(12) **United States Patent**
Das et al.

(10) **Patent No.:** US 12,332,136 B2
(45) **Date of Patent:** Jun. 17, 2025

(54) **METHOD FOR DETERMINING A MAGNITUDE OF A MASS TO BE PLACED ON A WHEEL ASSEMBLY USING ACCELERATION DATA**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **18/400,543**

(22) Filed: **Dec. 29, 2023**

(65) **Prior Publication Data**

US 2025/0172450 A1 May 29, 2025

Related U.S. Application Data

(60) Provisional application No. 63/603,221, filed on Nov. 28, 2023.

(51) **Int. Cl.**
G01M 1/32 (2006.01)
G01M 1/22 (2006.01)

(52) **U.S. Cl.**
CPC *G01M 1/326* (2013.01); *G01M 1/225* (2013.01)

(58) **Field of Classification Search**
CPC G01M 1/225; G01M 1/28; G01M 1/336
See application file for complete search history.

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(57) **ABSTRACT**

A method is provided for determining a magnitude of a mass to be placed on a wheel assembly using data from one or more inertial measurement units (IMU's). The one or more IMU's are mounted to a removably attachable object that is attached to a wheel of the vehicle in a manner that inhibits the object from coming off of the vehicle when the vehicle is in motion. Each of the IMU's include an accelerometer. A set of acceleration data is collected from the one or more IMU's while the vehicle is in motion. The acceleration data is applied to a predictive model to determine the magnitude of the mass.

4 Claims, 18 Drawing Sheets
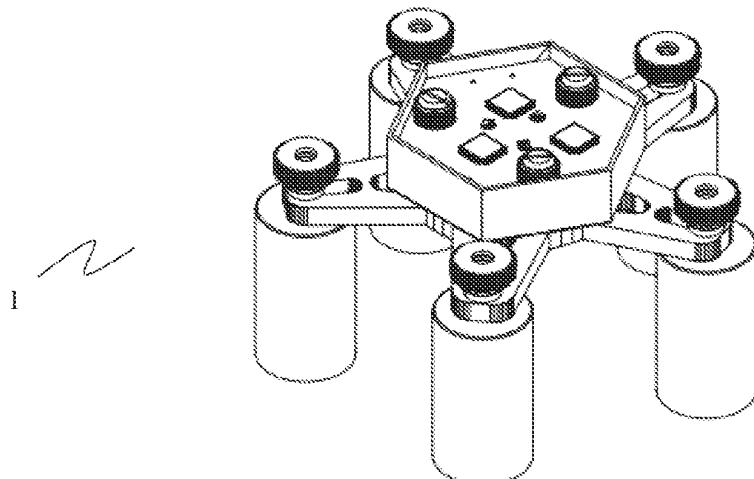
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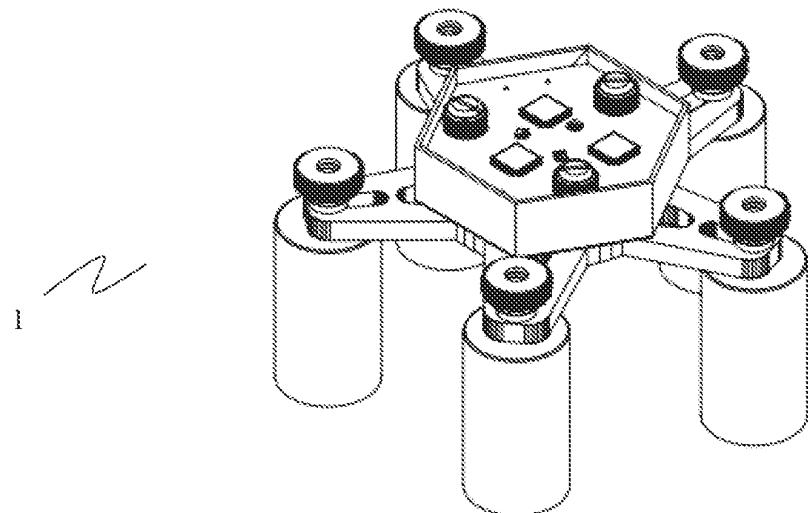
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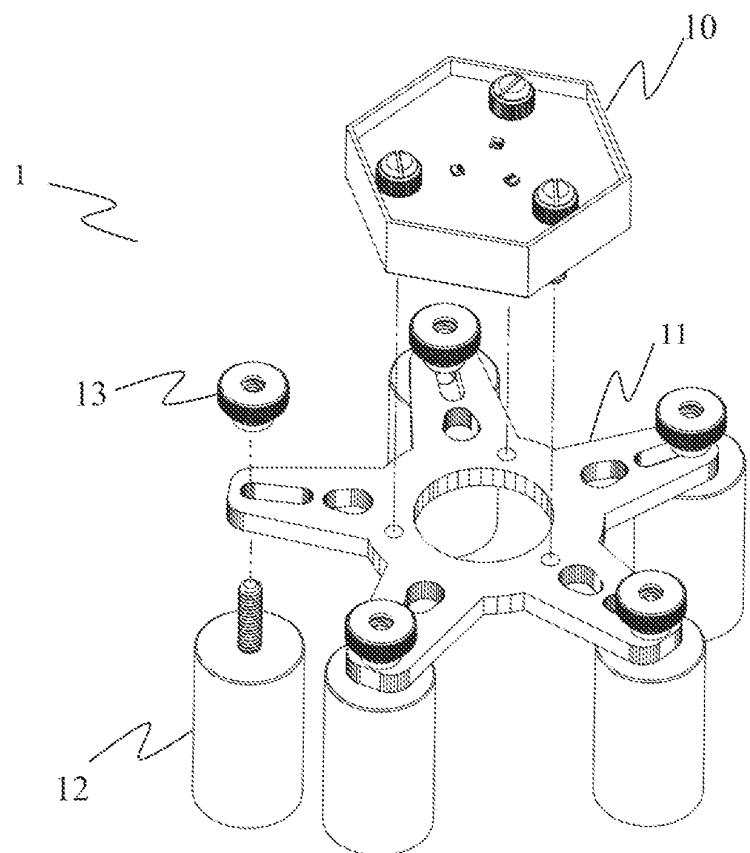
Figure 1B

Figure 2

Figure 3

HEURISTIC – First Section

Get Processed Data — 30

31 — Get the acceleration for each of the sensors.

33 — Calculate the SNR for each sample.

34 — Calculate the average of the three sensor SNRs for each sample.

Derive the angular velocity (RPM). — 35

Calculate the RPM SNR. — 36

Smooth the angular velocity signal. — 37

Derive the angular acceleration. — 38

Square the angular acceleration signal. — 39

Average Sensor SNR

RPM

RPM SNR

Squared Angular Acceleration

1   2   3   4

Figure 4

HEURISTIC – Second Section

35 ────② ③──── 36

RPM   RPM SNR

34 ──────① ④────── 39

Average Sensor SNR   Angular Acceleration

Determine the
Heuristic Score by
calculating the
weighted sum of the
Heuristic Factors for
each sample.   40

Take the moving
average of the
Heuristic Score.   41

42   45
Is MPH
range given?   Is
data window
given?

Yes   No   44   No   Yes

Select Heuristic
Data in MPH range.   Use all Heuristic
Data.   Use all Heuristic
Data.   Use data window to
select Heuristic Data.

