrical equipment. One common method of reducing the effect of external noise is to take at least two separate measurements of the test subject. If the results from the tests agree with each other, no  
5 one external noise event occurred during the data collection sequence and the data collected is accurate. If the results disagree, however, an external noise event occurred during one of the data acquisition periods and new data will need to be collected. PLL machines are particularly hampered by EN because they must "lock" back onto the signal before they can acquire the new data, which results in a several second long delay. This drawback is magnified because the tolerated difference between  
10 the two data sets is typically set very small to maintain the overall precision of the system.

Clearly, there is a need for a balance analyzer that can produce accurate balance data in a short period of time. There is also a need for a balance analyzer that is more tolerant of noisy environments and that can recover from external noise events faster than a PLL-based machine can.

## SUMMARY

The present invention provides a method and apparatus for analyzing rotor balance that can quickly produce accurate balance data, that is tolerant of noisy environments, and that can recover quickly after an EN event. The present invention eliminates the need for a PLL analyzer by using a real time, high speed digital signal processor and/or computer that is synchronized to the rotation of the  
20 rotor. Sensors generate signals indicative of the position and of the dynamic force generated by the rotating test subject. A digital signal processor, such as a computer, collects the data produced by the

sensors during a plurality of test subject rotations. The computer uses the information collected to determine the average period of rotation. The computer also creates an array containing values indicative of the average dynamic force exerted when the test subject is in a particular orientation. These values are related to the location and the mass of the rotor balance.

5           One aspect of the present invention is a method and apparatus for analyzing shaft balance. One embodiment of the apparatus comprises: at least one sensor that produces an analog signal relating to a test subject; an analog-to-digital converter connected to the at least one sensor that converts the analog signal to a digital signal; and a computer connected to the analog-to-digital converter that provides information related to the shaft imbalance of the test subject. One embodiment of the method  
10       comprises the acts of generating a first analog signal indicative of a position of a rotating test object; generating a second analog signal indicative of a dynamic force generated by a rotating test object; digitizing the first and second analog signals; and calculating information related to the shaft imbalance based on the digitized signals.

          Another aspect of the present invention is a balance analyzer. One embodiment of this balance  
15       analyzer comprises at least one first sensor, operatively connected to a test subject, that produces a signal indicative of a dynamic force produced by the test subject; at least one second sensor, operatively connected to the test subject, that produces a signal indicative of an orientation of the test subject; and a digital signal processor, operatively connected to at least one first sensor and to the at least one second sensor, that calculates information indicative of an imbalanced mass associated with  
20       the test subject.

Yet another aspect of the present invention is a computer usable medium having computer readable program code embodied therein for analyzing shaft balance. One embodiment of the computer readable program code comprises a computer readable program code that causes a computer to sample at least one electrical signal indicative of a dynamic force exerted on a test fixture by a rotating test subject; a computer readable program code that causes the computer to sample an electrical signal indicative of a position of the rotating test subject; and a computer readable program code that causes the computer to calculate information indicative of an imbalanced mass associated with the test subject.

Still another aspect of the present invention is a method of analyzing shaft balance. One embodiment comprises the act of generating at least one first signal indicative of a dynamic force generated by a test subject; generating a second signal indicative of an orientation of the test subject; providing at least one first signal and the second signal to a digital signal processor; and digitally processing at least one first signal and the second signal to obtain a digital code that contains information about the test subject. This embodiment may further comprise the act of calculating a magnitude and a phase angle indicative of the dynamic force using the digital code.

One feature and advantage of the present invention is that it can provide a more accurate mass and location information about the imbalanced mass using time and amplitude-normalization techniques. Yet another feature and advantage is that the present invention can compensate for variation in testing conditions, which would cause inaccuracy and/or increased cycle times in a PLL system. Still another feature and advantage of the present invention is a position sensor that is physically synchronized to one particular location on the device under test, which allows the present invention to detect actual

rotation speed, and to begin sampling and processing data during the first rotation after the signals stabilize. These and other features, aspects, and advantages of the present invention will become better understood with reference to the following description, appended claims, and accompanying drawings.

