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(71) Applicant *(for all designated States except US)*: **VOLVO LASTVAGNAR AB** [SE/SE]; SE-405 08 Göteborg (SE).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **CARRESJÖ, Erik** [SE/SE]; Västra Trädal 230, S-442 71 Käma (SE). **HASSELBERG, Per** [SE/SE]; Småtrollens väg 9, S-423 49 Torslanda (SE).

(74) Agent: **FRÖHLING, Werner**; Volvo Technology Corporation, Corporate Patents, 06820, M1.7, S-405 08 Göteborg (SE).

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(54) Title: WHEEL-MONITORING APPARATUS

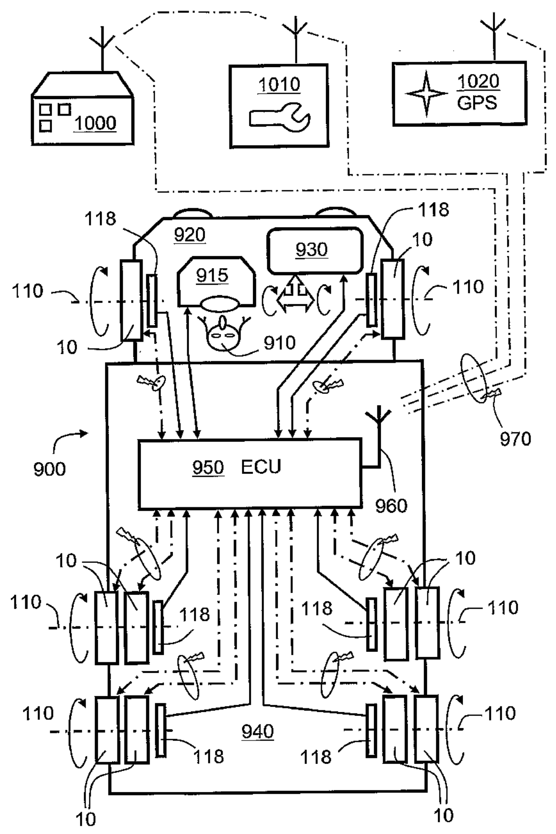

FIG. 16

(57) Abstract: There is provided a wheel-monitoring apparatus (600, 680, 690, 2200) for monitoring operation of a wheel (10, 2500, 3000) of a vehicle (900). The apparatus (600, 680, 690, 2200) includes a sensor module (400) operatively mounted to revolve with the wheel (10, 2500, 3000). The module (400) is coupled in communication with a processing arrangement (710, ECU 950) of the vehicle (900). The module (400) senses at least one physical parameter of the wheel (10, 2500, 3000) and generates a corresponding sensor signal for the processing arrangement (950). The processing arrangement (710, ECU 950) processes the sensor signal to compute information indicative of operation of the wheel (10, 2500, 3000). The apparatus (600, 680, 690, 2200) includes a sensor (118) for sensing an angular orientation (θ) of the wheel (600, 680, 690, 2200). The processing arrangement (710, ECU 950) is operable to process the sensor signal in respect of the angular orientation (θ, ω). Moreover, the module (400) senses dynamic changes occurring in the physical parameter within one or more revolutions of the wheel (10, 2500, 3000) as communicated in the sensor signal to the processing arrangement (710, ECU 950) for computing the information indicative of operation of the wheel (10, 2500, 3000).

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WHEEL-MONITORING APPARATUS

Field of the invention

The present invention relates to apparatus operable to monitor characteristics of wheels and/or their associated tyres; for example, to an apparatus for monitoring characteristics of wheels and/or their associated tyres and conveying information indicative of these aforementioned characteristics via a communication link to an electronic control unit (ECU) and/or control system, for example for user-display. Moreover, the present invention also concerns methods of monitoring characteristics of wheels and/or their associated tyres. Furthermore, the present invention also relates to software and software products executable on computing hardware for executing these aforesaid methods.

Background of the invention

Tyres, also known as "tires" in American-English, are critical components in road vehicles. Contemporary tyres not only ensure adhesion of their associated road vehicles to road surfaces in widely varying weather conditions, but also perform vibration and shock isolation functions. Moreover, during their operating lifetime, tyres are required to survive potentially up to several thousand or even millions of deformation cycles without exhibiting work-hardening failure, and yet exhibit a relatively modest degree of energy dissipation therein as a result of viscous dampening effects. As an additional operating requirement, contemporary tyres need to be robust against scuffing and objects impacting thereonto. Yet further, tubeless tyres are required to robustly grip onto their associated wheel hubs even when subject to considerable stresses, for example during emergency braking. In response to these aforementioned requirements for contemporary tyres, the tyres are constructed from elastic synthetic rubber, natural rubber and/or plastics material reinforced by meshes of metal wire, carbon fibre and similar. Modern tyres are therefore to be respected as highly optimized and advanced products.

Tyre failure during operation can potentially result in immobilization of an associated vehicle or even accident. Moreover, tyres operated at unsuitable pressures can adversely influence associated vehicle fuel economy; fuel economy is becoming increasingly pertinent in view of increases in fuel costs as well as in view of carbon dioxide generation and its perceived impact on World climate change.

It is known to mount sensors onto automobiles to monitor characteristics such as tyre pressure and acceleration in one or more orthogonal axes, and to convey information representative of these characteristics via wireless communication links to electronic control units (ECU) forming parts of data management systems of the vehicles. By employing such arrangements, it is possible to warn drivers of a need to inflate one or more tyres of their vehicles in order to improve driving quality and safety.

In a published Japanese patent no. JP 2003211924 (Mazda Motor), there is a disclosed a pneumatic sensor device suitable for use with a tyre of a vehicle for detecting tyre pressure and generating corresponding tyre pressure information. The device includes a transmitter for transmitting the pressure information together with an identification code for distinguishing the sensor device from other such sensor devices simultaneously included on other wheels of the vehicle. A control unit of the vehicle is operable to receive the transmitted pressure information and its associated identification code. The received pressure information is stored in a memory of the control unit. The control unit is operable to raise an alarm in an event that tyre pressure is not correct pursuant to predefined criteria.

In a published United Kingdom patent application no. GB 2385931 A, tyre monitors are described which are mounted adjacent to tyres near their tyre inflation valve stems. The tyre monitors include sensors to measure pressure, temperature and rotation direction of their respective tyres. Moreover, the monitors are operable to communicate measured sensor signals via transmitters to their respective receiver for subsequent processing and eventual presentation on a display unit. A vehicle mounted controller in communication with the receiver is operable to determine whether pressure information is associated with a front tyre or a rear tyre based on the strength of the wireless signal received at the receiver, and whether pressure data is associated with a right tyre or left tyre based on associated rotation direction data.

Commercial vehicles need to be operated as efficiently as possible to save on fuel costs, especially when heavy bulk goods are to be transported. Moreover, when commercial vehicles are non-operational, they are then not earning money for their fleet operators. Moreover, fleet operators often have contractual obligations to their customers to provide delivery within agreed deadlines, for example as in "just in time" manufacturing with critical delivery times.

A technical problem addressed by the present invention is therefore to provide a more advanced wheel and tyre monitoring apparatus. Moreover, the present invention seeks to provide such wheel and tyre monitoring apparatus in a manner better suited, for example, to the requirements of commercial fleet operators; such fleet operators can, for example, include heavy commercial vehicle fleet operators, taxi fleet operators, and automobile leasing and hiring enterprises.

Summary of the invention

An object of the present invention is to provide an improved wheel and/or tyre monitoring apparatus which is capable of enhancing safety and reliability of vehicles.

This object is addressed by a wheel-monitoring apparatus as defined in appended claim 1. According to a first aspect of the invention, there is provided a wheel-monitoring apparatus for monitoring operation of at least one wheel of a vehicle, the apparatus including one or more sensor modules operatively mounted to revolve with the at least one wheel, the one or more modules being operatively coupled in communication with a processing arrangement (ECU) of the vehicle, the one or more modules being operable to sense at least one physical parameter of the wheel and to generate at least one corresponding sensor signal for the processing arrangement, the processing arrangement (ECU) being operable to process the at least one sensor signal to compute information indicative of operation of the at least one wheel, the apparatus including a sensor arrangement for sensing an angular orientation (θ) of the at least one wheel,

characterized in that

the processing arrangement (ECU) is operable to process the at least one sensor signal in respect of the angular orientation (θ) and/or an angular frequency (ω) of rotation of said at least one wheel; and

the one or more modules are operable to sense dynamic changes occurring in the at least one physical parameter within one or more revolutions of the at least one wheel as communicated in the at least one sensor signal to the processing arrangement (ECU) for computing the information indicative of operation of the at least one wheel.

The invention is of advantage in that the apparatus is capable of providing enhanced monitoring of operation of the at least one wheel, thereby enhancing safety and reliability, by monitoring wheel characteristics within each revolution of the at least one wheel.

It will be appreciated that the angular frequency of rotation (ω) is derivable from a first-order time derivative of a corresponding angular orientation (θ), namely $\omega = d\theta/dt$.

Optionally, in the wheel-monitoring apparatus, the one or more modules include a temperature sensor for sensing a temperature (T_{mod}) thereat, the one or more modules being operable to communicate a signal indicative of the temperature (T_{mod}) to the processing arrangement (ECU) for use in computing the information indicative of operation of the at least one wheel. Monitoring the temperature (T_{mod}) enables a pressure (P) measured within a tyre or inflated cavity of the at least one wheel to be at least partially corrected for temperature effects when executing computations regarding wheel operation. Moreover, in an event that an excessive temperature rise is detected, a warning can be optionally issued by the apparatus.

Optionally, in the wheel-monitoring apparatus, the one or more modules include at least one of:

(a) a pressure sensor operable to sense a pressure (P) existing within a tyre or an inflated cavity of the at least one wheel, the one or more modules being operable to communicate a signal indicative of the pressure (P) to the processing arrangement (ECU) for use in computing the information indicative of operation of the at least one wheel;

(b) a strain gauge sensor for measuring flexure of the tyre or the inflated cavity of the at least one wheel, the module being operable to communicate a signal indicative of the flexure to the processing arrangement (ECU) for use in computing the information indicative of operation of the at least one wheel;

(c) an accelerometer for measuring acceleration (A_x, A_y, A_z) in at least one axis at a mounting location (L1, L2, L3; L4) of the one or more modules on the at least one wheel, the one or more modules being operable to communicate a signal indicative of the acceleration (A_x, A_y, A_z) to the processing arrangement (ECU) for use in computing the information indicative of operation of the at least one wheel; and

(d) a magnetic sensor for measuring a magnetic field applied to the one or more modules, the one or more modules being operable to communicate a signal indicative of the applied magnetic field to the processing arrangement (ECU) for use in controlling operation of the apparatus.

Such physical parameters have been found to be beneficial to monitor when assessing operation of the at least one wheel. It will be appreciated that the one or more modules can be equipped with a subset of the options (a) to (d); for example, a module can be provided with only a pressure sensor, or only an accelerometer, or a combination of a pressure sensor and an accelerometer. Moreover, certain modules are optionally provided with only a single-axis accelerometer, whereas other such modules are provided with triple-axis accelerometers. Other combinations of sensors included within the modules are possible pursuant to the present invention.

More optionally, in the wheel-monitoring apparatus, the accelerometer is a multi-axis accelerometer operable to measure components of acceleration (A_x, A_y, A_z) in at least one of radial, tangential and transverse axes in respect of rotations of the at least one wheel. For rendering the module compact and less expensive to manufacture, the accelerometer is beneficially a silicon micromachined device. Such silicon devices are extremely compact, robust, cost effective and are capable of providing precise and accurate measurement of acceleration.