43   46

Combine Heuristic Data
from MPH range and
Time Interval.   47

Heuristic Data Window

⑤

Figure 5

HEURISTIC – Third Section

Heuristic Data Window

Select interval from Heursitic Data Window?   50

No   Yes

Find the time interval with the maximum heuristic score.   51

Return the longest interval of continuous data.   52

Calculated Heuristics   53
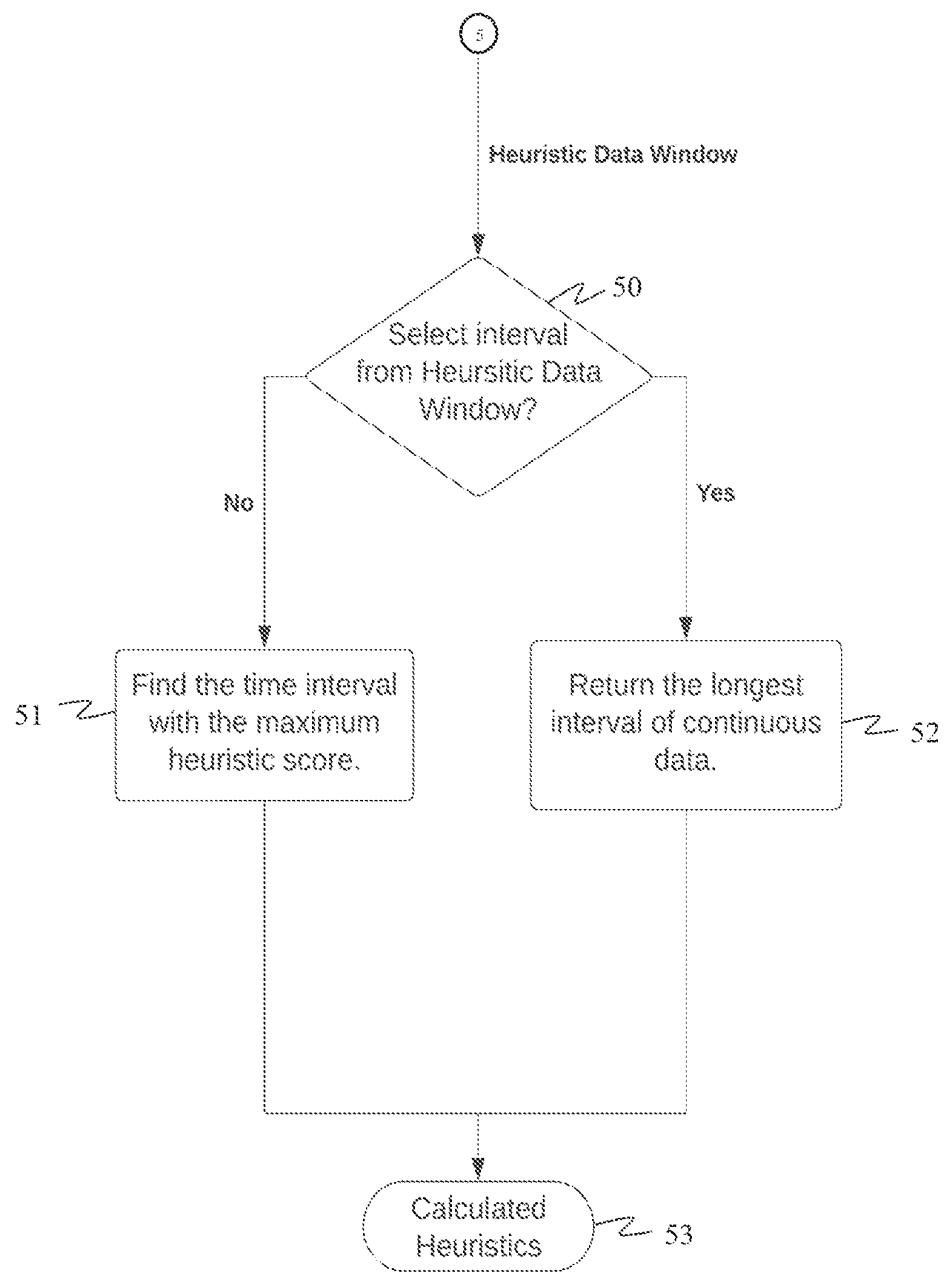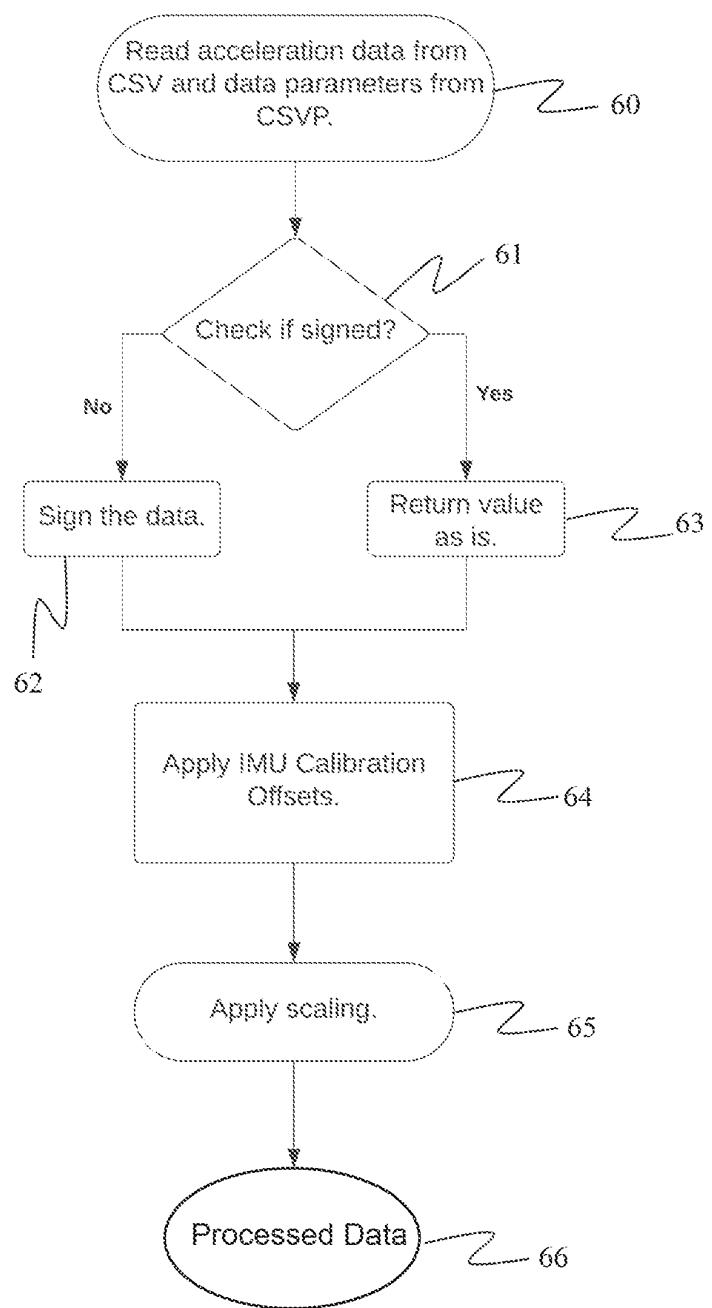
Figure 6