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### **BRIEF DESCRIPTION OF THE DRAWINGS**

Figure 1A is a side view of the balance fixture with attached analyzer.

Figure 1B is an end view of the balance fixture with attached analyzer.

Figure 2 is a flow chart that depicts one testing procedure

Figure 3 is a flow chart of a vectorial algorithm program.

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### **DETAILED DESCRIPTION**

Figs. 1A and 1B show one embodiment of an apparatus for analyzing shaft balance 10. Fig.

1A shows a balance fixture 11 with a test subject 12, a spindle or stator 14, a rigid frame 18, a top cantilever 20, and a bottom cantilever 22. Fig. 1B shows a top balance sensor/transducer 24, a bottom balance sensor/transducer 26, an index pulse sensor/transducer 28, and an index mark 30. Electrical data signals 32, 34, and 36 travel between the balance fixture 11 and a digital signal processor, such as a programmed general purpose computer 37, on electrical wires. The computer 37 contains and executes a vectorial algorithm program 38 and an analyzer program 40.

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In operation, the test subject 12 is first placed between the cantilevers 20, 22 and is accelerated to a high angular velocity. After this "spin-up" step, the transducers 24, 26, and 28 produce electrical signals 32, 34, and 36 indicative of the magnitude and position of the imbalanced mass (if any). The

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vectorial algorithm program 38 and the analyzer program 40 use these signals 32, 34, and 36 to compute a mass and location to add and/or subtract to the test subject 12. This computed mass and location will cancel the effect of the imbalanced mass.

The top balance transducer 24 in this embodiment is positioned near (or mounted to) the top cantilever 20 and produces an analog electrical signal 32 indicative of a dynamic force produced by the test subject 12. Specifically, the transducer 24 in this embodiment will measure a radial force (i.e., perpendicular to the test subject's axis of rotation) transmitted by the test subject 12 to the top cantilever 20. The output of the transducer 24 will be a sinusoidal waveform occurring at a frequency equal to the rotational speed of the test subject 12. The bottom balance transducer 26 is similarly positioned near (or mounted on) the bottom cantilever 22. It similarly produces an analog electrical signal indicative of the dynamic, radial force transmitted to the bottom cantilever 22 by the test subject 12. Accordingly, the top balance transducer 24 and the bottom analog transducer 26 can be any device or combination of devices capable of measuring the force (or the resulting position, velocity, and/or acceleration) generated by the rotating test subject over the range of possible test frequencies. Examples of appropriate sensors include, but are not limited to: strain gauges, piezoelectric transducers, and accelerometers. Sensors that directly produce a digital output signal are also within the scope of the present invention.

The index pulse transducer 28 in this embodiment is mounted to the balance fixture 11 adjacent to the path of the index mark 30 that is physically located on the test subject 12. The transducer 28 produces an electrical pulse signal 36 each time the index mark 30 passes by or near it. Accordingly, the index pulse transducer 28 can be any device capable of detecting the index mark 30 and producing

pulse signal 36 at test speed frequencies. Examples of appropriate devices include, but are not limited to: Hall effect sensors, optical-electric sensors, and electrical contact sensors. In addition, although the embodiment shown in Figs. 1A and 1B only uses one index mark 30, additional index marks 30 can be used if the transducer 28 is capable of operating at the resulting frequency.

5           The computer 37 in this embodiment comprises an analog-to-digital ("A/D") card that periodically samples the signals 32, 34, and 36 and produces one or more first digital codes indicative of the magnitude of each signal 32, 34, and 36. As will be discussed in more detail with reference to Figs. 2-3, these digital codes are used by the central processor of the computer to produce one or more second digital codes indicative of the magnitude and location of the imbalance. Accordingly, the  
10       computer 37 and the A/D converter together act as a digital signal processor. In addition, the A/D card may include a second digital processor that is specially adapted to perform calculations on the first and second digital codes, which may be particularly desirable for test procedures requiring high sampling rates. Appropriate computers, A/D converters, and digital processors are well known and widely available in the art.