More optionally, in the wheel-monitoring apparatus, the processing arrangement (ECU) is operable to apply auto-alignment to one or more sensing axes of the accelerometer to effectively align them to at least one of true radial, tangential and transverse axes in respect of rotations of the at least one wheel. Such auto-alignment is capable of simplifying installation of the one or more modules by rendering placement of the one or more modules on the at least one wheel less angularly critical.

More optionally, in the wheel-monitoring apparatus, the processing arrangement (ECU) includes an angular resolver for implementing the auto-alignment which is operable to seek during its calibration to null lateral acceleration components and to seek to null tangential acceleration components integrated over one or more complete revolutions of the at least one wheel. By applying such auto-alignment, more representative signals describing operation of the at least one wheel are derivable for the processing arrangement to analyse. Optionally, acceleration measurements can be implemented for a part of a revolution, for example a half-revolution, of the at least one wheel and the measurements for a remaining half-revolution of the at least one wheel synthesized therefrom for integration purposes; such an implementation is to be construed to mean integration for a complete revolution of the wheel.

Yet more optionally, in the wheel-monitoring apparatus, the processing arrangement (ECU) is operable to calibrate its auto-alignment during at least one of:

(a) a calibration procedure when configuring the processing arrangement (ECU) in relation to its one or more modules; and

(b) in a dynamic manner during driving of the vehicle.

Optionally, in the wheel-monitoring apparatus, the one or more modules are mounted at one or more locations (L1, L2, L3, L4) on the at least one wheel, the one or more locations including:

(a) on a hub of the at least one wheel substantially at an axis (B-B) of rotation of the at least one wheel;

(b) on a hub of the at least one wheel at a radial distance from the axis of rotation (B-B) of the at least one wheel;

(c) on a hub of the at least one wheel in fluid communication with a filling valve of a tyre or a filling valve of an inflatable cavity of the wheel for sensing a pressure (P) within the tyre or the cavity;

(d) within a tyre or an inflatable cavity of the at least one wheel for sensing a pressure (P) within the tyre or the cavity, the at least one module being mounted to a peripheral surface of a hub of the at least one wheel;

(e) within a tyre or an inflatable cavity of the wheel for sensing a pressure (P) within the tyre or the cavity, the one or more modules being mounted to an inside side-wall surface of the tyre or the cavity for measuring flexural characteristics of the side-wall; and

(f) on an inside surface of a peripheral rim of the at least one wheel for measuring acceleration thereat.

Mounting the one or more modules at these different locations is of benefit in that certain types of defect in the at least one wheel are more reliably sensed when the one or more modules are mounted at specific favourable locations. For example, wheel imbalance is better sensed with a module mounted on the wheel near its hub, whereas flexural characteristics of the tyre or inflatable cavity are better sensed with a module attached to a side wall of the tyre or flexible inflatable cavity. More optionally, a module is mounted to an inside rim of a tyre, adjacent to its treads.

Optionally, in the wheel-monitoring apparatus, the one or more modules include at least one wireless interface for communicating between the one or more modules and the processing arrangement (ECU), the one or more modules forming a wireless network wherein certain of the one or more modules are operable to function as one or more relay nodes for conveying signal exchange between the processing arrangement (ECU) and other of the one or more modules. By establishing such a communication network, modules mounted in wireless shadows where they are occluded by conductive elements are operable, via the network, to provide their measured signals to the processing arrangement.

Optionally, in the wheel-monitoring apparatus, the one or more modules include at least one wireless interface for communicating between the one or more modules and the processing arrangement (ECU), the one or more modules forming a wireless network which is dynamically reconfigurable for conveying signals between the one or more modules and the processing arrangement (ECU). An ability exhibited by the network to dynamically reconfigure itself is of advantage in that the apparatus is able to continue operating with reduced monitoring functionality in an event of one or more of the modules ceasing to provide their respective signals to the processing arrangement (ECU). Such a reconfigurable property of the network not only renders the apparatus more robust, but also allows the apparatus to adapt when additional modules are added to the apparatus.

Optionally, in the wheel-monitoring apparatus, the one or more modules include at least one wireless interface for communicating between the one or more modules and the processing arrangement (ECU), the one or more modules forming a wireless network which is dynamically reconfigurable in response to the one or more modules changing between functional and non-functional states in operation, for enabling the apparatus to continue to function with modified functionality in respect of monitoring operation of the at least one wheel. Such an operating characteristic circumvents the apparatus becoming non-function merely on account of one of its modules developing a problem in operation, for example its battery becomes fully discharged in operation.

Optionally, in the wheel-monitoring apparatus, the one or more modules are each provided with a corresponding identification code (ID) for communicating to the processing arrangement (ECU) so that the processing arrangement (ECU) is able to recognize from which module corresponding signal data has been sent. Use of such identification codes (ID) enables one or more wheels which have developed problems, or have been found to have potential problems, to be clearly identified and a corresponding unambiguous informative warning sent to the driver of the vehicle and/or to a service facility responsible for addressing such problems or potential problems.

Optionally, in the wheel-monitoring apparatus, the one or more modules include one or more sources of electrical power for energizing the one or more modules, the one or more sources of electrical power including at least one rechargeable battery and one or more generators for recharging the one or more sources, the one or more generators deriving energy from rotations of the at least one wheel. On account of the one or more modules rotating with their respective wheels, providing electrical slip rings or inductive electrical couplings represents a considerable practical complication, especially in view of regions around wheels of contemporary wheels already being heavily populated with other components such as ABS rotation sensors, disc brakes, suspension components and so forth. However, after prolonged use, local sources of power can become exhausted unless recharged or replaced; inclusion of the one or more generators are capable of addressing such problems.

More optionally, in the wheel-monitoring apparatus, the one or more generators are at least one of:

(a) an electromagnetic generator based upon movement of a mass operable to move in response to rotations of the at least one wheel; and
(b) a piezo-electric generator based upon force generated by a mass operable to apply a varying force to a piezo-electric device in response to rotations of the at least one wheel.

In order to gather more representative measurements indicative of operation of the at least one wheel, the wheel-monitoring apparatus is optionally implemented such that the one or more modules are radially distributed around the at least one wheel for sensing operation of the at least one wheel at a plurality of angular locations therearound.

Certain conductive components in and around the at least one wheel are susceptible to creating radio shadows and causing Faraday screening. In order to address problems arising from such radio shadows and Faraday screening, in the wheel-monitoring apparatus, at least one of the one or more modules optionally includes a wireless interface coupled to an electrically conducting mesh of a tyre of the at least one wheel, the conducting mesh being operable to function as a wireless patch antenna for the at least one module for supporting wireless communication between the at least module and the processing arrangement (ECU).

Optionally, the apparatus includes a display coupled in communication with the processing arrangement (ECU) for presenting information to a driver of the vehicle indicating at least one of:

(a) an operating status of the one or more modules;
(b) a condition of the at least one wheel;

(c) one or more faults or potential faults associated with the at least one wheel;

(d) information regarding one or more actions to be taken by a driver of the vehicle in an event of one or more faults or potential faults associated with the at least one wheel being identified; and

(e) an indication of whether or not at the at least one wheel of the vehicle has been modified.

The display is however not limited to displaying such information as in (a) to (e) and is optionally capable of presenting other analysis information provided from the processing arrangement, for example a time record of changes in one or more wheel parameters as sensed by the one or more modules; for example, the display can beneficially present a graph representing tyre pressure as a function of time, a list describing a configuration of modules presently coupled in communication with the processing arrangement, and so forth.

Optionally, in the wheel-monitoring apparatus, the processing arrangement (ECU) is provided with a wireless interface for communicating with a service facility remote from the vehicle, the processing arrangement (ECU) being operable to communicate information indicative of functionality of the at least one wheel, the information being indicative of one or more faults or potential faults associated with the at least one wheel as computed from signals provided from the one or more modules, and for receiving instructions from the service facility regarding actions to be taken for addressing the one or more faults or potential faults.

More optionally, for providing enhanced support for the vehicle, the wheel-monitoring apparatus further comprises a global positioning unit for generating a signal indicative of a spatial position of the vehicle, and for conveying information via the processing arrangement (ECU) to the wireless interface to the service facility indicative of the spatial position of the vehicle.

Optionally, the modules themselves are provided with local computing capability. Beneficially, in the wheel-monitoring apparatus, the one or more modules include a processor coupled to an associated data memory, the one or more modules via their pressure sensors being operable to record a pressure (P) within a tyre or inflated cavity of the at least one wheel in relation to time (t) as determined by a clock arrangement (CLK) included within the one or more modules, and the processor is operable to monitor changes in the pressure (P) with time (t) to identify one or more of:

(a) a gradual leak of air or gas from the tyre or inflated cavity indicative of a need to recharge the tyre or inflated cavity with air or gas;

(b) any abrupt depressurization of the tyre or inflated cavity indicative of a puncturing or rapid deflation event having occurred, or the tyre or inflated cavity having been exchanged.

Such processing is useful for detecting events, for example unauthorized swapping of tyres or tampering events, occurring when an associated wheel is temporarily dismantled from the vehicle and outside a wireless communication range of the processing arrangement (ECU). More optionally, in the wheel-monitoring apparatus, the one or modules are operable to communicate to the processing arrangement a message that sensed data pertaining to the tyre or inflated cavity of the at least one wheel being potentially unreliable due to the abrupt depressurization. Generation of such a message is useful for enhancing safety; unauthorized or unintentional swapping of a tyre or wheel of the vehicle can potentially contribute to safety risks or degraded reliability about which the driver of the vehicle is beneficially informed.

Optionally, in the wheel-monitoring apparatus, the one or more modules are operable to monitor the pressure (P), irrespective of whether or not the one or more modules are in their hibernating energy-saving state. Such operation renders tampering executed on the vehicle when in a parked state detectable.

Optionally, in the wheel-monitoring apparatus, the one or more modules are operable to switch between an active state and an energy-saving hibernating state. The hibernating state is of benefit in that it prolongs a period of use of the batteries associated with the one or more modules and renders frequent recharging of the batteries less necessary thereby prolonging their operating lifetime. Rechargeable batteries are only capable of withstanding a finite number of discharge cycles before their electrical storage capacity deteriorates.

Optionally, in the wheel-monitoring apparatus, the one or more modules are operable to switch between the active state and the hibernating state in response to one or more instructions communicated by wireless to the one or more modules. By using such wireless instructions, it is feasible to force all the one or more modules into their hibernating state promptly after, for example, parking the vehicle and switching-off its combustion engine; the hibernating state conserves energy in batteries of the one or more modules when the vehicle is not in use. Likewise, a single wireless instruction is capable of waking up the one or more modules from their hibernating state when the vehicle is started again.

Optionally, in the wheel-monitoring apparatus, the one or more modules are themselves capable of autonomously switching to their hibernating state to conserve their batteries.

Beneficially, the one or more modules are operable to switch from the active state to the energy-saving hibernating state in response to a period of time (t) in which the one or more modules detect one or more of:

(a) a cessation of changes in pressure (P) of a tyre or inflated cavity of the at least one wheel during a predetermined period of time (t); and

(b) a cessation of changes in acceleration (A_x, A_y, A_z) sensed on the at least one wheel during a predetermined period of time (t).