Figure 7

CALCULATION OF SNR
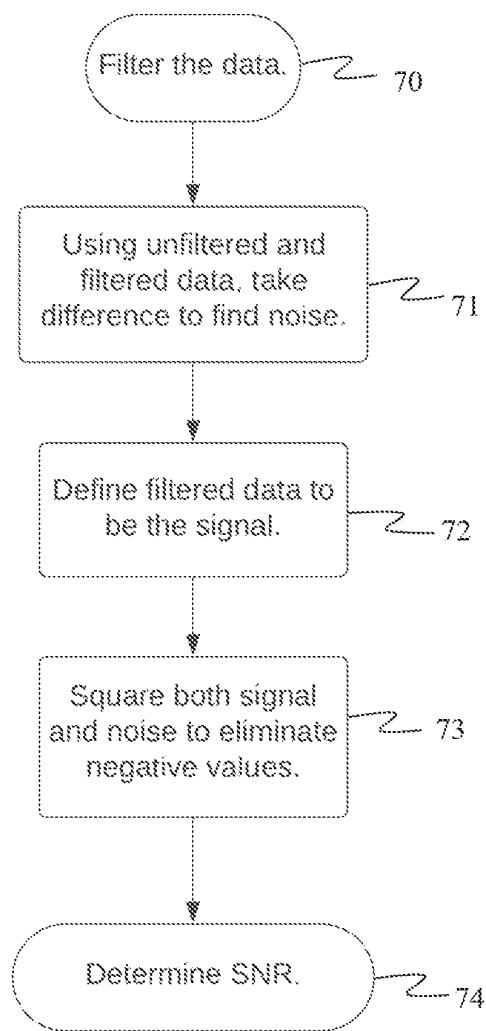
Figure 8

Figure 9

Figure 10

11

100

Figure 11

10

112

110

113

111

114
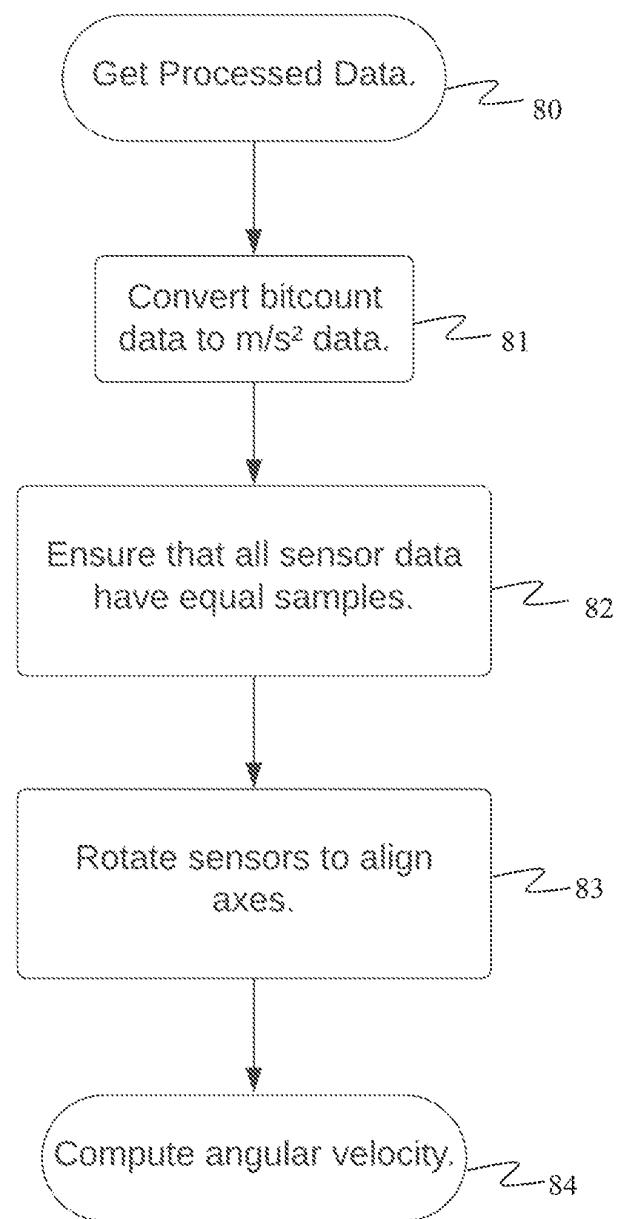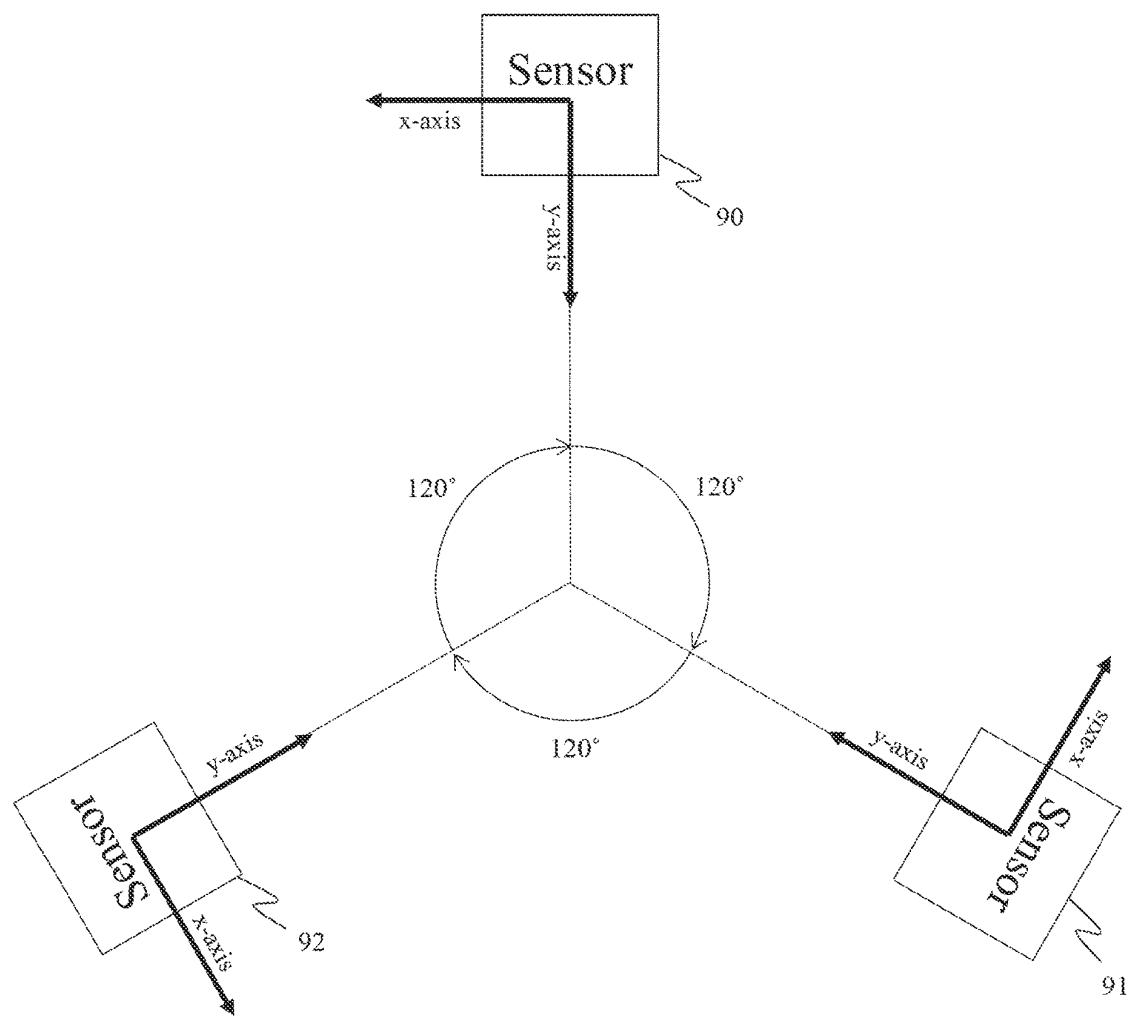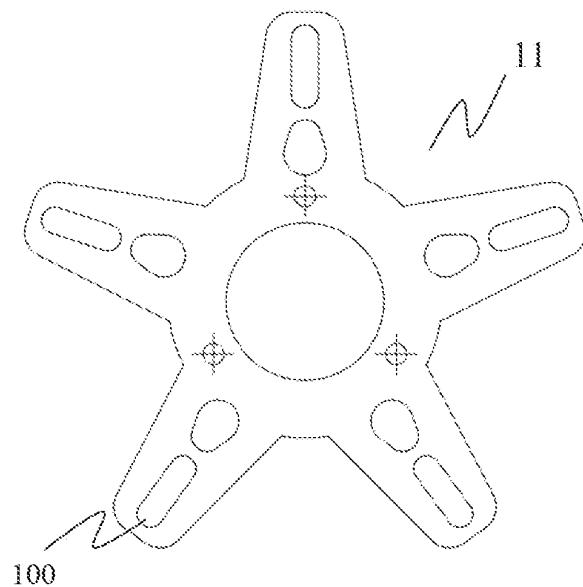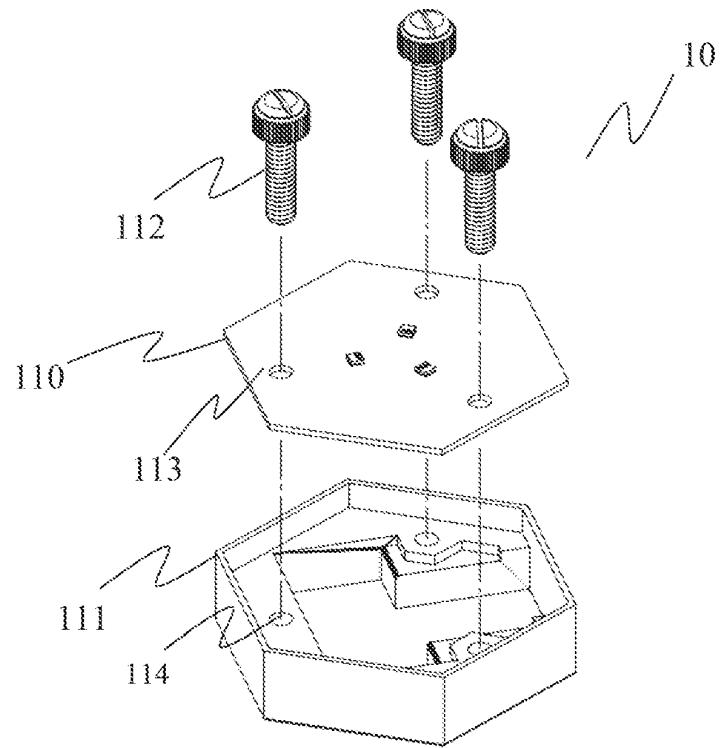
Figure 12

TRIANGLE METHOD

Determine vertical shift
(centripetal acceleration) for each
sensor.   — 120

Create acceleration vectors from the
origin to each sensor.   — 121

Create a triangle using the tips of the
vectors as the vertices.   — 122

Find centroid of the triangle.   — 123

Convert the coordinates of the
centroid to distances.   — 124
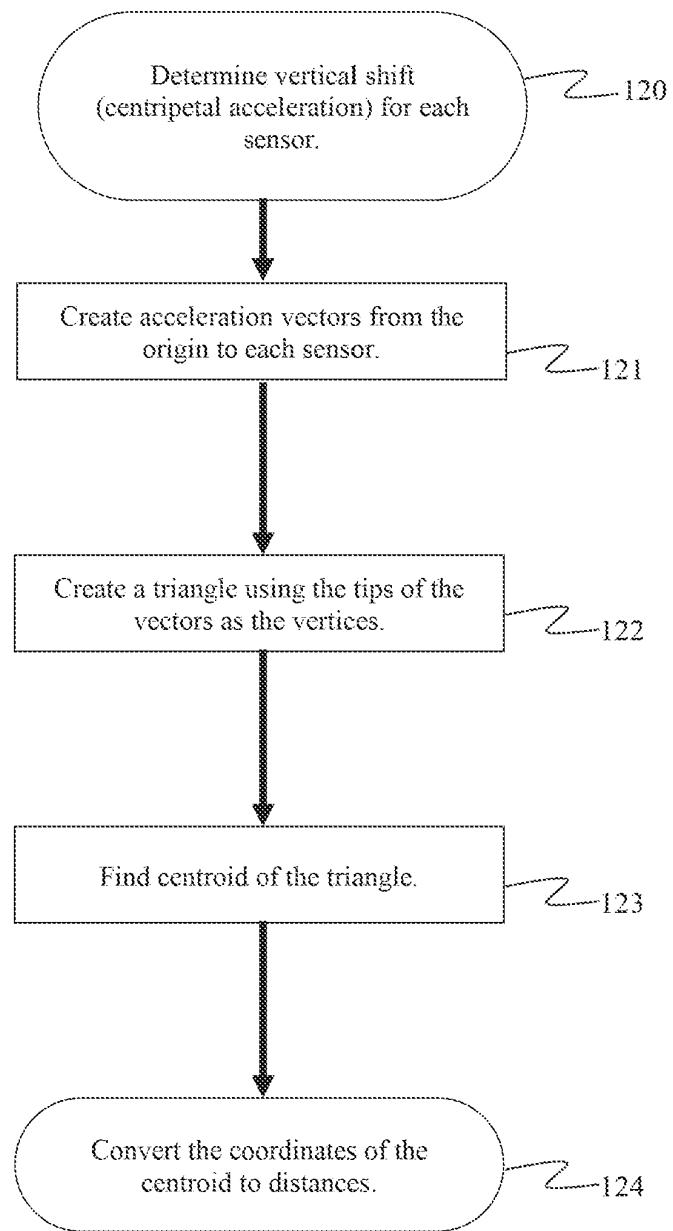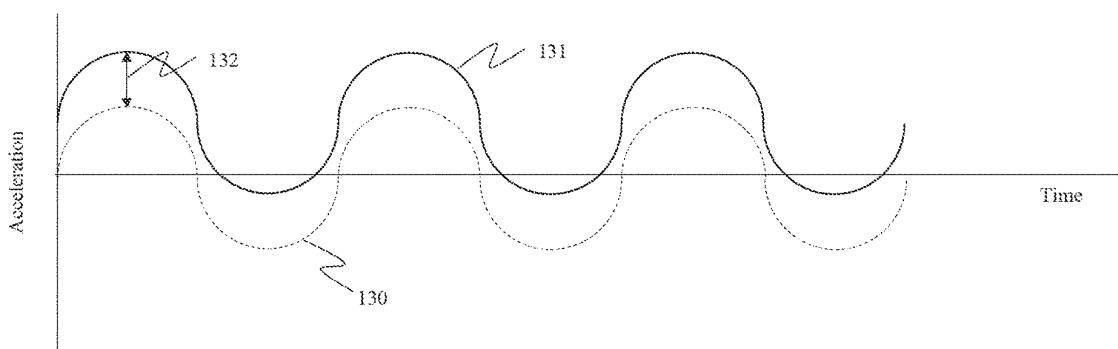
Figure 13