15           Fig. 2 is a flow chart that depicts one testing procedure. At block 100, the test cycle begins when an operator clamps the test subject 12 and the spindle 14 to the balance fixture 11. The test subject 12 in this embodiment is then accelerated (at block 102) to a testing speed by an electrical (or air, steam, etc.) motor (not shown). This testing speed is arbitrary, but should be a predetermined fraction of the test subject's expected operating speed. It is preferable to avoid taking data during the  
20       spin-up phase 102 due to rotational noise ("RN"). Rotational noise is variation in the transducer signals

that results from the RPM changing as the rotor goes to full test speed. During spin up of the rotor, RN is very high and any data collected will not be sufficiently accurate.

After the test subject 12 has reached a testing speed at block 104, the analyzer 10 waits at for the transducer signals 32, 34 to settle. The total settle time ("TST") for the analyzer 10 includes the time needed by the mechanical fixtures to reestablish a steady state motion after a disturbance by noise (fixture "damping time") and the time necessary for the transducers 24 and 26 reach steady state after a noise event (transducer "settle time"). TST also includes an analyzer settle time ("analyzer settle time"), measured from the point when the transducer signals are stable to when they are synchronized and data acquisition starts. However, this time can generally be ignored under most operating conditions. As described in more detail below, the embodiment in Figs. 1A and 1B begins collecting synchronized data (block 108) when it receives the first index pulse 36 (block 106) after the fixture and transducer have settled. Accordingly, the analyzer settle time for the embodiment is, on the average, equal to one half of a revolution. One half of a revolution takes 3.9 milliseconds at 7620 RPM, which is negligible when compared than total acquisition time for either the preferred embodiment or a PLL analyzer.

The data acquisition time ("ACU") is the time required to generate values for the signal's amplitude and phase once the signal has settled. The data collected during each ACU period is sent to the vectorial algorithm program 38. At block 112, the vectorial algorithm program 38 calculates the magnitude and phase of the sine wave signals from the transducers 24 and 26 using the sampled data points. Determining the amount and angular location of the necessary balance weight(s) requires the calculation and application of four variables: A, B, Ph1 and Ph2. "A" and "Ph1" represent the amplitude and phase of the sinusoidal balance signal from the top transducer 24 in Fig. 1B. "B" and

"Ph2" are the amplitude and phase of the sinusoidal balance from the bottom transducer 26 in Fig. 1B. The phase of each balance signal is measured relative to the index pulse signal 36 that occurs once per revolution of the rotor. The embodiment shown in Figs. 1A and 1B obtains values for A, B, Ph1, and Ph2 without a PLL by taking advantage of high speed digital signal processing capabilities, cheaply available in today's computers.

Once accurate and precise values for A, B, Ph1, and Ph2 are obtained, the analyzer program 40 calculates, at block 114, the balance weight's amount and angular location. The details of this well-known calculation are described in J.N. Macduff and J.R. Curren, Vibration Control 222-240 (McGraw-Hill Book Company, Inc. 1958), in R.L. Maxwell, Kinematics and Dynamics of Machinery 350-355 (Prentice Hall, Inc. 1960), and in N.O. Myklestad, Fundamentals of Vibration Analysis 226-230 (McGraw-Hill Book Company, Inc. 1956), which are each herein incorporated by reference. When the calculated balance weights are added at the calculated angle of installation, a balanced rotor is obtained. In some cases, only one weight is added rather than two. In other cases, a weight is subtracted rather than added to obtain balance. After weight is added or subtracted, the balance analyzer 10 can be used to confirm that the rotor is balanced and within specifications.