Similarly, the one or modules are beneficially capable of automatically and autonomously returning to their active state without the processing arrangement needing to send any explicit instructions. Beneficially, in the wheel-monitoring apparatus, the one or more modules are operable to switch from the energy-saving hibernating state to the active state in response to the one or more modules detecting one or more of:

(a) a resumption of changes in pressure (P) of a tyre or inflated cavity of the at least one wheel associated with rotations of the at least one wheel; and

(b) a resumption of changes in acceleration (A_x, A_y, A_z) sensed on the at least one wheel.

In their hibernating state, the one or more modules are beneficially operable to briefly switch momentarily to their active state to identify whether the processing arrangement is issuing a active state command and/or physical parameters such as pressure and/or acceleration have began to fluctuate in a manner indicative that the at lest one wheel is in motion.

Optionally, in the wheel-monitoring apparatus, the at least one physical parameter includes at least one of:

(a) a pressure (P) within a tyre or inflated cavity of the at least one wheel as measured at the one or more modules;

(b) an acceleration (A_x, A_y, A_z) as measured substantially at the one or more modules;

wherein the processing arrangement (ECU) is operable to apply an harmonic analysis to signals corresponding the pressure (P) and/or the acceleration (A_x, A_y, A_z), the harmonic analysis being operable to identify harmonic components in respect of angular frequency (ω) corresponding to a temporal rate of change of the angular orientation (θ) of the at least one wheel.

Optionally, in the wheel-monitoring apparatus, the harmonic analysis applies computation to at least one of:

(a) magnitudes of the harmonic components; and

(b) relative phase relationships between the harmonic components.

Certain problems or potential problems are susceptible to being identified merely by processing magnitudes of the harmonic components, whereas detection of flexural problems beneficially requires analysis of both harmonic magnetic and relative harmonic phase data in the processing arrangement; see Figure 10 for example regarding skewing of presented peaks on account of changes in relative phase in harmonic components identified by the processing arrangement.

Optionally, in the wheel-monitoring apparatus, the processing arrangement (ECU) is operable to employ the harmonic analysis for identifying an occurrence of at least one of:

(a) the at least one wheel is imbalanced;
(b) a specific type of imbalance is present in the at least one wheel;
(c) the at least one wheel is skewed in relation to its axle;
(d) the at least one wheel is loose and wobbling about on its fasteners;
(e) a tyre, an inflated cavity and/or a spring matrix of the at least one wheel has defects in its flexural characteristics;
(f) a tyre or an inflated cavity of the at least one wheel is insufficiently inflated;
(g) a tyre or an inflated cavity of the at least one wheel is over inflated;
(h) a tyre or an inflated cavity of the at least one wheel is oval or has a higher-order lobed distortion;
(i) the at least one wheel has a mass imbalance therein; and
(j) wheel bearings associated with an axle rotationally supporting the at least one wheel in operation are vibrating or rattling in an unexpected manner indicative of a fault, or a potentially developing fault.

The processing arrangement is not limited to detecting problems (a) to (j) above and is capable of detecting other problems, for example rattling noises in bearings associated with an axle of the wheel as manifested in acceleration or acoustic sensed signals at the one or more modules.

Optionally, in the wheel-monitoring apparatus, the processing arrangement (ECU) is operable to perform the analysis of the harmonic components by applying:

(a) a rule-based algorithm for identifying one or more faults or potential faults from the harmonic components; and/or
(b) a neural network pre-programmed to identify one or more faults or potential faults when presented with data describing the harmonic components; and/or
(c) an harmonic filter for highlighting a specific combination of one or more harmonic components which are indicative of one or more faults or potential faults with the at least one wheel.

Other approaches to harmonic component analysis can optionally also be employed in the apparatus.

Beneficially, in the wheel-monitoring apparatus, the processing arrangement (ECU) is provided with a predetermined list of types of wheels susceptible to being employed with the vehicle and associated expected characteristics, and the one or more modules are operable to communicate information to the processing arrangement (ECU) regarding an identification of a type of wheel onto which the one or more modules are mounted, and the processing arrangement (ECU) is operable to compare measured signals provided from the one or more modules with signals that would be expected from the one or more modules as simulated from the predetermined list, and wherein a disparity between the measured signals and the simulated signals is indicative of one or more faults or potential faults. Such an approach is susceptible to avoiding a need to perform an harmonic analysis and therefore is computationally less intensive for the processing arrangement.

Optionally, computational load within the vehicle is distributed so as to avoid causing data processing overload at the processing arrangement, especially when many of the modules are included on wheels of the vehicle. Beneficially, in the wheel-monitoring apparatus, the one or more modules include one or more processors therein, and computation effort executed in operation for identifying one or more faults or potential faults in the at least one wheel is shared between the one or more processors and the processing arrangement (ECU).

In order that the processing arrangement is operable to perform a correct monitoring of wheels of the vehicle, it requires a recent list or record of modules present on the wheels. In order to compile such a list or record in the wheel-monitoring apparatus, the processing arrangement (ECU) is operable to send a message requesting the one or more modules to respond back to the processing arrangement (ECU) for declaring their identification codes (ID) to the processing arrangement (ECU) for enabling the processing arrangement to identify its configuration of one or more modules, and for identifying any changes in the configuration of one or more modules occurring.

Optionally, to assist with detection of problems or potential problems, the wheel-monitoring apparatus is implemented such that the one or more modules are operable to also respond with data indicative of expected characteristics of the at least one wheel to which the one of more modules are mounted.

Operational integrity the wheel-monitoring apparatus is desirable so that detection of problems and potential problems is as effective as possible. Beneficially, in the wheel-monitoring apparatus, the processing arrangement (ECU) is operable to compare rotation measurements from the sensor arrangement for sensing the angular orientation (θ) of the at least one wheel against signals supplied from the one or more corresponding modules for checking functional operation of the sensor arrangement and/or the one or more modules.

Optionally, so as to obtain greater functionality from existing components already included on the vehicle, when implementing the wheel-monitoring apparatus, the sensor arrangement is an ABS wheel angular orientation sensor associated with brakes of the vehicle.

According to a second aspect of the invention, there is provided a method as defined in appended claim 38. There is provided a method for monitoring operation of at least one wheel of a vehicle using a wheel-monitoring apparatus pursuant to the first aspect of the invention, the apparatus including one or more sensor modules operatively mounted to revolve with the at least one wheel, the one or more modules being operatively couplable in communication with a processing arrangement (ECU) of the vehicle,

the method including steps of:

(a) sensing using the one or more modules at least one physical parameter of the at least one wheel and to generate at least one corresponding sensor signal for the processing arrangement;

(b) sensing an angular orientation (θ) of the at least one wheel using a sensor arrangement of the apparatus;

(c) processing in the processing arrangement (ECU) the at least one sensor signal to compute information indicative of operation of the at least one wheel,

characterized in that

the processing arrangement (ECU) is operable to process the at least one sensor signal in respect of the angular orientation (θ) and/or an angular frequency (ω) of rotation of said at least one wheel; and

the at least one module is operable to sense dynamic changes occurring in the at least one physical parameter within one or more revolutions of the at least one wheel as communicated in the at least one sensor signal to the processing arrangement (ECU) for computing the information indicative of operation of the at least one wheel.

Optionally, the method includes steps of sensing a temperature (T_{mod}) of the one or more modules using a temperature sensor thereat, and communicating from the one or more modules a signal indicative of the temperature (T_{mod}) to the processing arrangement (ECU) for use in computing the information indicative of operation of the at least one wheel.

Optionally, when implementing the method, the one or more modules include at least one of:

(a) a pressure sensor operable to sense a pressure (P) existing within a tyre or an inflated cavity of the at least one wheel, the one or more modules being operable to communicate a signal indicative of the pressure (P) to the processing arrangement (ECU) for use in computing the information indicative of operation of the at least one wheel;

(b) a strain gauge sensor for measuring flexure of the tyre or the inflated cavity of the at least one wheel, the one or more modules being operable to communicate a signal indicative of the flexure to the processing arrangement (ECU) for use in computing the information indicative of operation of the at least one wheel;

(c) an accelerometer for measuring acceleration (A_x, A_y, A_z) in at least one axis at a mounting location (L1, L2, L3, L4) of the one or more modules on the at least one wheel, the one or more modules being operable to communicate a signal indicative of the acceleration (A_x, A_y, A_z) to the processing arrangement (ECU) for use in computing the information indicative of operation of the at least one wheel; and

(d) a magnetic sensor for measuring a magnetic field applied to the one or more modules, the one or more modules being operable to communicate a signal indicative of the applied magnetic field to the processing arrangement (ECU) for use in controlling operation of the apparatus.

More optionally, when implementing the method, the accelerometer is a multi-axis accelerometer operable to measure components of acceleration (A_x, A_y, A_z) in at least one of radial, tangential and transverse axes in respect of rotations of the at least one wheel. Beneficially, the accelerometer is a silicon micromachined (MEMS) device.

Optionally, the method includes a step of applying auto-alignment using the processing arrangement (ECU) to one or more sensing axes of the accelerometer to effectively align them to at least one of true radial, tangential and transverse axes in respect of rotations of the at least one wheel.

More optionally, when implementing the method, the processing arrangement (ECU) includes an angular resolver for implementing the auto-alignment which is operable to seek during its calibration to null lateral acceleration components and to seek to null tangential acceleration components integrated over one or more complete revolutions of the at least one wheel.

More optionally, when implementing the method, the processing arrangement (ECU) is operable to calibrate its auto-alignment during at least one of:

(a) a calibration procedure when configuring the processing arrangement (ECU) in relation to its at least one module; and

(b) in a dynamic manner during driving of the vehicle.

Optionally, when implementing the method, the one or more modules are mounted at one or more locations (L1, L2, L3, L4) on the at least one wheel, the one or more locations including:

(a) on a hub of the at least one wheel substantially at an axis (B-B) of rotation of the at least one wheel;

(b) on a hub of the at least one wheel at a radial distance from the axis of rotation (B-B) of the at least one wheel;

(c) on a hub of the wheel in fluid communication with a filling valve of a tyre or a filling valve of an inflated cavity of the at least one wheel for sensing a pressure (P) within the tyre or the cavity;

(d) within a tyre or an inflatable cavity of the at least one wheel for sensing a pressure (P) within the tyre or the cavity, the one or more modules being mounted to a peripheral surface of a hub of the at least one wheel;

(e) within a tyre or an inflatable cavity of the wheel for sensing a pressure (P) within the tyre or the cavity, the one or more modules being mounted to an inside side-wall surface of the tyre or the cavity for measuring flexural characteristics of the side-wall; and

(f) on an inside surface of a peripheral rim of the at least one wheel for measuring acceleration thereat.

More optionally, when implementing the method, the one or more modules include at least one wireless interface for communicating between the one or more modules and the processing arrangement (ECU), the one or more modules forming a wireless network wherein certain of the one or more modules are operable to function as one or more relay nodes for conveying signal exchange between the processing arrangement (ECU) and other of the one or more modules.

Optionally, when implementing the method, the one or more modules include at least one wireless interface for communicating between the one or more modules and the processing arrangement (ECU), the one or modules forming a wireless network which is dynamically reconfigurable for conveying signals between the one or more modules and the processing arrangement (ECU).

Optionally, when implementing the method, the one or more modules include at least one wireless interface for communicating between the one or more modules and the processing arrangement (ECU), the one or more modules forming a wireless network which is dynamically reconfigurable in response to the one or more modules changing between functional and non-functional states in operation, for enabling the apparatus to continue functioning with modified functionality when monitoring operation of the at least one wheel.

Optionally, when implementing the method, the one or more modules are each provided with a corresponding identification code (ID) for communicating to the processing arrangement (ECU) so that the processing arrangement (ECU) is able to recognize from which module corresponding signal data has been sent.