Figure 14

Figure 15A

Figure 15B

90°

Sensor

150

180° —————————————————— 0°

160

Sensor   Sensor

270°

Figure 16A

90°

171

170

172

180° ————————————————— 0°

+ x-axis

173   174

160
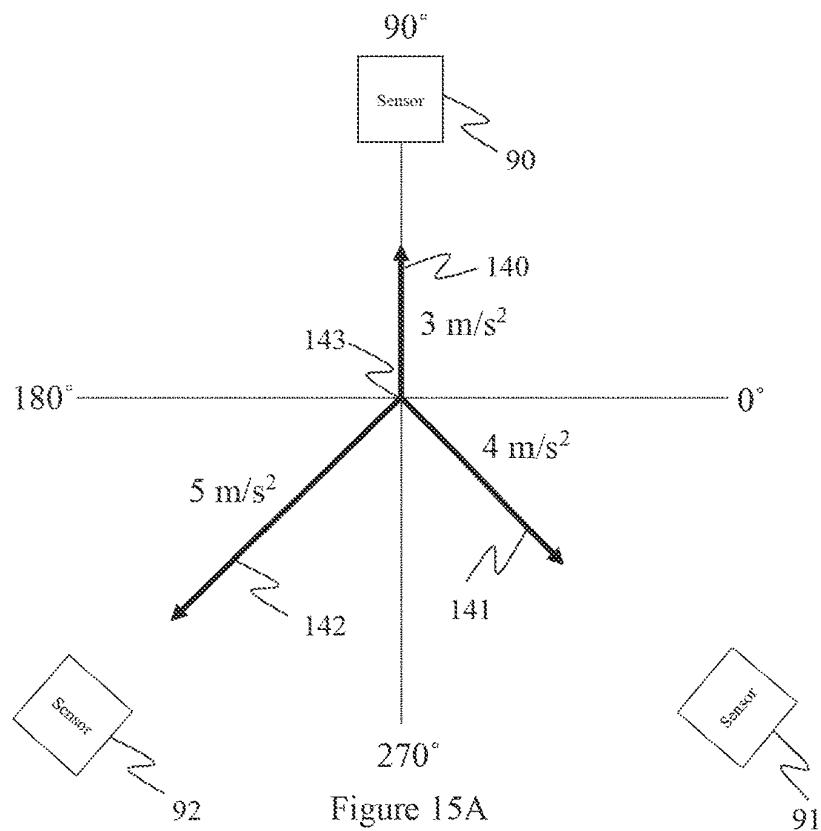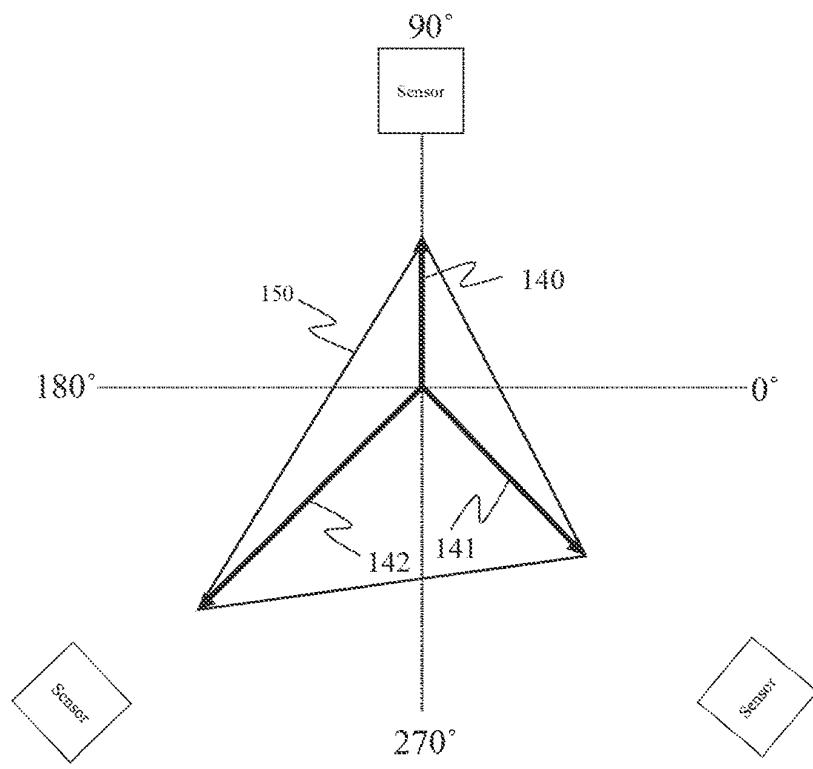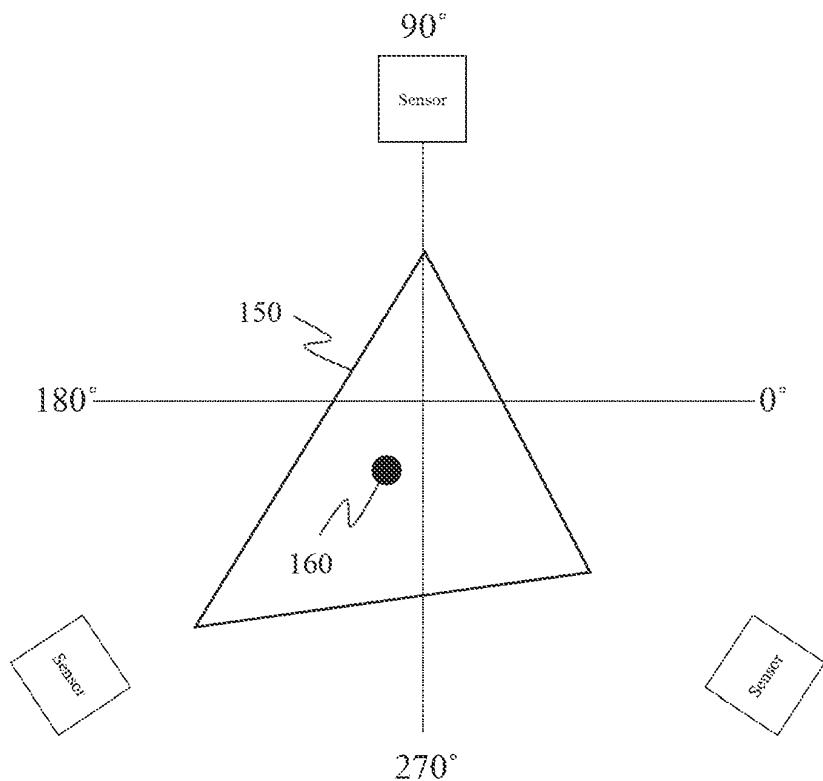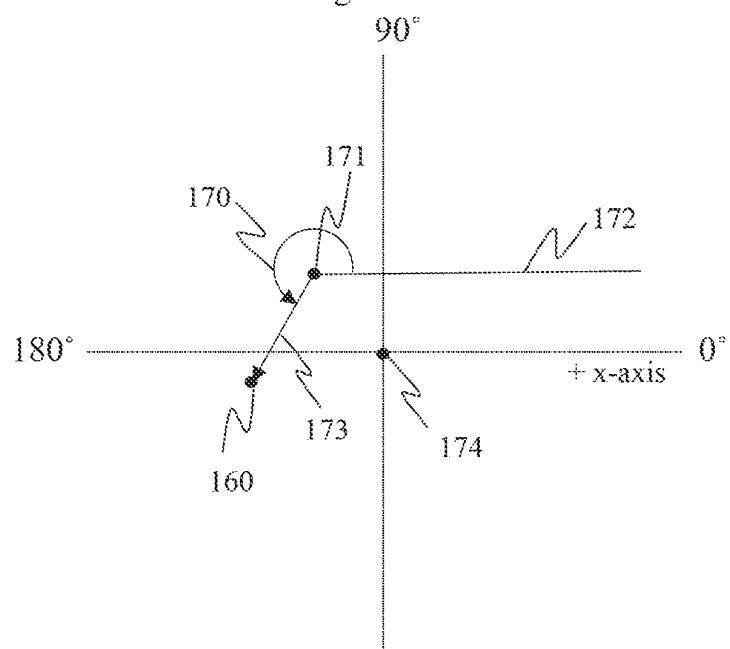
Figure 16B

ORDER ANALYSIS/CORRECTIVE MASS DETERMINATION
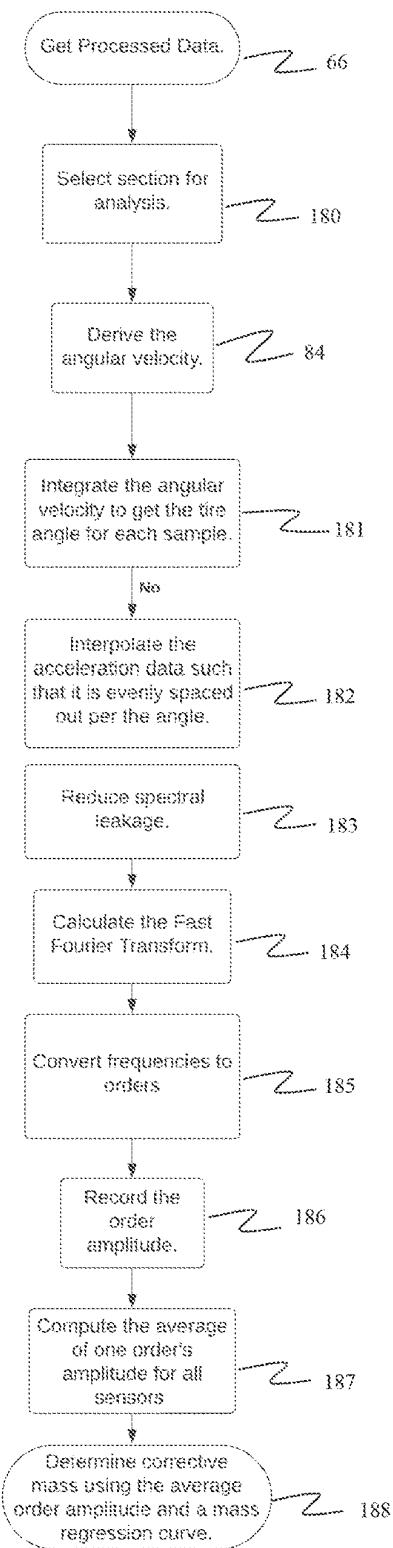