Fig. 3 is a flow chart of the vectorial algorithm program 38. At block 50, the vectorial algorithm program 38 is given the total number of samples to be taken. At block 52, the top and bottom transducer outputs 32 and 34 are sampled in digital form simultaneously with the state of the index pulse 36. At block 54, these acts are repeated until the vectorial algorithm program 38 obtains the predetermined number of samples.

The analyzer 10 embodiment in Fig. 1-3 initially stores the data from signals 32, 34, and 36 in real time without regard to synchronization to rotor rotation (synchronization will be done later). In this embodiment, the three signals are each sampled about every 1/360th of a revolution. This embodiment will continue sampling the three signals for 0.5 seconds (approximately 50 revolutions at 6000 RPM).  
 5 Accordingly, the computer's memory will contain approximately 18,000 values at the end of sampling.

The data acquisition (referenced in blocks 52-54) starts at the first index pulse 36 after the transducers and mechanical fixtures settle. At block 56, the number of periods observed in the sample period is determined from the number of index pulse signals 36 observed. Specifically, in this embodiment, the number of transducer periods observed during the test, "n," is equal the number of  
 10 index pulse signals observed minus one (typically  $n=49$ , for the example being used). At block 58, the analyzer then determines the number of samples from each transducer signal taken during the n periods and sets it equal to "k." The time required to obtain the n periods, called "T," is calculated from the sample rate and the number of samples taken. The average period from one index to the next index is then calculated by dividing T by n (i.e.,  $T/n$ ). Because the index signal 36 is directly related to the  
 15 rotor's position,  $T/n$  is the average period for one rotation during the sampling event. At block 60, the computer 37 calculates the average number of samples per period by dividing k by n (i.e.,  $k/n$ ). At block 62, this computed  $k/n$  value is rounded or truncated to an integer and is assigned the variable name "m."

The next act in the data acquisition process, referenced in block 64, is to average, point-by-  
 20 point from the index pulse 36, the "n" (~49) wave forms from the top transducer and the "n" (~49) wave forms from the bottom transducer. The averaging for each cycle starts with its first sampled value

after each index pulse 36. This provides direct synchronization of the data to the rotation of the rotor on a revolution by revolution basis. The sampled point averaging continues for  $m$  points (until the average period of  $T/n$  is reached). The result is an array,  $V_i$ , for each balance signal representing an average waveform that is one average cycle long. That is, the computer 37 computes the average of the first sampled value 32, 34 after each index pulse 36 and stores the computed average in  $V_i[1]$ . The computer then computes the average of the second sampled value 32, 34 after each index pulse 36 and stores the computed average in  $V_i[2]$ . The computer repeats this process until it computes the average of the " $m$ -th" sampled value after each index pulse 36 and stores the computed average in  $V_i[m]$ . The parameters  $A$ ,  $B$ ,  $Ph1$ , and  $Ph2$  are then calculated from these averaged signals.

In some embodiments, the point-by-point averaging technique can be supplemented by an interpolation technique. In these embodiments, for example,  $V_i[1]$  may contain the average value that the transducers would have measured had the sampling point occurred when the rotor had turned exactly one degree from the index point.  $V_i[2]$  may contain the average value that the transducers would have measured had the sampling point occurred when the rotor had turned exactly one degree from the index point. The actual values used to compute  $V_i[1]$  and  $V_i[2]$  are linearly interpolated from the closest sampled points. These embodiments may be desirable because they may require a smaller data set.