Optionally, when implementing the method, the one or more modules include one or more sources of electrical power for energizing the one or more modules, the one or more sources of electrical power including at least one rechargeable battery and one or more generators for recharging the one or more sources, the one or more generators deriving energy from rotations of the at least one wheel. The one or more generators are beneficially at least one of:

(a) an electromagnetic generator based upon movement of a mass operable to move in response to rotations of the at least one wheel; and
(b) a piezo-electric generator based upon force generated by a mass operable to apply a varying force to a piezo-electric device in response to rotations of the at least one wheel.

Optionally, to improve wheel problem detection, the method is implemented so that the one or more modules are radially distributed around the at least one wheel for sensing operation of the at least one wheel at a plurality of angular locations therearound.

Optionally, when implementing the method, at least one of the one or more modules includes a wireless interface coupled to an electrically conducting mesh of a tyre of the at least one wheel, the conducting mesh being operable to function as a wireless patch antenna for the at least one of the one or more modules for supporting wireless communication between the at least one of the one or more modules and the processing arrangement (ECU).

Optionally, when implementing the method, the apparatus includes a display coupled in communication with the processing arrangement (ECU) for presenting information to a driver of the vehicle indicating at least one of:

(a) an operating status of the one or more modules;

(b) a condition of the at least one wheel;

(c) one or more faults or potential faults associated with the at least one wheel;

(d) information regarding actions to be taken by a driver of the vehicle in an event of one or more faults or potential faults associated with the at least one wheel being identified; and

(e) an indication of whether or not one or more wheels of the vehicle have been modified.

Optionally, when implementing the method, the processing arrangement (ECU) is provided with a wireless interface for communicating with a service facility remote from the vehicle, the processing arrangement (ECU) being operable to communicate information indicative of functionality of the at least one wheel, the information being indicative of one or more faults or potential faults associated with the at least one wheel as computed from signals provided from the one or more modules, and for receiving instructions from the service facility regarding actions for addressing the one or more faults or potential faults.

Optionally when implementing the method, there is employed a global positioning unit for generating a signal indicative of a spatial position of the vehicle, and for conveying information via the processing arrangement (ECU) to the wireless interface to the service facility indicative of the spatial position of the vehicle.

Optionally, when implementing the method, the one or more modules include a processor coupled to an associated data memory, the one or more modules via their pressure sensors being operable to record a pressure (P) within a tyre or inflatable cavity of the at least one wheel in relation to time (t) as determined by a clock arrangement (CLK) included within the one or more modules, and the processor is operable to monitor changes in the pressure (P) with time (t) to identify one or more of:

(a) a gradual leak of air or gas from the tyre or inflatable cavity indicative of a need to recharge the tyre or inflatable cavity with air or gas;

(b) any abrupt depressurization of the tyre or inflatable cavity indicative of a puncturing event or a rapid deflation event having occurred, or the tyre or inflatable cavity having been exchanged.

Optionally, when implementing the method, the one or more modules are operable to communicate to the processing arrangement a message that sensed data pertaining to the tyre or inflatable cavity of the at least one wheel being potentially unreliable on account of the abrupt depressurization of the tyre or cavity.

More optionally, when implementing the method, the one or more modules are operable to monitor the pressure (P), irrespective of whether or not the one or more modules are in their hibernating energy-saving state.

Optionally, when implementing the method, the one or more modules are operable to switch between an active state and an energy-saving hibernating state. Beneficially, the one or more modules are operable to switch between the active state and the hibernating state in response to one or more instructions communicated by wireless to the one or more modules.

Optionally, when implementing the method, the one or more modules are operable to switch from the active state to the energy-saving hibernating state in response to a period of time (t) in which the one or more modules detect one or more of:

(a) a cessation of changes in pressure (P) of a tyre or inflatable cavity of the at least one wheel during a predetermined period of time (t); and

(b) a cessation of changes in acceleration (A_x, A_y, A_z) sensed on the at least one wheel during a predetermined period of time (t).

Optionally, when implementing the method, the one or more modules are operable to switch from the energy-saving hibernating state to the active state in response to the one or more modules detecting one or more of:

(a) a resumption of changes in pressure (P) of a tyre or inflatable cavity of the at least one wheel associated with rotations of the at least one wheel; and

(b) a resumption of changes in acceleration (A_x, A_y, A_z) sensed on the at least one wheel.

Optionally, the method is implemented such that the at least one physical parameter includes at least one of:

(a) a pressure (P) within a tyre or inflatable cavity of the at least one wheel as measured at the one or more modules;

(b) an acceleration (A_x, A_y, A_z) as measured substantially at the one or more modules;

wherein the processing arrangements (ECU) is operable to apply an harmonic analysis to signals corresponding to the pressure (P) and/or the acceleration (A_x, A_y, A_z), the harmonic analysis being operable to identify harmonic components in respect of angular frequency (ω) corresponding to a temporal rate of the angular orientation (θ) of the at least one wheel.

More optionally, when implementing the method, the harmonic analysis includes computations pertaining to at least one of:

(a) magnitudes of the harmonic components; and

(b) relative phase relationships between the harmonic components.

More optionally, when implementing the method, the processing arrangement (ECU) is operable to employ the harmonic analysis for identifying an occurrence of at least one of:

(a) the at least one wheel is imbalanced;

(b) a specific type of imbalance present in the at least one wheel;

(c) the at least one wheel is skewed in relation to its axle;

(d) the at least one wheel is loose and wobbling about on its fasteners;

(e) a tyre, an inflatable cavity and/or a spring matrix of the at least one wheel has defects in its flexural characteristics;

(f) a tyre or an inflatable cavity of the at least one wheel is insufficiently inflated;

(g) a tyre or an inflatable cavity of the at least one wheel is over inflated;

(h) a tyre or an inflatable cavity of the at least one wheel is oval or has a higher-order lobed distortion;

(i) the at least one wheel has a mass imbalance therein; and

(j) wheel bearings associated with an axle rotationally supporting the at least one wheel in operation are vibrating or rattling in an unexpected manner indicative of a fault, or a potentially developing fault.

More optionally, when implementing the method, the processing arrangement (ECU) is operable to perform the analysis of the harmonic components by applying:

(a) a rule-based algorithm for identifying one or more faults or potential faults from the harmonic components; and/or

(b) a neural network pre-programmed to identify one or more faults or potential faults when presented with data describing the harmonic components; and/or

(c) a harmonic filter for highlighting a specific combination of one or more harmonic components which are indicative of one or more faults or potential faults with the at least one wheel.

Optionally, to reduce computational load when implementing the method, the processing arrangement (ECU) is provided with a predetermined list of types of wheel susceptible to being employed with the vehicle and associated expected characteristics, and the one or more modules are operable to communicate information to the processing arrangement (ECU) regarding an identification of a type of wheel onto which the one or more modules are mounted, and the processing arrangement (ECU) is operable to compare measured signals provided from the one or more modules with signals that would be expected from the one or more modules as simulated from the predetermined list, and wherein a disparity between the measured signals and the simulated signals is indicative of one or more faults or potential faults.

Optionally, for distributing computation load when implementing the method, the one or more modules include one or more processors therein, and computation effort executed in operation for identifying one or more faults or potential faults in the at least one wheel is shared between the one or more processors and the processing arrangement (ECU).

Optionally, when implementing the method, the processing arrangement (ECU) is operable to send a message requesting the one or more modules to respond back to the processing arrangement (ECU) for declaring their identification codes (ID) to the processing arrangement (ECU) for enabling the processing arrangement to identify its configuration of one or more modules, and for identifying any changes in the configuration of one or more modules occurring.

Optionally, when implementing the method, the one or more modules are operable to also respond with data indicative of expected characteristics of the at least one wheel to which the one of more modules are mounted.

Optionally, when implementing the method, the processing arrangement (ECU) is operable to compare rotation measurements from the sensor arrangement for sensing the angular orientation (θ) of the at least one wheel against signals supplied from the one or more corresponding modules for checking functional operation of the sensor arrangement and/or the one or more modules. More optionally, the sensor arrangement is beneficially an ABS sensor associated with brakes of the vehicle.

According to a third aspect of the invention, there is provided a vehicle including a wheel-monitoring apparatus pursuant to the first aspect of the invention, the apparatus being operable to monitor operation of at least one wheel of the vehicle.

Optionally, the vehicle is at least one of: a heavy commercial vehicle, a construction vehicle, an automobile, a motorcycle, a scooter, an aircraft, a helicopter, a bicycle. Additionally, the present invention is susceptible to being adapted for other uses, for example for monitoring a rotor of an electrical wind turbine operable to generate electricity from wind power.

According to a fourth aspect of the present invention, there is provided a wheel including one or more modules mounted thereonto, the one or more modules operable to function with a wheel-monitoring apparatus pursuant to the first aspect of the invention.

According to a fifth aspect of the invention, there is provided a module for mounting onto a wheel operable to function with a wheel-monitoring apparatus pursuant to the first aspect of the invention.

According to a sixth aspect of the invention, there is provided a tyre for a vehicle, said tyre including a module pursuant to the fifth aspect of the invention.

Optionally, the module is mounted to a side wall of the tyre.

According to a seventh aspect of the present invention, there is provided a software product recorded on a data carrier, the product being executable on computing hardware for executing a method pursuant to the aforementioned second aspect of the invention.

Features of the invention are susceptible to being combined together in any combination without departing from the scope of the invention as defined by the appended claims.

Description of the diagrams

Embodiments of the present invention will now be described, by way of example only, with reference to the following diagrams wherein:

Figure 1 is an illustration of a wheel of a contemporary heavy commercial vehicle;

Figure 2 is a schematic cross-sectional view of a portion of the wheel of Figure 1;

Figure 3 is a schematic cross-sectional view of a tyre (tire) of the wheel of Figure 1;

Figure 4 is a cross-sectional view of a contemporary front wheel assembly of a heavy commercial vehicle;

Figure 5 is a cross-sectional view of a contemporary rear wheel assembly of a heavy commercial vehicle;

Figure 6 is a schematic cross-sectional view of the wheel of Figure 1 illustrating potential locations for mounting monitoring modules pursuant to the present invention; the potential locations include hub-mounting at a location L1, hub rim-mounting at a location L2, and in-tyre mounting at a location L3 or L4;

Figure 7 is a schematic cross-sectional view of a tyre of the wheel of Figure 1 with its monitoring module mounted at a location L2 on a rim of a hub of the wheel with a wire connection from the module to a patch antenna exposed on the hub;

Figure 8 is a schematic cross-sectional view of a tyre of the wheel of Figure 1 with its monitoring module mounted at a location L3 on the tyre, the module being provided with a film antenna wrapped around an edge of the tyre and exposed on an exterior surface of the tyre;

Figure 9 is a schematic diagram illustrating spatial movement of a monitoring module mounted on the wheel of Figure 1, together with a representation of a spring suspension together with a representation of forces acting upon the wheel when in operation;

Figure 10 is an graph illustrating a general form of acceleration signal obtainable in operation from the monitoring module mounted at the location L3 as shown in Figure 6;

Figure 11 is a first embodiment of a wheel- and tyre-monitoring apparatus pursuant to the present invention for use with the wheel of Figure 1, the monitoring apparatus being operable to process acceleration signals;

Figure 12 is a second embodiment of a wheel- and tyre-monitoring apparatus pursuant to the present invention for use with the wheel of Figure 1; the monitoring apparatus being operable to process pressure signals;

Figure 13 is a third embodiment of a wheel- and tyre-monitoring apparatus pursuant to the present invention for use with the wheel of Figure 1, the monitoring apparatus being operable to process both acceleration and pressure signals;

Figure 14 is a schematic diagram of a monitoring module operable to be mounted onto the wheel of Figure 1 and to sense operation characteristics of the wheel 10;

Figures 15a to 15e illustrate various alternative network communication topographies for monitoring modules mounted at various location on the wheel of Figures 1 and 6;

Figure 16 is a schematic illustration of a wheel monitoring system pursuant to the present invention for a heavy commercial vehicle in conjunction with a remote control facility and service facility;

Figure 17 is an illustration of the wheel of Figure 1 provided with a module including an accelerometer, the module and its accelerometer being mounted such that its sensing axes are angularly misaligned with true traverse, radial and tangential axes of the wheel;

Figure 18 is a fourth embodiment of a wheel- and tyre-monitoring apparatus pursuant to the present invention for use with the wheel of Figure 17, the monitoring apparatus being operable to process acceleration signals;

Figure 19 is an illustration of a wheel including an air-less tyre based upon a spring matrix providing the wheel with elasticity, the wheel being provided with modules suitable for use in implementing a monitoring apparatus pursuant to the present invention; and

Figure 20 is an illustration of a wheel including a hybrid suspension system comprising an outer spring matrix and an inner inflatable flexible cavity, the outer spring matrix and the inflatable cavity when inflated cooperating to provide the wheel with elasticity, the wheel and its hybrid suspension being provided with modules suitable for use in implementing a monitoring apparatus pursuant to the present invention.