Figure 17
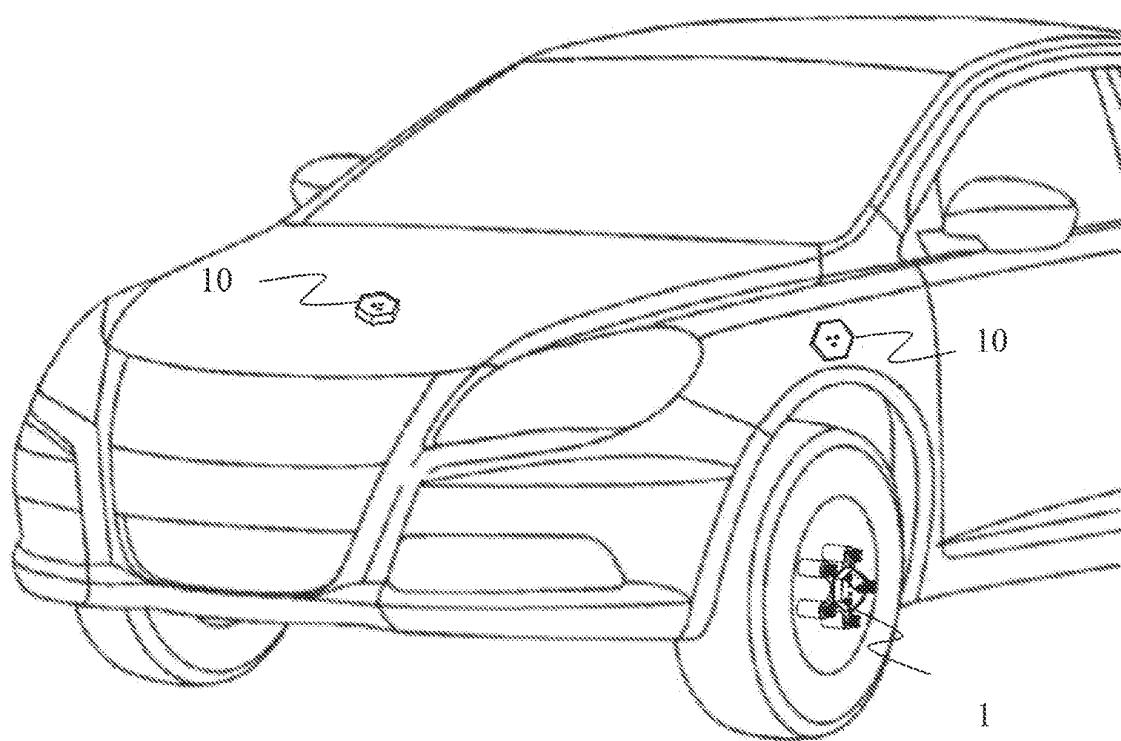
Figure 18
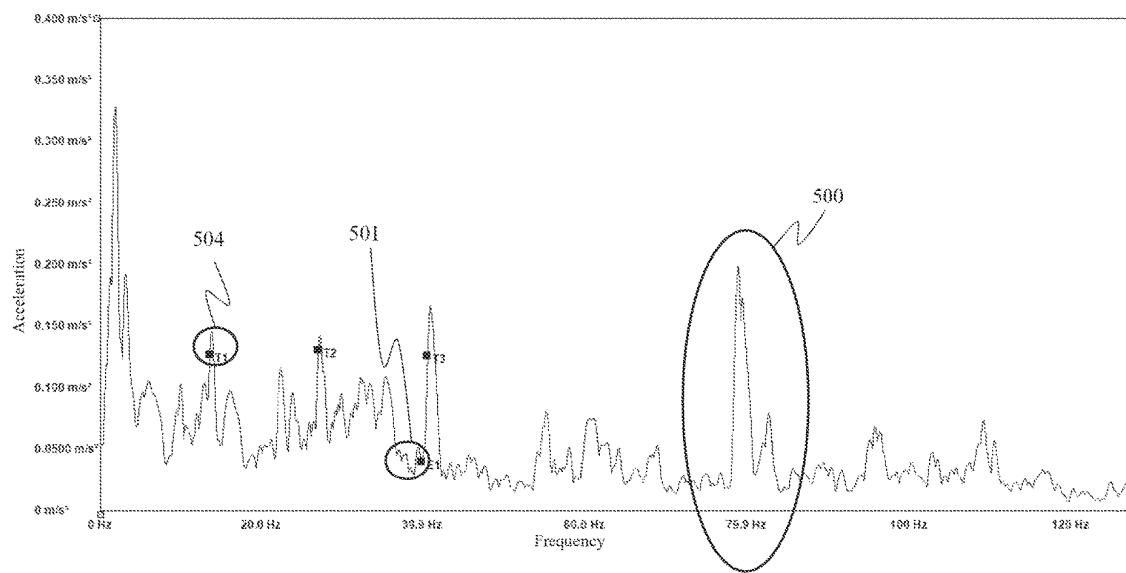
Figure 19

METHOD FOR DETERMINING A MAGNITUDE OF A MASS TO BE PLACED ON A WHEEL ASSEMBLY USING ACCELERATION DATA

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 63/603,221 filed Nov. 28, 2023, which is incorporated by reference herein.

This application is related to the following concurrently filed U.S. Non-Provisional Patent Applications:

1. U.S. application Ser. No. 18/400,534 filed Dec. 29, 2023 entitled "Method for determining a location to place a mass on a wheel assembly."
2. U.S. application Ser. No. 18/400,546 filed Dec. 29, 2023 entitled "Method for detecting vibrational anomalies of a vehicle using a plurality of devices that are removably attachable to the vehicle."

BACKGROUND OF THE INVENTION

"Vibrational anomalies of a vehicle" refers to any repetitive motion of a vehicle or component or assembly of a vehicle that could cause either a quality-of-ride issue or wear on a part of the vehicle. Vibrational anomalies can be caused by a variety of issues such as, but not limited to, engine issues, drivetrain issues, chassis or wheel issues, including tire balancing issues. Some of the most commonly occurring vibrational anomalies are present in vehicle tires and wheel assemblies. "Tire balance" refers to the distribution of mass within a vehicle tire or the entire wheel assembly, including the rim, on which the vehicle tire is mounted. Tire balance may also be referred to as "tire unbalance" or "tire imbalance." As described in U.S. Pat. No. 6,595,053 (Parker), which is incorporated by reference herein, the balancing of vehicle wheel assemblies is most often accomplished by removing the tire/wheel assemblies from the vehicle and mounting each of the assemblies on an off-car-balancer. One example of an off-car balancer is The Road Force® Elite wheel balancer, which is commercially available from Hunter Engineering Company, Bridgeton, Missouri. The off-car balancer rotates the tire/wheel assembly, measures the imbalance forces, and displays the amount and location of weight to add to the wheel to bring the tire/wheel assembly into a balanced condition. Most off-car balancers spin the wheel at a relatively low and fixed speed or RPS (the equivalent of 30 mph). But many vibrational anomalies, such as tire eccentricity, only occur at high speeds. Off-car balancers will not detect most anomalies induced by high speeds, a change in vehicle weight which changes the applied road force, or anomalies caused by other systems of the vehicle.

As also described in U.S. Pat. No. 6,595,053, a tire/wheel assembly may be balanced so that it produces negligible forces when rotated on the off-car balancer, but the same assembly may cause significant imbalance forces when mounted on the vehicle and rotated using the vehicle's bearings and axle. The imbalance forces of a tire/wheel assembly will remain constant between the off-car balancer and vehicle or truck, only if the relationship between the tire wheel assembly and the axis of rotation is the same for the two mountings. Achieving the desired on-car wheel balance with only an off-car balancer involves both accurately mounting the wheel on the balancer and then accurately mounting the tire/wheel assembly on the vehicle's hub.

Along with the previously mentioned inability to detect high-speed vibrational anomalies, there are additional limitations to off-car balancers.

As described in U.S. Pat. No. 6,595,053 and further described in U.S. Pat. No. 11,480,491 (Canfield et al.), on-car balancers can both help eliminate the mounting accuracy problems as well as operate at the high speeds of the vehicles. Although on-car balancers are available, they are not very popular because of setup difficulties, operational limitations, and safety issues. There are two aspects of on-car balancing. First, data must be collected. Second, the data must be analyzed to determine what, if any, action needs to be taken to correct any detected imbalance forces. Another possibility with on-car balancers is the addition of other types of vehicles that are not supported by off-car balancers, such as railcars which have railcar wheels that also experience imbalance forces.

SUMMARY OF THE PRESENT INVENTION

In one preferred embodiment, a method is disclosed for determining vibrational anomalies of a vehicle using a removably affixed on-car device. A sensor module is removably attached to one or more wheels of the vehicle in a manner that inhibits the objects from detaching when the vehicle is in operation. In another preferred embodiment, multiple sensors are removably attached to multiple locations of the vehicle, for example the body and wheel, in a manner that inhibits the objects from detaching when the vehicle is in operation. Each of the one or more sensors include one or more IMU's mounted to the vehicle and configured to measure parameters that are used for calculating the vibrational anomalies when the vehicle is in operation. Motion data is captured by one or more IMU's and is collected. The collected motion data is processed to determine the presence of one or more vibrational anomalies of the vehicle. A recommended corrective action to be taken is determined when the result of the processed data indicates the presence of one or more vibrational anomalies of the vehicle. All of the preferred embodiments may also be enhanced using an OBD-type of interface, wired or wireless based communications, and other motion and vibration measurement devices, such as cameras and the like.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the present invention will now be described by way of example with reference to the accompanying drawings:

FIG. 1A is one embodiment of the on-car device which is removably attached to the vehicle-under-test.

FIG. 1B is an exploded view of the embodiment of the device shown in FIG. 1A which shows the sensing module, the platen, and one cup lowered beneath the platen.

FIG. 2 is one example embodiment of using multiple devices, one device attached to the wheel and another device attached to the body of the vehicle.

FIG. 3 is a flowchart of a simplistic Overview of the method used to determine the corrective mass and corrective angle.

FIG. 4 is the first section of the Heuristic flowchart. This section shows the process followed when determining the Heuristic Factors which are Average Sensor SNR, RPM, RPM SNR, and Squared Angular Acceleration.