At block 66, the peak magnitude ( $A$  or  $B$ ) is calculated as the root-mean square ("RMS") of all the values in the average wave form  $V_i$  times 1.414. At block 68, the phase ( $Ph1$  or  $Ph2$ ) calculation begins by determining the positive peak location in the averaged sample array of  $m$  values. The value,

$p$ , is the location in the array of  $m$  values, of the positive peak of the sine wave. Using just the positive values of the sine wave,  $v_i$ , the location is calculated using the following equation:

$$p = \frac{\sum_{i=1}^m [v_i * i]}{\sum_{i=1}^m [v_i]}$$

To get the phase (in degrees),  $p$  is multiplied by  $360/m$  and then 90 degrees are subtracted. Those skilled in the art will recognize that other calculations of phase (not presented here) are possible that include the negative peaks or both negative and positive data from  $V_i$ . This completes the acts that this embodiment requires for data acquisition. At block 70, the vectorial algorithm embodiment 38 then outputs the magnitude and phase of both transducer signals to the analyzer program 40.

The previously described embodiments of the present invention have many advantages over the prior art, including: improved accuracy, lower TAKT, and improved noise tolerance. One way that accuracy is increased is through amplitude normalization. The actual RPM of the rotor often drifts both 0.2% higher and 0.2% lower than the desired rotor drive speed. Because the balance signal is proportional to the square of the rotational speed, a total RPM drift of 0.4% (i.e.,  $\pm 0.2\%$ ) results in a 0.8% variation in the balance signal. The uncertainty resulting from this variation is further magnified because the transducer signal is frequently used to calibrate the fixture prior to using it for balancing. Thus, the total uncertainty resulting from the RPM drift will equal 1.414 times 0.8% or 1.1% (i.e., the

RMS of the variation during calibration and the variation during balance testing). The present invention can compensate for this variation because the multiplying the sampled data values by:

$$(RPM_{nom} / RPM_{act})^2$$

5 where the actual RPM can be computed by multiplying the number of samples between index pulses 36 by the sampling frequency and where the nominal RPM during the test period is known from the value of T/n. Accordingly, during both the calibration mode and the balance mode of the disclosed embodiment, each signal amplitude (A and B) is normalized to the value it would have been had the drift not occurred (i.e., at 6000 RPM in the example previously provided). Those skilled in the art will  
10 recognize that this calculation may be done during ACQ by a sufficiently fast multitasking computer 37 and/or after ACQ is complete.

Another way the present invention improves accuracy is by using time normalization. As previously described, the vectorial algorithm program 38 computes the values for  $V_i$  in a point-by-point manner, which allows fast cycles to cancel slow cycles. That is, some of the cycles during the sampling  
15 period will be faster than the nominal RPM and some will be slower. Accordingly, the "j-th" sampled data point in a fast cycle will represent a slightly different position than the "j-th" sampled data point in a slow cycle. However, because there are an equivalent number of fast and slow cycles, these variations will cancel each other during the averaging process. Thus,  $V_i$  will contain data indicative of what would have occurred had the RPM drift not occurred.

20 These averaging and normalization procedures allow the present invention to account for revolution-to-revolution variations in the spindle speed during test by time-normalizing the data to the

nominal RPM, which greatly reduces the 1.1% variation in accuracy expected when the exact RPM is not known during sampling of the transducer signals. More accurate amplitude and phase information is desirable because it yields, upon analysis, more accurate mass and loci for addition/subtraction of mass, which allows the present invention to produce a more perfectly balanced spindle. In addition, although the averaging and normalization techniques were discussed with reference to RPM drift variation, their benefits will also apply to any other source of random variation, such as signal noise, sampling errors, or transducer imprecision.