Description of embodiments of the invention

Commercial enterprises which operate fleets of vehicles, for example fleets of heavy commercial vehicles, face different problems with vehicle maintenance and safety in comparison to private automobile owners for which contemporary tyre monitoring devices have already been developed as elucidated in the foregoing. Reliability and safety for an enterprise operating a fleet of vehicles is extremely important on account of one accident, breakdown or legal incident potentially adversely affecting the enterprise's reputation and relationship with its customers. Vehicle maintenance, and avoidance of vehicle technical problems before they arise and cause disruption, is of considerable importance to enterprises operating fleets of vehicles.

In a fleet of vehicles, for example heavy commercial vehicles, there are multiple vehicles, and a set of wheel hubs for the vehicles which are equipped with new tyres at various times. Wheel hubs can potentially be swapped between vehicles and be sporadically furnished with new tyres when their existing tyres are deemed to have been worn out. Moreover, in certain climates, for example Northern Europe and Canada, there is a legal requirement to switch between winter tyres and summer tyres; such switch between winter tyres and summer tyres is achieved by exchanging wheel hubs rather than removing tyres from their respective hubs.

Enterprises operating fleets of vehicles normally achieve greatest commercial efficiency when their vehicles are virtually all in use earning revenue; vehicles undergoing repair or standing idle represent an investment which does not generate profit, and can even represent a depreciation in value. An issue associated therewith is efficient maintenance of vehicles which are intensively in use, especially with regard to their wheels and tyres. The present invention is of benefit by enabling improved monitoring and prediction of potential problems with wheels and tyres; fleet vehicles can, for example, be recalled or rescheduled for maintenance purposes. Increased quality of monitoring is achieved by using more optimal and innovative sensor configurations and associated data processing.

Referring to Figure 1, there is shown in side view a schematic diagram of a wheel of a heavy commercial vehicle. The wheel is indicated generally by **10.** Moreover, the wheel **10** comprises a steel hub indicted by **20** and a tyre (tire) denoted by **30.** The tyre **30** is contemporarily often tubeless, namely does not include any separate inner tube. A circular inner flange **40** of the hub **20** includes a circular arrangement of mounting holes **50** for receiving bolts or similar fasteners for attaching the wheel **10** to an axle (not shown in Figure 1) of its associated vehicle. Extending radially outwards from the inner flange **40** is a substantially frusto-conical web **60** having a radial series of circular or elliptical ventilation holes **70** formed therein as illustrated, for example one of these ventilation holes **70** enables access to an air valve **80** in fluid (air) communication with a volume enclosed by the tyre **30** for purposes of inflating or deflating the tyre **30.** At its perimeter, the frusto-conical web **60** is coupled to a circular rim **90** for receiving the tyre **30.**

In Figure 1, a cross-sectional axis is denoted by A-A and a corresponding cross-sectional view of the wheel **10** is shown in Figure 2 for substantially an upper portion of the wheel **10.** The wheel **10** has a general form which has evolved over many years to substantially an optimal implementation for reasons which will now be elucidated. The inner flange **40** is provided with its regularly spaced configuration of mounting holes **50** for mounting the wheel **10** securely using aforementioned bolts or fasteners to an end of a wheel axle **110** of the corresponding vehicle; the wheel axle **110** is operable to rotate about an axis **B-B.** An excess of holes **50** is often provided to be certain of retaining the wheel **10** onto the wheel axle **110.** Usually, for heavy commercial vehicles, a disc brake **115** is included near an end of the wheel axle **110** in relative close proximity to the frusto-conical web **60** and its associated ventilation holes **70.** Moreover, an ABS angular sensor encoder **118** for implementing an ABS baking system for sensing an angular orientation of the axle **110** and hence that of the wheel **10** is contemporarily included as standard components on heavy commercial vehicles; the angular sensor encoder **118** is operable to generate a signal indicative of an angular orientation θ of the wheel **10.** The angular sensor encoder **118** is often implemented as an optical, electrostatic and/or magnetic sensing device.

In operation, when bringing a commercial vehicle weighing 10 tonnes from a speed of 80 km/hour to standstill within a few seconds corresponds to absorbing kinetic energy in an order of 3×10^6 Joules which can result in an instantaneous rate of energy dissipation in the disc brake **115** associated with the axle **110** in an order of ten's of kilowatts. The holes **70** in the frusto-conical web **60** thus enable air circulation to reach one or more metal discs of the disc brake **115** for cooling purposes. Moreover, the holes **70** in the web **60** also assist to reduce an unsprung weight of the wheel **10** without adversely influencing its mechanical strength, as well as providing access for the valve **80**. The rim **90** has various ridges formed therein to enhance its mechanical strength and also has end ridges **170** to provide reliable retention of the tyre **30** in operation. The tyre **30** encloses a volume denoted by **120** which is maintained at an elevated pressure P during operation.

Referring next to Figure 3, an illustrative cross-sectional view of a portion of the tyre **30** is shown. The tyre **30** includes inner edges **180** for abutment onto the ridges **170** of the circular rim **90**. The inner edges **180** are often reinforced using steel rings or bands **200** molded into the tyre **30**. Moreover, the tyre **30** includes one or more reinforced woven metal and/or reinforced fibre meshes **210** embedded by molding into the tyre **30**. A tread portion **220** of the tyre **30** has a greater radial thickness in comparison to a lateral thickness of side walls **230** of the tyre **30**; the tread portion **220** is thicker for accommodating treads of the tyre **30**. In operation, the tread portion **220** is operable to provide a firm grip to a road surface (not shown) as well as a water draining function, whereas the walls **230** are designed to periodically elastically flex when the wheel **10** with its associated tyre **30** rotate in operation on the road surface.

There are several potential modes of failure of the tyre **30**, and even of the wheel **10**, which an enterprise operating a fleet of vehicles, for example heavy commercial vehicles, employing such wheels **10** would desire to identify and correct before various modes of failure cause breakdown, accident or delay involving vehicles. Problems that are encountered include:

(a) the air pressure P in the tyre **30** is too low causing excessive flexure of the walls **230** and associated one or more meshes **210** with a risk of them work-hardening and prematurely fracturing; when the air pressure P is too low, there arises an excessive contact area between the tyre **30** and a road surface interfacing to the tyre **30** causing excessive tyre wear, and also increased rolling resistance and hence poor vehicle fuel economy; too much contact area between the tyre **30** and the road surface can also paradoxically result in inferior grip between the tyre **30** and the road surface in icy and snowy conditions because contact force between the tyre **30** and the road surface is not as concentrated as ideally desired to force the tyre **30** to conform to surface irregularities in the road surface susceptible to providing grip. Excess deformation of the tyre **30** when its internal air pressure P is too low potentially causes excess energy dissipation by a degree of non-elastic deformation within the tyre **30** with associated temperature rise resulting therefrom which can, in a worst case, exceed a temperature which material from which the tyre **30** is fabricated is able to tolerate. Moreover, when the pressure P within the tyre **30** is too low, there is also a risk that the inner edges **180** loose their seal with the ridges **170** when subject to severe lateral stress, for example when scuffing along a curb stone, with subsequent sudden loss of air from the tyre **30**;

(b) one or more of bolts or fasteners applied to the holes **50** for securing the wheel **10** to the wheel axle **110** can potentially be inadequately tightened during attachment of the wheel **10** to the axle **110**, or are susceptible to potentially working loose in operation; such loosening and potential loss of one or more of the bolts or fasteners can result in the wheel **10** wobbling or rattling on the axle **110** and, in a worst case, even becoming detached from the axle 110 and rolling off (!);

(c) the tyre **30** and/or the valve **80** can develop a leak such that a partial loss of the pressure P within the tyre **30** in operation arises; if such loss of pressure P is undetected, problems as outlined in (a) in the foregoing can potentially arise; however, the pressure P is a function of a temperature of the tyre T_{tyre}, and also whether or not the tyre **30** is periodically maintained by being recharged with compressed air or other gas through its valve **80**;

(d) the tyre **30** can develop in use an imbalance, for example a portion of rubber of the tyre **30** can become unevenly eroded with use, or a balancing weight earlier added to the wheel **10** can become detached from the wheel **10**; in a situation of a double-tyre arrangement as illustrated in Figure 5 often employed at a rear of a heavy commercial vehicle, it is known for a building brick or similar object to occasionally become wedged between the double-tyres and represent a dangerous projectile in an event of the object subsequently becoming dislodged by centrifugal force whilst the double wheel is rotating; such ejected objects from tyres potentially represents a considerable danger when they smash through an automobile front window resulting in injury or accident; and

(e) the tyre **30** can become oval or distorted in some other symmetrical manner which does not necessarily cause an asymmetrical imbalance to the wheel **10**; moreover, the hub **20** itself can become bent and thereby skewed out-of-plane without necessarily causing an asymmetrical imbalance in the wheel **10**.

Referring to Figures 4 and 5, there are shown diagrams of example contemporary manufactured front and rear wheel assemblies of a heavy commercial vehicle to illustrate how compact regions around vehicle wheels are in practice. There is little extra volume in the front and wheel assemblies for accommodating additional instrumentation for monitoring wheel operating conditions. Amongst other factors, components associated with the aforesaid brake **115** are included in close proximity to the wheel **10** in operation; the brake **115** has associated therewith other components such as servo actuators for forcing brake pad components against a disk component of the brake **115**. However, it is conventional practice to include around the wheel axle **110** and in close proximity to the wheel **10** the aforesaid ABS sensor encoder **118** (not shown in Figures 4 and 5) for measuring the angular position θ of the wheel **10** when mounted on its axle **110**.

Characteristics which are beneficial to measure in order to monitor wheel **10** and associated tyre **30** condition include temperature T, pressure P and instantaneous acceleration *A* during operation. It is additionally also feasible to include film strain gauges within or bonded onto walls **230** of the tyre **30** to measure their wall flexure. Temperature T and acceleration A can be measured at various spatial positions on the wheel **10** with mutually different results, whereas the pressure P developed within the volume denoted by **120** enclosed by the tyre **30** in operation is effectively similar because the pressure P equalizes in a relatively short period of time; pressure equalization is estimated to occur within a few milliseconds on account of pressure pulses being able to propagate at a velocity in an order of 250 metres/second within the volume **120.** The wheel **10** has a diameter in the order of 1 metre.