FIG. 5 is the second section of the Heuristic Flowchart, continued from FIG. 4. This shows the process followed in determining the Heuristic Score and Heuristic Data Window of each section of data.

FIG. **6** is the third section of the Heuristic flowchart, continued from FIG. **5**. This shows the process followed in selecting the interval which has the highest heuristic score.

FIG. **7** is a Data Processing flowchart which converts the data received from the module and processes it from an unsigned bitcount to a signed, scaled, and calibrated format.

FIG. **8** is a flowchart of the process followed when determining the signal-to-noise ratio (SNR).

FIG. **9** is a flowchart that demonstrates the process used to derive the angular velocity of the wheel from the sensor data.

FIG. **10** shows one preferred embodiment's orientation of the axes for each sensor in the on-car device.

FIG. **11** is a top view of one example embodiment of the platen to show the mounting holes and the cup slots for a 5-lug wheel assembly.

FIG. **12** is an exploded view of one embodiment of the module which includes the enclosure, the printed circuit board, the three sensors located on the printed circuit board, the printed circuit board mounting holes, the enclosure mounting holes, and the mounting hardware bolts.

FIG. **13** is a flowchart of the process followed (Triangle Method) for determining the coordinates of the imbalance mass.

FIG. **14** is an example of how the signal collected by an IMU is shifted in the positive direction due to its centripetal acceleration when it is attached to a wheel assembly in motion.

FIG. **15A** is an example of how the acceleration vectors derived from the data are aligned using the Triangle Method.

FIG. **15B** shows the triangle that is drawn from the acceleration vectors.

FIG. **16A** shows the derived centroid of a triangle from the sensor data.

FIG. **16B** shows how the corrective angle is derived.

FIG. **17** is a flowchart of the applied order analysis process when determining the imbalance mass.

FIG. **18** shows one example embodiment of multiple possible locations for the attachment of the device to the body of the vehicle.

FIG. **19** shows example data that was collected by an accelerometer that was placed on the body of the car close to the tire that was being analyzed.

DETAILED DESCRIPTION OF THE INVENTION

Certain terminology is used herein for convenience only and is not to be taken as a limitation on the present invention. The words "a" and "an", as used in the claims and in the corresponding portions of the specification, mean "at least one."

The discussion below is a continuation of the discussion on "vibrations" as presented in U.S. Pat. Nos. 11,480,491 and 11,287,348. U.S. Pat. Nos. 11,480,491 and 11,287,348 (Canfield et al.), which are incorporated by reference herein, refers to "vibrations" and "translational vibrations." Some vibrations are the result of translational forces, whereas other vibrations are not the result of translational forces. One type of translational vibration is "imbalance forces" which can be caused by an imbalanced rotating mass. The present invention determines the presence of one or more "vibrational anomalies." In one embodiment, the vibrational anomaly or anomalies are those of a vehicle. In another embodiment, the vibrational anomaly or anomalies are specific to that of a tire/hub/wheel assembly.

U.S. Pat. No. 11,480,491, and the discussion below, also refer to a vehicle being "in operation." For a passenger vehicle or truck (e.g., a motor vehicle, an electric vehicle (EV)), "in operation" includes having the vehicle in motion or having the vehicle's engine on (in the case of a motor vehicle), but not necessarily having the vehicle in motion. For other types of vehicles, such as railcars, being "in operation" requires having the vehicle in motion.

U.S. Pat. No. 11,480,491, and the various embodiments described below, each make use of either one or a plurality of Inertial Measurement Units (hereafter IMU's). Any IMU may be used that has a form factor and durability suitable for the environment described herein. One suitable IMU is the IMU described in U.S. Pat. No. 10,284,752 (Canfield et al.), which is incorporated herein by reference. Sample measured data, which are used for calculating the imbalance forces during motion of the vehicle, are captured by one or a plurality of IMU's. These data include, but are not limited to, linear acceleration and angular velocity.

One preferred embodiment of the present invention determines a corrective action which can be taken for several different types of vibrational anomalies of a vehicle. The process for such a determination utilizes an object removably attached to the vehicle, such as any of the apparatuses shown in U.S. Pat. No. 10,969,292 (Canfield et al.) and U.S. Pat. No. 11,480,491, both of which are incorporated by reference herein. Other objects and attachment mechanisms are within the scope of the present invention. The object is also interchangeably referred to herein as "device" or "measurement device."

One preferred embodiment of the device **1** shown in FIG. **1A** includes one or more IMU's which are used to collect motion data of the vehicle. The device **1** is one preferred embodiment that can be attached to a vehicle's lug nuts through mounting cups **12**, shown in FIG. **1B**, but with the removal of the mounting cups **12** and their respective platen **11**, the module **10** can be mounted at any location on the vehicle to analyze any kind or combination of vibrational anomalies. One preferred embodiment has one or more devices mounted to the lug nuts of a wheel/hub assembly as well as additional locations (as presented in FIG. **2**). This mounting location allows for the device to measure and identify the vibrational anomalies that may arise from the wheel/hub assembly, such as those from imbalance, eccentricity, or radial road force, or any form of mass distribution or imbalance related vibrations (or vibrational anomalies). One preferred embodiment of a process for collecting motion data of the wheel is described by the following Data Collection Process:

1) Locate a section of road that allows the vehicle to attain and maintain a consistent speed for a desired Data Collection Interval, such as 15 seconds, and then attain and maintain a consistent testing speed, either a Low-Speed or High-Speed test. One example of a Low-Speed and High-Speed is used in the referenced embodiment with the Low-Speed being maintained at 30 MPH and the High-Speed being maintained at 60 MPH. In preferred embodiments of the present invention, High-Speed (interchangeably referred to herein as the "second speed) is between 1.5 and 3.0 times the Low-Speed (interchangeably referred herein as the "first speed."), although other ratios are within the scope of the present invention.

2) Prepare the Measurement Device with trial parameters. These parameters include, but are not limited to, sensor sensitivity and filter specifications.

3) Affix the device or devices to the wheel lug nuts. It should be noted that the number of wheel lug-mounted devices is only limited to the number of wheels on a given vehicle.

4) Drive the vehicle to the testing site.

5) Attain Low-Speed and set cruise control, if possible, to maintain a consistent speed.

6) Start collecting Low-Speed data. Initiating data collection can be done in a variety of different ways. Three such ways are listed below.

    a. Automatically using an algorithm wherein device **1** detects the consistent speed of the vehicle and begins collecting data for a predetermined time interval or until the vehicle speed is no longer consistently within the preferred data collection speed parameters.

    b. Manually controlling the data collection via any type of remote control.

    c. Automatically controlling the data collection via an OBD-type reader configured to use vehicle data in order to remotely control the device **1** or devices.

7) Maintain Low-Speed for the prescribed Data Collection Interval.

8) Stop collecting Low-Speed data and store the dataset.

9) Accelerate to High-Speed and set cruise control, if possible, to maintain a consistent speed.

10) Start collecting High-Speed data.

11) Maintain High-Speed for the prescribed Data Collection Interval.

12) Stop collecting High-Speed data and store the dataset.

13) Once the prescribed data has been collected, one or more example methods for processing may be executed:

    a. The Low-Speed and High-Speed data can be exported by any means for analysis.

    b. The device **1** internally executes the analysis algorithms which are further detailed in this specification and communicates the results by any optical, tethered, wired, or remote control means.

The data can now be used to determine the corrective measures needed. One preferred embodiment of such a process is shown by the flowchart in FIG. **3** in blocks **20**, **21**, **22**, and **23**. The steps and outcomes of the flowchart are as follows: Find the best Low-Speed section using the Heuristic. Heuristic refers to an algorithm that chooses a section of data based upon set criteria. These criteria determine the hierarchy of the characteristics considered in the decision-making process. The Heuristic is shown in FIG. **4**, continues to FIG. **5**, and is concluded in FIG. **6**.

The first step of the Heuristic is to determine the Heuristic Factors needed to calculate the Heuristic Internal. There can be an unlimited number of Heuristic Factors, but in this example embodiment, only four Heuristic Factors have been identified. One preferred embodiment for the determination of the Heuristic Factors is shown in FIG. **4**. The steps and outcomes of the flowchart are as follows:

Block **30**: Get Processed Data. The data must be processed from its raw bitcount format into calibrated, signed, and scaled data. This process is visualized in FIG. **7** in blocks **60**, **61**, **62**, **63**, **64**, **65**, and **66**. The steps and outcomes of the flowchart are as follows:

Block **60**: Read acceleration data from CSV file and data parameters from CSVP (CSVP refers to a CSV file that contains the data Parameters). The CSV data includes, but is not limited to, acceleration, gyroscopic, and magnetometer data for all three axes (x, y, and z) of each sensor as a bitcount. The bitcount can be 8, 16, 20,

24, or 32 bits in length, depending on the data export and file formats. The present invention primarily makes use of the acceleration data in this disclosure, while the gyroscopic and magnetometer data are used in related functions, data collection, and analysis which include, but are not limited to, lateral runout, alignment, etc. The CSVP data parameters include information such as IMU Calibration Offsets (used for range correction) and sensor sensitivity, which is determined by the maximum possible samples. Preset possible sensitivities include, but are not limited to, +/−2G, +/−4G, +/−8G, and +/−16G, each of which, divided by 65,536 or the maximum bitcount of the IMU used, results in a different corresponding bitcount per G. For instance, a +/−2G range yields a resolution of 16,384 bits per G, while a +/−16G range yields a resolution of 2,048 bits per G.

Blocks **61**, **62**, and **63**: The unsigned data from the CSV files are first converted to signed data.