The following example illustrates this invention's TAKT advantage over a PLL method processor. Each balance fixture in the example is assumed to have identical fixtures and to be used in a similar manner. It is also assumed that both methods used fixtures that have a damping time of 0.2 seconds to reestablish steady state signals after a disturbance by noise. It is further assumed that both methods will use two ACU periods to check for the presence of EN after spin up. In a situation where no EN noise is present, the typical TAKT sequences are illustrated below:

|    |              | PLL        | Disclosed Embodiment |                      |
|----|--------------|------------|----------------------|----------------------|
| 15 | Load part    | 2.0 Sec    | 2.0 Sec              |                      |
|    | Spin Up (RN) | 8.0        | 8.0                  |                      |
|    | TST          | 3.2        | 0.2                  |                      |
|    | ACU          | 3.0        | 0.5                  |                      |
|    | ACU          | 3.0        | 0.5                  |                      |
| 20 | Spin Down    | 5.0        | 5.0                  |                      |
|    | Unload part  | <u>2.0</u> | <u>2.0</u>           |                      |
|    | TAKT time    | 26.2 Sec   | 18.2 Sec             | (difference = 8 Sec) |

25 The TAKT required for one EN event is illustrated below:

|    |              | PLL        | Disclosed Embodiment           |
|----|--------------|------------|--------------------------------|
|    | Load part    | 2.0 Sec    | 2.0 Sec                        |
|    | Spin Up (RN) | 8.0        | 8.0                            |
|    | TST          | 3.2        | 0.2                            |
| 5  | ACU          | 3.0        | 0.5                            |
|    | ACU          | 3.0        | 0.5                            |
|    | (assumed EN) |            |                                |
|    | TST          | 3.2        | 0.2                            |
|    | ACU          | 3.0        | 0.5                            |
| 10 | ACU          | 3.0        | 0.5                            |
|    | Spin down    | 5.0        | 5.0                            |
|    | Unload part  | <u>2.0</u> | <u>2.0</u>                     |
|    | TAKT time    | 35.4 Sec   | 19.4 Sec (difference = 16 Sec) |

15 One reason for the improved TAKT is the digital signal processor's ability to begin analyzing data immediately after receiving stable signals. Unlike a PLL system, this embodiment does not need to "lock on" after the spin-up period or after an EN event. Another reason for the improved TAKT is the higher bandwidth allowed by a digital signal processor. Additional EN events will result in an even

20 greater TAKT advantage over the PLL method. These TAKT savings are particularly significant during high volume production where time saved is money saved.

The disclosed embodiment also has improved tolerance for noisy environments. This improvement is primarily the result of the lower ACU time. A machine is less likely to experience a transient external noise events when ACU only lasts 0.5 seconds than when ACU lasts three seconds.

25 As shown above, the faster ACU also reduces the time required to obtain new data if EN taints the original data.

Although the present invention has been described in considerable detail with reference to certain preferred embodiments thereof, variations are possible. For example, the parameters provided

in this disclosure were only intended to illustrate the general concept and can be altered consistent with the invention. This specifically includes, but is not limited to, changing the sampling rate, the test speeds, the sampling size, and the sampling rate. This invention could also be combined with a filter to attenuate non-transient noise and/or noise whose frequency differs significantly from the testing conditions.

5           Accordingly, those skilled in the art will recognize that the accompanying figures and this description depicted and described embodiments of the present invention, and features and components thereof. With regard to means for fastening, mounting, attaching or connecting the components of the present invention to form the mechanism as a whole, unless specifically described otherwise, such means were intended to encompass conventional fasteners such as machine screws, nut and bolt  
10 connectors, machine threaded connectors, snap rings, screw clamps, rivets, nuts and bolts, toggles, pins and the like. Components may also be connected by welding, friction fitting, adhesives, or deformation, if appropriate. Unless specifically otherwise disclosed or taught, materials for making components of the present invention were selected from appropriate materials, such as metal, metallic alloys, fibers, polymers and the like, and appropriate manufacturing or production methods including casting,  
15 extruding, molding and machining may be used. In addition, any references to front and back, right and left, top and bottom and upper and lower were intended for convenience of description, not to limit the present invention or its components to any one positional or spacial orientation. Therefore, it is desired that the embodiments described herein be considered in all respects as illustrative, not restrictive, and that reference be made to the appended claims for determining the scope of the invention.