Figure 6 illustrates schematically categories of locations whereat sensors are beneficially mounted to the wheel **10**. When several sensors are included at each category of location, the several sensors are beneficially distributed at positions angularly distributed around the wheel **10** for providing most representative information indicative of operation of the hub **20** and its tyre **30**.

At a location L1, fasteners are beneficially employed to attach a first sensor module to the hub **20** or even via one or more of the holes **50** to the axle **110**. The first sensor module is capable of monitoring the tyre pressure P by way of fluid (air or gas) communication to the valve **80**, is capable of monitoring a temperature T_{hub} of the hub **20** and is capable of sensing accelerations A in one-, two- or three- orthogonal axes (x, y, z) at the hub **20** depending upon type of accelerometer employed. Beneficially, one or more of a pressure sensor and an accelerometer included in the first sensor module for performing measurements are silicon micromachined integrated electronic components contemporarily known as MEMS ("Micro-Electronic Mechanical Systems"). The temperature T_{hub} of the hub **20** will often be different from the temperature T_{tyre} of the tyre **30**; a temperature T_{mod} measured at the first module is hence not ideally representative of the tyre **30** temperature T_{tyre} and thus condition of the tyre **30**; the hub **20** will often be subject to direct cooling air flows, and during braking events will be heated up rapidly by warm air flowing from the associated disc brake **115** which, as elucidated in the foregoing, can be subject to sudden peak dissipations of energy of many kiloWatts, for example during and shortly after performing emergency braking. The first module at the location L1 is not totally screened by conductive components which renders short-distance wireless communication possible between the first module and an electronic control unit (ECU) or electronic management system of the vehicle. The first sensor module at the location L1 is most accessible and susceptible to being retrofitted to vehicles with minimal mechanical changes being required.

A second sensor module is beneficially mounted to an inside surface of the rim **90** at a location L2 and thereby is subject directly to the pressure P developed within the tyre **30** in operation. The second module at this location L2, when measuring the temperature T_{mod} thereat, is capable of providing an accurate measurement of the temperature T_{tyre} of the tyre **30** as well as the aforesaid pressure P. Moreover, one or more accelerometers included within the second module for measuring the acceleration A at the location L2 are at a greater radial distance from the axis **B-B** (see Figure 2) than the first module at the location L1, and are therefore subject to greater radial components of acceleration resulting from rotation of the wheel **10**. A disadvantage of mounting the second sensor module at the position L2 is that the mesh **210** in combination with the rim **90** have a tendency to form a Faraday cage which severely attenuates wireless transmissions from the second module, unless the second module has an antenna exit through the rim **90**, for example a small air-tight hole through which an antenna wire coupled to the second module at the position L2 is extended out onto the frusto-conical web **60** for enhancing wireless communication efficiency. In Figure 7, there is shown an example wherein the second module at the location L2 is coupled via an antenna wire **300** through an insulated feed-through **310**, installed in the rim **90** and operable to withstand the pressure P, to a film metal patch antenna **320**; optionally, the patch antenna **320** is affixed to the frusto-conical web **60** for mechanical protection. Alternatively, or additionally, the second module at the location L2 is electrically coupled to the mesh **210** of the tyre **30** and is operable to employ this mesh **210** as an antenna for communicating by wireless to the aforesaid electronic control unit (ECU) or an electronic vehicle management system. As a yet further alternative, the second module at the location L2 can be directly electrically coupled by wire through the feed-through **310** or by conductive film connection to the first module and optionally derive power therefrom as well as communicating measurement data thereto.

A third sensor module is beneficially mounted on an inside surface of the tyre **30** at a location L3, for example by bonding the third module onto the tyre **30** using rubber or plastics material bonding agents or similar before the tyre **30** is mounted to the hub **20**; alternatively, use of snap-type press-fit mounting of the third sensor module to the tyre **30** is also feasible and faster to employ when manufacturing and servicing the tyre **30**. The third module at the location L3 is capable of measuring the temperature T_{mod} thereat and thereby providing a direct representative indication of tyre temperature T_{tyre}, a representative direct indication of the pressure P and is also able to provide an representative indication of flexural characteristics of the walls **230** of the tyre **30** by way of acceleration *A* measurements or strain gauge measurements; however, the acceleration signals generated by the third module at the location L3 are a complex modulation of various acceleration components as the wheel **10** rotates in operation and its side walls **230** flex, whereas the accelerometer of the first module mounted at the location L1 is operable to generate acceleration signals which include a relatively greater magnitude of linear acceleration components therein which renders the first module at the location L1 potentially better suited for monitoring such linear acceleration components. Optionally, the third module at the location L3 is also coupled to one or more resistive-film or fibre-optical strain gauge sensors (not shown) coupled onto or even embedded within the rubber material of the tyre **30**, for example onto the side wall **230** and/or peripheral rim of the tyre **30**. The third module mounted at the location L3 suffers a similar wireless communication problem to the second module at the location L2 in that the mesh **210** in combination with the rim **90** functions as a Faraday cage to attenuate wireless communication from the volume **120** within the tyre **30**. In order to improve wireless communication, the third module at the location L3 is optionally provided with a thin-film conductive antenna **350**, for example fabricated by metal film sandwiched between layers of flexible insulating material such as Kapton as illustrated in Figure 8. The antenna **350** is beneficially wrapped around the inner edges **180** and up around an outside wall surface of the tyre **30**. The second module at the location L2 is also susceptible to being provided with such a thin-film antenna, for example disposed over an edge of the rim **90** and even extending onto the frusto-conical web **60**. However, such thin-film antennas are susceptible to being damaged when the tyre **30** is installed onto the hub **20** unless adequately protected with a rubber protective film **360** or similar component added to provide mechanical protection. Alternatively, or additionally, the third module is susceptible to having its antenna coupled electrically to the mesh **210** of the tyre **30** which is then capable of functioning as an antenna; the third module is beneficially provided with an electrical piercing pin for penetrating during installation through an inside of the side wall **230** for providing an electrical connection to the conductive mesh **210**. Yet alternatively, the second module at the location L2 can be operable to function as a wireless relay node for conveying signals from the third module via the second module to an electronic control unit (ECU) of the vehicle; such nodal communication between modules mounted onto the wheel **10** will be elucidated in more detail later and corresponds to the modules cooperating to form a communication network.

A fourth module in Figure 6 is susceptible to being mounted on an inside rim of the tyre **30**. Similar considerations pertain the fourth module mounted at the location L4 as for the third module mounted at the location L3 except that flexure of the wall **230** is not directly sensed but rather operative deformation of a thread region of the tyre **30**.

Measurement signals generated by the first, second, third and fourth modules at the locations L1, L2, L3 and L4 respectively will now be further elucidated with reference to Figure 9.

In Figure 9, there is shown the axis of rotation **B-B** around which the wheel **10** revolves in operation. The wheel **10** is provided via the axle **110** with a leaf spring and/or air pneumatic suspension coupled to a chassis CH of the vehicle; the suspension is denoted by a spring constant K_S. Forces applied to the tyre **30** from a road surface in contact with the tyre **30** are denoted by a force F(t); the tyre **30** has a spring compliance described by a spring constant K_T which is dependent on the pressure P within the tyre **30** and also mechanical design of the tyre **30**. The first, second and third sensor modules at the locations L1, L2 and L3 respectively are each denoted by a module **400** which circumscribes in operation a radial path denoted by **410** when the wheel **10** rotates around the axis **B-B** corresponding to the axle **110**. The radial path **410** has a radius *r* and the module **400** is inclined at an inclination angle ϕ relative to a normal radial direction **420**. The module **400** is operable to measure at least one of:

(a) a temperature T_{mod} at the module **400**;

(b) the pressure P at the module **400**; and

(c) linear acceleration in one or more axes x, y, z as, for example, illustrated in Figure 9, wherein the z-axis is parallel to the axis **B-B** when the inclination angle ϕ is 0 degrees, the y-axis corresponds to a radial direction for the wheel **10** when the inclination angle ϕ is 0 degrees, and the x-axis corresponds to a tangential direction whose associated acceleration is weakly affected by the inclination angle ϕ when near 0 degrees.

When the module **400** is mounted at the location L1, it measures the pressure P of the tyre **30** via its valve **80**.

As elucidated in the foregoing, the module **400** is optionally furnished with other types of sensors, for example resistive strain gauges, piezo-electric strain gauges, moisture sensors, and so forth if desired. It is convenient, for initial identification purposes during configuration routines, that the module **400** is provided with a magnetic sensor, for example implemented using a magnetic reed-relay switch operable to electrically conduct when a permanent magnet having, for example, a near-field magnetic field strength of 100 milliTesla is placed in near proximity to the module **400**, for example within a distance of 10 cm therefrom.

With reference to Figure 9, when the wheel **10** rotates at a constant angular rate ω, and the inclination angle ϕ is substantially 0 degrees, the acceleration A_x measured by the x-axis accelerometer is given by Equation 1 (Eq. 1):

$$A_x = g\sin(\omega t + \lambda) \qquad \text{Eq. 1}$$

wherein

A_x = an x-axis acceleration measurement;

r = a radius from the axis **B-B** at which the module **400** is mounted;

ω = an angular rotation rate of the wheel **10**;

g = a gravitational constant (circa 10 m/s/s); and

λ = an angular offset.

When the wheel **10** rotates at the constant angular rate ω, and the inclination angle ϕ is substantially 0 degrees, the acceleration A_y measured by the y-axis accelerometer is given by Equation 2 (Eq. 2):

$$A_y = r\omega^2 + g\sin(\omega t + \lambda) \qquad \text{Eq. 2}$$

wherein

A_y = a y-axis acceleration measurement;

r = the radius from the axis **B-B** at which the module **400** is mounted;

ω = the angular rotation rate of the wheel **10**;

g = the gravitational constant (circa 10 m/s/s); and

λ = an angular offset.

Beneficially, the wheel **10** when mounted on its axle **110** is provided with the aforementioned ABS angular sensor encoder **118** for measuring the positional angle θ of the wheel **10** and the angular turning rate $\omega = {}^{d\theta}/_{dt}$ of the wheel **10**. Disparity of the measured acceleration A_x from Equation 1 with measurements from such an ABS sensor encoder **118** is susceptible to being used detect one or more of:

(i) detecting malfunction of the ABS sensor encoder **118**; and

(ii) slip of the tyre **30** relative to the hub **20**, especially pertinent when sensing at the location L3 (although this slip only exceptionally occurs usually with catastrophic results).

Assuming such an ABS encoder sensor **118** is functioning correctly, checking the acceleration A_x against change in turning angle θ determined by the ABS sensor encoder **118** can be, for example, employed to dynamically confirm correct operation of the module **400**. Such dynamic confirmation of correct module function is a feature provided by the present invention.