Block **64**: Apply IMU Calibration Offsets. The IMU Calibration Offsets correct the sensor's bitcount range to account for imperfections in the sensor data. This is accomplished by collecting data with the device placed on a level surface so that the sensor is vertically aligned with gravity. In this orientation the sensor will give a reading that corresponds to the value of gravity (1G or 9.8 m/s^2). The data is also collected with the sensor vertically aligned opposite gravity. In this orientation the sensor will give a reading that corresponds to the negative value of gravity (−1G or −9.8 m/s^2). If the sensitivity is set at 16G then these two bitcount values would theoretically equal 2048 and −2048 after the unsigned data is converted to signed data. For both electronic and physical reasons those readings can differ from the expected values. The measured readings are referred to as the IMU Calibration Offsets. For example, the value that corresponds to 9.8 m/s^2 could be 2050 bitcount and the value that corresponds to −9.8 m/s^2 could be −2044 bitcount. It can be seen that the range has increased from its expected value. By subtracting the average of these two values

$$\left(\frac{2051 + (-2045)}{2} = 3 \right)$$

to the signed data, it will correct the range of the collected and now signed data such that a reading of 2048 bitcount will correspond to 9.8 m/s^2 and a reading of −2048 bitcount will correspond to −9.8 m/s^2.

Block **65**: Apply Scaling. Scaling will stretch or compress the span of the data that exists between 9.8 m/s^2 and −9.8 m/s^2 so that the data values correspond with the selected sensitivity. For a sensitivity of 16G, the mathematical span between the reading for +9.8 m/s^2 and the reading for-9.8 m/s^2 should be 4096 bitcount. In an example where the bitcount measurement for +9.8 m/s^2 is 2050 and the bitcount measurement for −9.8 m/s^2 is −2044, the span would be equal to 4094 bitcount. As the span is not equal to the mathematical span of 16G, that means that the data is compressed and needs to be uncompressed by a factor of

$$\frac{4096}{4094} = 1.0004885.$$

Each data point is multiplied by this scaling factor to correct for this compression. Conversely, if the original data was stretched, the scaling factor would be less than one to compress the data. All of the CSV unsigned data has now been signed, the calibrations applied, and the data scaled, if necessary.

Block **66**: Processed Data. The outcome after all calculations have been processed.

Block **31**: Get the acceleration for each of Sensors in the device.

Block **33**: Calculate the SNR for each dataset. One embodiment of this process is shown in the flowchart in FIG. **8**. The steps and outcomes are as follows:

Block **70**: Filter the data. A filter, such as a Savitsky-Golay or Gaussian filter, is applied to mitigate or eliminate noise so the RPM is clearer than other vibrations.

Block **71**: Using unfiltered and filtered data, take the difference to find noise.

Block **72**: Define the filtered data to be the signal.

Block **73**: Square both the signal and the noise to eliminate negative values.

Block **74**: Determine the SNR. The SNR is the ratio of the squared signal and noise. It is calculated for each sample.

Block **34**: Calculate the average of the three sensor SNRs for each sample shown as Output 1 in FIG. **4**.

Block **35**: Derive the angular velocity. The exact angular velocity, or RPM, of the wheel is required to understand the wheel dynamics and vibrations. While there are many ways to collect the angular velocity data of a vehicle in motion, such as taking data from an OBD reader, one preferred embodiment utilizes the multiple IMU data to derive the exact angular velocity of the wheel, as other methods may have inaccuracies. One preferred embodiment for this process is shown in the flowchart in FIG. **9**. The steps and outcomes of the flowchart are as follows:

Block **80**: Get Processed Data. One preferred embodiment for retrieving Processed Data **66**, which is described above, is shown in FIG. **7**. The result is calibrated and signed bitcount.

Block **81**: Convert bitcount data to m/s² data. All data is multiplied by a G conversion factor that is determined by the sensitivity setting found in the CSVP data.

Block **82**: Ensure that all sensor data have an equal number of samples for each axis. Some methods for ensuring equality would be to resample or truncate the data. The sensor with the lowest number of samples will determine the number of samples for all sensors. The datasets for the other sensors will be corrected to match the lower sample rate. In the preferred embodiment, the sensor sample rates are precisely synchronized, and no extra equalization of the individual axes datasets is necessary.

Block **83**: Rotate sensors to align axes. In one preferred embodiment containing three sensors as shown in FIG. **10**, Sensors **90**, **91**, and **92** represent three IMU's which are oriented in device **1** such that they are precisely equidistant from the center of the module, 120° offset from each other and have their y-axes all pointing toward the center. The alignment of the axes that is referred to in Block **83** converts the data such that all sensors have the same orientation as Sensor **90**, where the y-axis is pointing down and the x-axis is pointing to the left. This alignment is required to compute the angular velocity.

Block **84**: Compute the angular velocity. Using

$$\omega = \sqrt{\frac{x_2 - x_3}{R\sqrt{3}}},$$

the angular velocity is determined in rad/s. This equation was derived from Kionix®, as described in a Kionix paper entitled "Using Two Tri-axis Accelerometers for Rotational Measurements." Jan. 10, 2008 (Document AN 019), 8 pages. In the angular velocity equation, the following is a listing of what each variable represents:

ω=angular velocity in rad/s

x_2=x-acceleration of Sensor **91**

x_3=x-acceleration of Sensor **92**

R=distance from each sensor to center of the platen

The computed angular velocity is the Derived RPM, shown as Output 2 in FIG. **4**.

Block **36**: Calculate the RPM SNR for each sample. One embodiment of this process is shown in the flowchart in FIG. **8** and has been described above. This results in a sample-by-sample SNR shown as Output 3 in FIG. **4**.

Block **37**: Smooth the angular velocity signal. In one preferred embodiment the signal is smoothed using a heavy moving average. With data collected at 2000 samples per second an example of a heavy moving average window would be 2000. The angular velocity can also be used to best determine the value of any applied filter or moving average.

Block **38**: Derive the angular acceleration. In one preferred embodiment, the derivative of the angular velocity is used to find the angular acceleration.

Block **39**: Square the angular acceleration signal. A constant speed is desired to simplify calculations. Therefore, acceleration is undesirable whether it is positive or negative. Thus, any data that shows an acceleration should be penalized. In order to penalize any and all acceleration the angular acceleration is squared, which can be used to determine the magnitude of angular acceleration. This determines the Squared Angular Acceleration Heuristic Factor shown as Output 4 in FIG. **4**.

At this point the following Heuristic Factors have been determined:

1. The Average Sensor SNR of all sensors associated with each data point is shown as Output 1 in FIG. **4**.

2. The RPM associated with each data point is shown as Output 2 in FIG. **4**.

3. The RPM SNR associated with each data point is shown as Output 3 in FIG. **4**.

4. The Squared Angular Acceleration associated with each data point which is shown as Output 4 in FIG. **4**.

Using the Heuristic Factors in the above list, the Heuristic Data Window can now be calculated. One embodiment of this process is shown in the flowchart of FIG. **5**. The steps and outcomes of this flowchart are as follows:

Block **40**: Compute the weighted sum of the Heuristic Factors for each sample. This weighted sum will be referred to as the Heuristic Score. The Heuristic Score is used to determine the section of the data that will be used in the analysis, the Heuristic Interval. An example of possible factors and their weights are as follows:

Average Sensor SNR 10.

Angular Velocity 0.

RPM SNR 0.

Angular Acceleration −30

The weight for the Angular Acceleration is negative to decrease the score of any data that has any acceleration.

An example of determining a Heuristic Score would be a data point with an SNR of 5 and an angular acceleration of 1, which would have a total score of:

$$5*10+1*(-30)=20 \text{ (Heuristic Score)}$$

The Heuristic Score is calculated for each data point in the signal.

Block **41**: Take the moving average of the Heuristic Scores. The window size of the moving average is determined before analysis. This averaged Heuristic Score is called the Heuristic Data.

Block **42**: Is MPH range given? In one preferred embodiment the MPH range will be entered as a preset based upon information provided as to what speed a quality-of-the-ride issue has been detected.

If "yes" to Block **42**, then:

Block **43**: Select Heuristic Data in the MPH range. The velocity of the vehicle at each data point can be determined. The Heuristic Data for all data points with a velocity that lies within the preset or predetermined MPH range will be analyzed. This will eliminate any data that was collected when the vehicle was not at the preset or predetermined speed.

If "no" to Block **42**, then:

Block **44**: Use all Heuristic Data.

Block **45**: Is data window given? The data window refers to a Time Interval. The Time Interval refers to a specific start and end time relative to the entire data set. The Time Interval limits the selection of Heuristic Data to be used allowing the user to isolate desired section of the data. For example, if a pothole was hit during the data collection at a known time, say 10 seconds into the collection, then a Time Interval may be given starting at 15 seconds and ending at 30 seconds to eliminate known artifacts not resulting from vehicular vibrations.

If "yes" to Block **45**, then:

Block **46**: Use the data window to select Heuristic Data.

If "no" to Block **45**, then:

Block **44**: Use all Heuristic Data.

Block **47**: Combine Heuristic Data from MPH range and Time Interval. The outcomes of both the MPH Range from Block **42** and the Time Interval from Block **45** are combined to create what is herein termed the Heuristic Data Window.

Now that the Heuristic Data Window that is to be used is known, the Heuristic Interval can be selected. One embodiment for this process is shown in the flowchart of FIG. **6**. The steps and outcomes are as follows:

Block **50**: Select interval from Heuristic Data Window?

If "no" to Block **50**, then:

Block **51**: Find the time interval with the maximum Heuristic Score. The maximum Heuristic Interval is determined by the moving average found in Block **41**.

If "yes" to Block **50**, then:

Block **52**: Return the longest interval of continuous data. In order get the best analysis, only a certain number of consecutive outliers—for example data points with acceleration above a threshold—are allowed before the interval can be considered for analysis.

With this, the Heuristic has been used to calculate or determine the best Low-Speed in Block **20** of FIG. **3**.

FIG. **3** Block **21** Example Method: Determine offset using Low-Speed Heuristic section. The offset is the difference between the tire/wheel bearing center and the device center derived at Low-Speed because most tire and wheel anomalies that occur at high speeds are not apparent at lower speeds. Once the device offset has been determined, any

measured off-center deviation of the rotational High-Speed data can be used to identify an imbalance, radial force variation, or eccentricity or other type of problem. There are a variety of factors that may lead to a small variation between the device center and the tire/wheel bearing center. Even if each factor only contributes a small variation, the combined variation could falsely indicate a large vibrational issue due to the uncorrected use of the device center to locate the vibration. Some of the reasons the device center would not line up with the bearing center include the following:

The cups **12** in FIG. **1B** shift in their corresponding slots **100** on the platen **11**. The slots **100** on the platen **11** are more clearly shown in FIG. **11**.