## Claims

1. A method of analyzing shaft balance, comprising:  
generating at least one first signal indicative of a dynamic force generated by a  
5 test subject;  
generating at least one second signal indicative of an orientation of the test  
subject;  
providing the at least one first signal and the at least one second signal to a  
digital signal processor; and  
10 digitally processing the at least one first signal and the at least one second signal  
to obtain a digital code that contains information about the test subject, the digital  
processing including sampling the at least one first signal and the at least one second  
signal, and producing a synchronized array of first data points and second data points;  
and  
15 digitally processing the synchronized array of first data points and second data  
points to produce a second digital code that contains information about an average  
signal and that compensates for rotational speed drift.
2. A method of analyzing shaft balance, comprising:  
generating at least one first signal indicative of a dynamic force generated by a  
20 test subject;  
generating at least one second signal indicative of an orientation of the test  
subject;  
providing the at least one first signal and the at least one second signal to a  
digital signal processor;

digitally processing the at least one first signal and the at least one second signal to obtain a digital code that contains information about the test subject, the digital processing including sampling the at least one first signal and the at least one second signal to produce a synchronized array of first data points and second data points; and

5       digitally processing the synchronized array of first data points and second data points to produce a second digital code that contains information about an average signal and that compensates for external noise.

3.       The method of claim 1, further comprising calculating a magnitude and a phase angle indicative of the dynamic force using the digital code.

10       4.       The method of claim 3, further comprising determining a mass and a location for a balance weight using the magnitude and the phase angle.

5.       The method of claim 4, wherein the balance weight reduces the dynamic force generated by the test subject.

6.       The method of claim 1, wherein the second signal is an index pulse.

15       7.       The method of claim 1, wherein the first signal is a radial force.

8.       The method of claim 1, further comprising calculating a number of periods observed using the digital code.

9.       The method of claim 1, wherein the information about the test subject is an average dynamic force.

20       10.       The method of claim 1, wherein the act of digitally processing at least the one first signal and the at least one second signal comprises:

calculating an actual rotational speed;

calculating a nominal rotational speed; and

digitally processing the at least one first signal to compensate for a difference between the actual rotational speed and the nominal rotational speed.

11. The method of claim 10, wherein the act of compensating for the difference between the actual rotational speed and the nominal rotational speed  
5 comprises:

multiplying an actual sampled data point by a conversion factor, wherein the conversion factor is related to square of a ratio of the nominal rotational speed and the actual rotational speed.

12. The method of claim 1, wherein the sampling begins after a first full  
10 period of a stable rotation of the test subject.

13. The method of claim 1, wherein the digital signal processor is a computer.

14. The method of claim 2, further comprising calculating a magnitude and a phase angle indicative of the dynamic force using the digital code.

15 15. The method of claim 14, further comprising determining a mass and a location for a balance weight using the magnitude and the phase angle.

16. The method of claim 15, wherein the balance weight reduces the dynamic force generated by the test subject.

17. The method of claim 2, wherein the second signal is an index pulse.

20 18. The method of claim 2, wherein the first signal is a radial force.

19. The method of claim 2, further comprising calculating a number of periods observed using the digital code.

20. The method of claim 2, wherein the information about the test subject is an average dynamic force.

21. The method of claim 2, wherein the act of digitally processing the at least one first signal and the at least one second signal comprises:

calculating an actual rotational speed;

calculating a nominal rotational speed; and

5       digitally processing the at least one first signal to compensate for a difference between the actual rotational speed and the nominal rotational speed.

22. The method of claim 21, wherein the act of compensating for the difference between the actual rotational speed and the nominal rotational speed comprises:

10       multiplying an actual sampled data point by a conversion factor, wherein the conversion factor is related to square of a ratio of the nominal rotational speed and the actual rotational speed.

23. The method of claim 2, wherein the sampling begins after a first full period of a stable rotation of the test subject.

15       24. The method of claim 2, wherein the digital signal processor is a computer.