The module **400** is also capable of measuring accelerations A_y and A_z in substantially y- and z-directions respectively when the inclination angle ϕ is non-zero which is, for example, pertinent for the third module at the location L3 when the wall **230** of the tyre **30** flexes, or at the locations L1 and L2 when the hub **20** is loose on its fasteners or skewed in relation to the axle **110**. Measured acceleration signals are provided approximately as defined in Equations 3 and 4 (Eqs. 3 and 4):

$$A_z = \left(r\omega^2 + g\sin(\omega t + \lambda)\right)\sin\phi \qquad \text{Eq. 3}$$

$$A_y = \left(r\omega^2 + g\sin(\omega t + \lambda)\right)\cos\phi \qquad \text{Eq. 4}$$

For the locations L1 and L2, the inclination angle ϕ for the module **400** mounted in an orientation as depicted in Figure 9 is normally substantially zero such that the acceleration A_z is normally of a relatively small magnitude and the acceleration A_y is a summation of forces arising from the force *F(t)* resulting from road surface characteristics, centrifugal components $r\omega^2$ arising from turning of the wheel **10** and the force of gravity g modulated by turning of the wheel **10**. However, in an event of imbalance of the wheel **10** arising from the hub **20** becoming skewed, for example:

(a) due to loosening of the fasteners or bolts used to attach the hub **20** via its holes **50** to the axle **110**;

(b) due to the hub **20** becoming deformed due to impact or accident or fracture, or

(c) the axle itself **110** being out of alignment due to fault or impact, the inclination angle ϕ becomes a function of an angle of rotation θ of the wheel **10** as defined by Equation 4 (Eq. 5):

$$\phi = \phi_{\max} \sin(\omega t + \mu) \qquad \text{Eq. 5}$$

wherein

ϕ_{max} = a misalignment angle; and

μ = angular offset regarding rotation of the wheel **10**,

such that Equations 3 to 5 are then susceptible to being used in combination for determining a nature of the measured accelerations A_y and A_z from the module **400** mounted at the locations L1 and L2. The acceleration signal A_z is thus useful, pursuant to the present invention, for identifying angular misalignment or fastener problems by monitoring using modules **400** at one or more of the locations L1 and L2. However, the module **400** mounted at the location L3 is subject to considerable flexure of the wall **230** which tends to dominate in magnitude with regard to angular change over angular misalignment of the axle **110** or lateral wobbling of the wheel **10**. Moreover, as elucidated in the foregoing, mounting the module **400** at the location L1 is beneficial for measuring the pressure P of the tyre **30** from its valve **80**, but the temperature T_{mod} measured by the module **400** at the location L1 is not an accurate representation of temperature T_{tyre} of the tyre **30** on account of intermittent heating of the brakes **115** in operation. Furthermore, mounting the module **400** at the location L2 is beneficial for measuring the pressure P of the tyre **30**, as well as measuring a representative operating temperature of the tyre **30** (namely $T_{mod} = T_{tyre}$ at the location L2).

When the module **400** is mounted at the location L3, it is capable of providing a representative measurement of the pressure P and the temperature of the tyre **30** (namely $T_{mod} = T_{tyre}$). However, periodic flexure of the wall **230** of the tyre **30** when the module **400** is mounted at the location L3 results in the inclination angle ϕ being a strong function of the angle of rotation θ of the wheel **30**; the inclination angle ϕ then becomes substantially, to a first approximation, the flexural angle of the wall **230** of the tyre **30**. For the module **400** mounted at the location L3, the inclination angle ϕ then becomes a series function as defined in Equation 6 (Eq. 6):

$$\phi = \phi_0 + G(P) + H(P)\sum_{i=1}^{n}\left(k_i \sin\left(i(\omega t + \varepsilon_i)\right)\right) \qquad \text{Eq. 6}$$

wherein

ϕ_0 = angular offset;

$G(P)$ = a function describing a change in angle of the wall **230** of the tyre **30** as a function of changes in the pressure P therein for a portion of the tyre **30** not in contact with a road surface;

$H(P)$ = a function dependent on the pressure P describing an angular deflection of the wall **230** when its portion of tyre **30** comes in contact with the road surface;

k = a harmonic coefficient;

i = a harmonic index number;

ω = the angular rate of rotation of the wheel **10**; and

ε_i = an angular offset.

Figure 10 provides in signal V1 a qualitative illustration of the angle ϕ when the module **400** is mounted at the location L3 and the wheel **10** is rotating; the inclination angle ϕ changes rapidly with flexure of the tyre wall **230** when a portion of the tyre **30** carrying the module **400** on its inside wall **230** comes into contact with a road surface. An abscissa axis in Figure 10 represents the rotation angle θ with time t, namely angle $\theta = \omega t$; an ordinate axis in Figure 10 represents substantially the wall inclination angle ϕ. A period **500** corresponds to one complete revolution of the wheel **10**, namely $\Delta\theta = 2\pi$.

In a first analysis method pursuant to the present invention, expected performance characteristics of the tyre **30** are computed and then compared against measured characteristics. The first method includes steps as follows:

(a) for a given type of tyre **30** defining the angle ϕ_0 and the functions G and H in Equation 5, for a given pressure P measured for the tyre **30**, for a given temperature T_{tyre} measured at the tyre **30**, and for a given angular rotation rate ω of the tyre **30** determined for example from the aforesaid ABS encoder sensor **118**, computing a corresponding expected simulated angle ϕ, and deriving therefrom a simulated magnitude of the acceleration A_z as would be expected to be generated from the accelerometer included in the module **400** mounted at the location L3;

(b) sensing representative samples of the acceleration A_z as measured by the module **400**; and

(c) checking to determine whether or not the simulated and measured accelerations A_z mutually differ by more than a predefined threshold amount; if they do not mutually substantially correspond, there is inferred therefrom that the tyre **30** is potentially defective and needs to be replaced.

For example, it is potentially possible to identify degradation of the mesh **210** before failure of the tyre **30** occurs in operation. Such simulation beneficially requires harmonic synthesis to be executed on computing hardware included within the module **400** and/or in an electronic control unit (ECU) of the vehicle to derive the simulated acceleration A_z.

In a second analysis method pursuant to the present invention, measured data representative of the acceleration A_z occurring in operation at the tyre **30** are sampled and then subject to harmonic analysis, for example by applying Fast Fourier Transform (FFT) or similar type of transform, to derive parameters therefrom and then comparing the computed parameters with those that are expected for the tyre **30**; if there is a mutual difference between the computed and expected parameters for the tyre **30** by more than a predefined threshold amount, potential failure of the tyre **30** can be detected and the tyre **30** replaced if necessary. The second method includes steps as follows are executed:

(a) sampling signals generated by the accelerometer in the module **400** representative of the acceleration A_z to provide corresponding sampled data, and then subjecting the sampled data to harmonic analysis, for example by way of an efficient Fast Fourier Transform (FFT) algorithm, to derive its harmonic content and hence a series of harmonic coefficients; optionally phase relationships between the harmonics, as denoted by ε_i in Equation 6 (Eq. 6), are also computed for use when making a comparison;

(b) from the harmonic analysis, in combination with a knowledge of temperature T_{tyre} and pressure P of the tyre **30**, determining a type of tyre **30** present on the wheel **10**, based upon a look-up reference list of tyre characteristics such as suppleness and elasticity as well as tyre wall shape and profile; and

(c) comparing the determined type of tyre **30** with the actual identification of type for the tyre **30**; if there is mutual variance therebetween by more than a predefine threshold amount, the tyre **30** is determined to be potentially faulty and potentially in need of being replaced.

When utilizing the aforesaid second method, in an event of the predicted tyre and the actual tyre **30** on the wheel **10** being mutually at variance, degradation or fault in the tyre **30** can thereby be inferred therefrom. As will be elucidated later, it is beneficial that the module **400** when mounted on the wall **230** of the tyre **30** as depicted in Figure 8 be provided with a distinguishing identification code (ID). The code is beneficially indicative of the characteristics of the tyre **30** to which the module **400** is attached at the position L3. The module **400** is operable to communicate the identification code (ID) by wireless to an electronic control unit (ECU) which is operable to execute the variance comparison.

Beneficially, harmonic analysis is also applied to one of more of the acceleration signals A_x and A_y for further confirming reliability of the harmonic analysis executed pursuant to this second method.

Whereas the module **400** mounted at the location L3 is especially effective for detecting potential problems or defects arising in respect of flexure and dissipation within the tyre **30**, the module **400** mounted at the location L1 is especially effective for measuring variations in asymmetry in the wheel **10**, and also for determining a type of asymmetry in the wheel **10** and its associated tyre **30**. Even more preferably for detecting imbalance and also type of imbalance in the wheel **10**, the module **400** is mounted in a non-rotating manner onto the shaft **110** substantially corresponding to the axis **B-B**. However, more wheel diagnostic information regarding imbalance in the wheel **10** is susceptible to being derived when the module **400** is mounted onto the wheel **10** and operable to rotated with the wheel **10**, preferably near its axis **B-B** of rotation, for example substantially at the location L1. As will be elucidated in more detail later, monitoring the pressure P as the wheel **10** rotates provides unexpectedly considerable additional information regarding performance of the tyre **30**, for example multi-lobed distortions of the tyre **30.**

Referring to Figure 11, there is shown a data processing apparatus pursuant to the present invention indicated generally by **600**; the data processing arrangement is operable to provide wheel- and tyre-monitoring. The data processing apparatus **600** is capable of being implemented in at least one of the module **400** and the aforesaid electronic control unit (ECU), depending upon where the processing is susceptible to being most conveniently and efficiently executed. Moreover, the processing arrangement **600** is susceptible to being implemented in at least one of hardware, and software executable in operation on computing hardware. The software is beneficially provided as a software product executable on the computing hardware. The software product is beneficially conveyed to the apparatus **600** on a data carrier; the data carrier is beneficially at least one of: a solid-state electronic data carrier, a wireless signal, an electrical signal, an optical-fibre signal, an optically and/or magnetically readable data carrier.

Under steady-state rotation of the wheel **10**, namely with constant angular velocity ω, temporal variations in the radial acceleration A_y, namely dAy/dt, are of substantially zero magnitude for the inclination angle ϕ being substantially zero, other than effects due to gravity g which are correlated with the rotation angle θ of the wheel **10**. Momentary acceleration generated from a road surface onto which the tyre **30** contacts in operation results in the force F(t) as shown in Figure 9 varying with time t and giving rise to varying components in a linear vertically-directed acceleration A_v experienced at the axle **110** which are not correlated with periodic rotation of the wheel **10**. However, components in the linear vertically-directed acceleration A_v which correlate with rotation of the wheel **10**, for example as referenced by way of the aforesaid ABS encoder sensor **118** providing an indication of the rotation angle θ of the wheel **10** and its angular frequency of rotation ω, are of benefit for determining imbalance in the wheel **10**, and also potentially elucidating a type of imbalance present in the wheel **10**. The ABS encoder sensor and its associated signal processing circuits are denoted by **118** in Figure 11. When one or more of the modules **400** are mounted onto the wheel **10** at one or more of the locations L1 to L3, they rotate in operation together with the wheel **10**. In consequence, the one or more accelerometers in the one or more modules **400** measuring the accelerations A_x and A_y as depicted in Figure 9 are all sensitive to linear vertically-directed acceleration in response to rotation of the wheel **10**. In order to suitably condition the accelerations A_x and A_y, it is necessary for the one or more modules **400** and/or an electronic control unit (ECU) in wireless communication therewith to perform angular resolving, for example as described in Equation 7 (Eq. 7):

$$A_v = d_1 \sin(\omega t).A_x + d_2 \cos(\omega t).A_y \qquad \text{Eq. 7}$$

wherein

d_1, d_2 = scaling constants.

Such angular resolution is executed in operation in a resolver denoted by **620** in Figure 11. The resolver **620** beneficially receives its angular reference for the rotation angle θ from the ABS encoder sensor and its associated circuits **118**. The resolver **620** is also beneficial in being operable to remove an angularly dependent component in the acceleration A_v due to gravity g which becomes constant in the resolved acceleration A_v. Removal of the acceleration component due to gravity g in the resolved acceleration A_v is beneficial for auto-scaling the constants d_1 and d_2 in Equation 7 (Eq. 7) for a condition that the wheel **10** is known to be correctly in balance, for example during a calibration routine performed after the wheel **10** is newly installed on the vehicle.