The PCB **110** shifts or is slightly offset in the enclosure **111**, as shown in one embodiment in FIG. **12**.

The Mounting bolts **112** shift or are not perfectly centered in their corresponding PCB mounting holes **113** and Enclosure mounting holes **114**, as shown in one embodiment in FIG. **12**.

One preferred embodiment in the process for determining the offset is termed herein as the "Triangle Method." The Triangle Method is represented in the flowchart of FIG. **13**. The steps and outcomes of the flowchart are as follows:

Block **120**: Determine the vertical shift (centripetal acceleration) for each sensor. The term "vertical shift" refers to a movement of the signal in the positive y-direction. In FIG. **14** the dotted line **130** represents the original sinusoidal signal which is created by gravity and a rotating sensor when the sensor is located precisely in the center of the axis of rotation. When the sensor is not precisely in the center of the axis of rotation, it moves in a circular path and experiences an additional centripetal acceleration which causes the signal to shift in the positive direction by an amount equal to the centripetal acceleration. The solid line **131** in FIG. **14** represents this shifted signal. The vertical shift is represented by **132**. The vertical shift in the signal is caused by the centripetal acceleration of the sensor. The vertical shift is determined by taking the average of the entire time span that is being evaluated.

Block **121**: Create the acceleration vectors from the origin to each sensor. This process is shown in FIG. **15A**. Align a vector from the origin **143** toward each sensor with a magnitude that is equal to the magnitude of the vertical shift of that sensor. An example where the centripetal acceleration of Sensor **90** is 3 m/s², shown as vector **140**, Sensor **91** is 4 m/s², shown as vector **141**, and Sensor **92** is 5 m/s², shown as vector **142**, is shown in FIG. **15A**.

Block **122**: Create a triangle using the tips of the vectors as the vertices. An example of this is shown in FIG. **15B** with the derived triangle shown as **150**.

Block **123**: Find the centroid of the triangle. This is done by taking the average of the coordinates for vertices **140**, **141**, and **142** of the triangle **150** in FIG. **15B**. The centroid **160** is shown in FIG. **16A**.

Block **124**: Convert the coordinates of the centroid to distances. These coordinates are derived using acceleration vectors and therefore have acceleration values. Using the equation $a_c = \omega^2 r$, these values can be converted into distances using the average acceleration. The average angular velocity is determined by taking the average of the angular velocity **84** over the selected MPH range.

The above calculation is completed using data from the x-axis sensor and from the y-axis sensor. Each calculation produces a point identified by a coordinate pair. The coor-

dinates found are offset and determine the location of the bearing center. The offset can be used for calibration in a High-Speed section. While the Low-Speed section is used to determine the offset, and thus calibrate and align the device to the wheel/hub assembly, the High-Speed section is used to determine the location and magnitude of vibrational anomalies in the wheel assembly.

FIG. **3**. Block **22** Example Method: Find the best High-Speed section using the Heuristic. Follow the same steps that were used on the Low-Speed section from Blocks **30** to **39** in FIG. **4** and Blocks **40** to **47** in FIG. **5**. Specific to the High-Speed section and due to the increased vibrations present at higher speeds, a time interval of data can be used to optimize results. Block **45** is a "yes", so the desired time interval is applied over the Heuristic Data from the High-Speed section to determine the Heuristic Interval which will be used in the following steps.

Block **23**: Determine the corrective mass and angle. The corrective angle is determined by applying the Triangle Method, described above, on the data from the interval determined from the Heuristic applied to the High-Speed Block **47**. This application of the Triangle Method determines the coordinates of the centroid **160**, the anomaly-altered center of mass of the tire/wheel assembly, of triangle **150** in FIG. **16**A. The angular location of centroid **160** relative to the offset **171** in FIG. **16**B, determined from the Low-Speed section, is used to determine the angular position of the corrective mass. Angle **170** in FIG. **16**B is measured from line **172**, which is parallel to the x-axis of the device and passes through the offset **171** to a vector **173** which goes from the offset **171** to the centroid **160**. This angle is the angle from the bearing center to the vibrational anomaly. The corrective angle is opposite angle **170**.

One embodiment for determining the magnitude of the corrective mass is done by a predictive model. In one example, the predictive model is an order regression (e.g., a second order regression) which is shown in the flowchart in FIG. **17**. Stated another way, FIG. **17** shows a process wherein acceleration data is applied to a predictive model (here, an order regression) to determine the magnitude of the mass. The scope of the present invention is not limited to using order regression, but includes other types of predictive models, such as classification models or neural networks.

The steps and outcomes are as follows:

Block **66**: Get Processed Data. One preferred embodiment for retrieving Processed Data **66**, which is described above, is shown in FIG. **7**.

Block **180**: Select section for analysis. This section is typically the section of data where there is a desired comfort of ride issue or section of data with vibrational anomaly to analyze.

Block **84**: Derive the angular velocity. One method is described previously and is shown in FIG. **9**.

Block **181**: Integrate the angular velocity to get the tire angle for each sample.

Block **182**: Interpolate the acceleration data such that it is evenly spaced out per tire angle.

Block **183**: Reduce Spectral Leakage. One preferred embodiment uses resampling methods.

Block **184**: Calculate the Fast Fourier Transform.

Block **185**: Convert frequencies to orders. This gives the order amplitude.

Block **186**: Record the order amplitude for that sensor. Repeat Blocks **180** through **187** for the rest of the sensors.

Block **187**: Compute the average of one order's amplitude for all sensors.

Block **188**: Determine the corrective mass using the average order amplitude and a mass regression curve. The mass regression is a relationship between those factors that are most influential toward the vibration of the wheel assembly. Those factors may include tire mass, rim radius, weight over the axle, and other factors.

The mass regression provides the corrective mass from Block **188** and, with the location of the corrective mass, opposite angle **170**, provides the solution for which corrective mass to apply and in what angular location, relative to the center of Device or wheel assembly, to correct for wheel/hub assembly vibrations.

In another preferred embodiment, vibrations not limited to the wheel/hub assembly can be further analyzed using one or more devices being mounted in a removably attached manner on other locations of the vehicle. One such embodiment with device **10** attached to the hood is shown in FIG. **2**. The device **10** can be one or more sensors, such as IMU's, with or without some sort of remote control, and could be affixed via a magnet, adhesive, or with any type of mechanical adapter. Locating it on the quarter panel as shown in FIG. **18** or elsewhere on the vehicle provides an unlimited number of locations for one or more devices **10** to be placed. This collected data can be used to determine the location of vibration caused by the wheel assembly or other vibration generated elsewhere in the vehicle, included but not limited to, the transmission, the differential, the engine, or any other vibrational source. Order Analysis, similar to how PICO Technology software analyzes the data from their device, is one preferred method by which the data can be analyzed to determine the type and source of vibration. For example, FIG. **19** is a graph showing the order analysis of vibrational data collected using the device and software from PICO Technology. The data was collected from an accelerometer that was placed inside the trunk of the vehicle (not shown) in a location that was as close to the tire being analyzed as possible. The vehicle was driven at a constant speed of 60 mph for this data collection. The diagrammed oval surrounding peak **500**, shows a strong signal at 79.9 Hz. The diagrammed circles surrounding graph location **501** and further identified by E1 indicate the frequency at which the engine was rotating as 39.9 Hz. The strong signal at 79.9 Hz is an indication that there is an issue related to either the engine or the drivetrain. Any combination of one or more device **1** and one or more device **10** could be used to accurately determine the type and location of virtually any type of vibration occurring within or on a vehicle, whether it is stationary or in motion.

An example follows in which data from both sensors, device **1** and device **10**, are used to identify the source of a vibrational anomaly. In FIG. **19**, the peak identified by circle **504** shows vibrations which occur at the same frequency as the rotation of the tire/wheel assembly. This vibrational data was collected by device **10**. If analysis of the acceleration data collected by Device **1** determines that there is no vibrational anomaly caused by the tire/wheel assembly, then the peak identified by circle **504** would indicate that the source of the vibrational anomaly may be in the drivetrain or the engine. For example, if the mass regression analysis from FIG. **17** from data for each wheel returns negligible corrective mass, then the vibration indicated by the peak **504** does not originate from the tire/wheel assembly and it may originate from the engine and/or drivetrain.

PICO Technology (www.picoauto.com and www.picotech.com) is headquartered in Cambridgeshire, United Kingdom, and markets products for Noise, Vibration and Harsh-

ness (NVH) testing, including PicoDiagnostics NVH kits. These commercially available kits may be used for collection and analysis of the vibrational data discussed above. However, other commercial products are within the scope of the present invention for collection and analysis of the vibrational data.

It will be appreciated by those skilled in the art that changes could be made to the embodiments described above without departing from the broad inventive concept thereof. It is understood, therefore, that this invention is not limited to the embodiments disclosed, but it is intended to cover modifications within the spirit and scope of the present invention.

What is claimed is:

1. A method for determining a magnitude of a mass to be placed on a wheel assembly using data from one or more inertial measurement units (IMU's), the one or more IMU's being mounted to a removably attachable object that is attached to a wheel of a vehicle in a manner that inhibits the object from coming off of the vehicle while the vehicle is in motion, each of the IMU's including an accelerometer, wherein the one or more IMU's rotate with the wheel assembly while the vehicle is in motion, the method comprising:

(a) collecting a set of acceleration data from the one or more IMU's that rotate with the wheel assembly, wherein the set of acceleration data is collected while the vehicle is in motion; and

(b) applying the acceleration data to a predictive model to determine the magnitude of the mass.

2. The method of claim 1 wherein the predictive model transforms the acceleration data to a frequency domain and computes an order amplitude which is used to determine the magnitude of the mass.

3. The method of claim 1 wherein the predictive model is an order regression.

4. The method of claim 1 wherein there are three IMU's, and step (a) further comprises collecting the set of acceleration data from the three IMU's, and step (b) further comprises applying the acceleration data from the three IMU's to the predictive model to determine the magnitude of the mass.

*   *   *   *   *