By performing harmonic analysis on the signal representing the acceleration A_v in respect of the angular frequency of rotation ω of the wheel **10**, for example in a harmonic analyzer denoted by **630** in Figure 11, the severity of the imbalance can be determined; for example, the amplitude of harmonics $Q(m)$ wherein m is a harmonic number in the acceleration A_v signal are beneficially individually scaled by a harmonic scaling function $y(m)$ in a scaler **640** and then summed in a summing unit **650** to compute an aggregate S_{tot} summed value. The aggregate value S_{tot} is then compared in a threshold detector denoted by **660** against a predefined threshold value *Th* to determine whether or not the wheel **10** needs attention to correct the imbalance, for example by adding balancing weights or exchanging the tyre **30**. Equations 8 and 9 describe associated computing required:

$$S_{tot} = \sum_{m=1}^{l} Q(m).y(m) \qquad \text{Eq. 8}$$

If $S_{tot} \rangle Th$, then the wheel **10** needs attention Eq. 9

Equation 9 corresponds to a decision point **DK1** illustrated in Figure 11.

Optionally, the harmonic scaling function *y(m)* implemented in the scaler **640** is made dependent upon a type of tyre **30** installed on the wheel **10**; for example, a robust knobbly tyre installed on the wheel **10** is potentially able to exhibit a greater degree of imbalance before representing any form of potential risk than a lean high-performance high-speed tyre optimized for reduced energy consumption during driving. Moreover, the harmonic scaling function *y(m)* implemented in the scaler **640** is beneficially also made a function of time *t*, namely *y(m, t)* in Equation 8, from an initial time t_0 at which the tyre **30** was installed onto the hub **20**. Furthermore, the harmonic scaling function *y(m)* is also beneficially made a function of the number of revolutions as determined from the ABS sensor encoder **118** that the wheel **10** has experienced since the tyre **30** was installed thereon, namely *y(m, N)* where *N* is the number of revolutions of the tyre **30**. A reason for rendering the harmonic scaling function *y(m, t)* or *y(m, N)* variable is that imbalance in a well-worn tyre **30** is more likely to potentially result in tyre **30** failure in comparison to a newly-installed substantially unworn tyre **30** whose internal mesh **210** has not been subjected to substantial work-hardening due to repetitive flexure.

The type of imbalance for the wheel **10** as determined from the amplitude of the harmonics *Q(m)* is determined from the relative amplitude of given harmonics; such determination is performed by harmonic analysis in an analyzer denoted by **670** in Figure 11. Moreover, such harmonic analysis is beneficially implemented using a set of software rules, by applying a harmonic stencil to the harmonics to identify a signature of a specific type of imbalance present, or by feeding data indicative of the amplitude of the harmonic *Q(m)* into a neural network trained to recognize occurrence of certain types of defects. One or more of the software rules, the harmonic stencil and the neural network are beneficially optionally rendered dependent upon a type of tyre **30** installed onto the hub **20**. Moreover, one or more of the rules, the harmonic stencil and the neural network are also beneficially optionally dependent upon an age and/or a degree of wear of the tyre **30**. When computing relative amplitude of harmonics *Q(m)* present in the acceleration A_v, normalization of the amplitude of the harmonics *Q(m)* is beneficially implemented as a part of signal processing employed as depicted in Figure 11.

For example, when fasteners in the aforementioned holes **50** attaching the hub **20** to the axle **110** have been inadequately tightened or work loose such that the hub **20** rattles around on its axle **110**, the suspension of the vehicle, for example as denoted by the spring K_s in Figure 9, is often so effective that the driver of the vehicle is unaware of there being any problem. The hub **20** slopping around on its bolts or fasteners gives rise to sudden small jolts of the wheel **10** as the wheel **10** rotates; it has even been known for the frusto-conical web **60** to generate a bell-like ringing tone as it is pulse excited into resonance corresponding to a "cos2θ mode" of flexure, namely hoop-like deformation of the rim **90** and the frusto-conical web **60**. These small sudden jolts give rise to signal energy in relatively high harmonics, for example in a range of 10^{th} to 20^{th} harmonic in the harmonics *Q(m)*, which the scaling function *y(m)* can be arranged to isolate for specifically detecting that the wheel **10** is loose on its fasteners for warning the driver of the vehicle.

Beneficially, several different scaling functions *y(m)* are applied concurrently to the harmonics *Q(m)* so that occurrences of several different types of imbalance are monitored simultaneously by the data processing apparatus **600**.

In an alternative, or additional, implementation of the data processing apparatus **600**, the pressure P measured by the module **400** is provided to the harmonic analyzer **630** instead of the resolved acceleration A_v in a manner as depicted in Figure 12; in Figure 12, the data processing apparatus **600** adapted to harmonically analyze the pressure P is indicated generally by **680**. Irregularities in the tyre **30**, for example local bulges or weaknesses causing blisters in the tyre **30**, are manifest as pressure pulses at certain angular θ positions as the wheel **10** rotates in operation. By analyzing variations in the pressure P as a function of rotation angle θ of the wheel **10**, namely components of the pressure P correlated with turning rate ω, it is feasible to provide additional monitoring of the tyre **30** for improving detection of defects, or potential defects, in the tyre **30**. The data processing apparatus **680** functions in a generally similar manner to the data processing apparatus **600** except that the pressure P is analyzed instead of the acceleration A_v. Optionally, a data processing apparatus pursuant to the present invention is provided by combining together the data processing apparatus **600**, **680** so as to provide for concurrent or periodically alternating harmonic analysis and monitoring of the acceleration A_v and the pressure P as depicted in Figure 13 and as indicated by **690** therein; there is provided a switching arrangement **695** in the data processing apparatus **690**, either implemented in software or hardware, for selecting between the pressure P and the acceleration A_v. An advantage of the data processing apparatus **690** illustrated schematically in Figure 13 is that more comprehensive monitoring to the wheel **10** is susceptible to being achieved in operation.

Aforementioned analysis of flexure of the wall **230** of the tyre **30** as sensed by the module **400** mounted at the location L3 is beneficially compared in the electronic control unit (ECU) and/or within the module **400** with results from harmonic signal analysis performed in respect of one or more modules **400** positioned at one or more of the locations L1 and L2. In an event that the comparison is such that the modules **400** located at mutually different locations L1 to L4 give rise to mutually conflicting analysis results, there is a high likelihood of potential problems with the wheel **10** and/or its tyre **30**; a warning message is beneficially then transmitted from the data processing apparatus **600**, **680** or **690** as appropriate to a driver of the vehicle and/or to a control centre of the enterprise operating a fleet of such vehicles that there is a need to perform maintenance on the vehicle, for example for devising logistics for a future maintenance schedule for the vehicle. Such logistics can include, for example, prearranging a replacement wheel to be available and informing a service facility regarding a time of arrival of the vehicle for maintenance purposes so that appropriate task scheduling at the service facility can be implemented.

One or more of the modules **400** mounted at one or more of the locations L1 to L4 are susceptible to being used, optionally in communication with an electronic control unit (ECU), to detect more gradual temporal changes in the tyre **30**, for example a gradual reduction in pressure P due to a slow leak therefrom, for example over a period of several weeks or months. Moreover, the one or more modules **400**, optionally in cooperation with the aforesaid electronic control unit (ECU) in wireless communication with the one or more modules **400**, can be used to monitor sudden depressurization of the tyre **30**, for example sudden depressurization and subsequent re-pressurization associated with installing a new replacement tyre **30** onto the hub **20**. Monitoring of such sudden depressurization is important when an earlier tyre **30** equipped with a module **400** mounted therein is exchanged for a replacement tyre **30** devoid of any such module **400**, so that parameters for various signal processing functions as depicted, for example, in Figure 11 can be appropriately selected by the apparatus **600**, **680** or **690**. When the identity and condition of the tyre **30** is not reliably known, there are beneficially adopted in the data processing apparatus **600**, **680** or **690** default values for parameters indicative of a tyre **30** with a substantially medium degree of tread wear. Beneficially, there is issued a message "not reliable information" or similar in an event of such sudden depressurization having been detected to alert the driver that the electronic control unit (ECU) is being supplied with potentially non-representative information. Such a situation can arise when unauthorised swapping of the tyre **30** has occurred or a tampering event has occurred for example.

The module **400** will now be described in overview with reference to Figure 14. In operation, the module **400** is required to be robust and also inexpensive in manufacture. Moreover, for example when mounted in the aforesaid location L3 or L4, the module **400** is relatively inaccessible and needs to function reliably without user intervention. Beneficially, the module **400** utilizes aforesaid microeletronic mechanical systems (MEMS) technology, for example based upon silicon micromachining fabrication processes. The module **400** includes a battery **700** comprising one or more electro-chemical cells operable to provide electrical power, amongst other components, to a computer processor **710**. A data memory **720** including a software product is coupled in communication with the processor **710**; the software product comprises software code which is executable upon the processor **710** and which is operable to coordinate functioning of the module **400**. The processor **710** has associated therewith a clock (CLK) and an analogue-to-digital (A/D) converter for converting analogue sensor signals to corresponding sampled sensor data; beneficially, the analogue-to-digital (A/D) is based upon a high-speed multi-channel sigma-delta type converter which exhibits modest power consumption. Sigma-delta converters are contemporarily employed in power-critical devices such as miniature hearing aids which are battery powered and need to function for long periods without attention, for example for battery change. The module **400** further comprises a short-distance wireless interface **730** for providing bidirectional communication to and from the module **400**; the wireless interface **730** is beneficially implemented using contemporary Blue Tooth, Weebre or similar wireless interface technology operating pursuant to associated standardized communication protocol.

The module **400** also includes an array of one or more sensors denoted by **750** whose corresponding one or more outputs are coupled to the aforesaid A/D converter. Depending upon intended location, namely locations L1, L2, L3 and L4, and a degree of wheel monitoring functionality desired, the array of sensor **750** includes one or more of:

(a) a pressure sensor **760** beneficially based upon a MEMS structure including a silicon micromachined membrane with strain-gauge or oscillatory resonant signal read-out;

(b) a temperature sensor **765** for measuring an air or surface temperature in proximity of the module **400**, wherein the temperature sensor **765** beneficially has a measuring range of -40 °C to +100 °C;

(c) an accelerometer **770** beneficially implemented in as MEMS structure including one or more silicon micromachined proof masses on a spring suspension with corresponding position readout for the one or more proof masses indicative of acceleration; optionally, for enhanced accuracy and response, the accelerometer is a force-feedback type accelerometer; the accelerometer **770** is beneficially sensitive to acceleration in one-, two- or three orthogonal axes. For best monitoring of wheel **10** and associated tyre **30** operation, the accelerometer **770** is implemented as a three-axis accelerometer;

(d) a magnetic sensor **775**, preferably implemented as a vacuum-encapsulated reed relay switch but also susceptible to being implemented as an Hall-effect device; the magnetic sensor **775** is optionally included for activating the module **400** using a strong magnetic brought into proximity of the module **400**; however, as will be elucidated in more detail later, other approaches to activating the module **400** are also possible and are pursuant to the present invention; and

(e) a strain-gauge sensor **780** which is most potentially pertinent to the module **400** when mounted at the location L3 onto the wheel **10**. The sensor **780** can be affixed to the tyre **30** prior to the tyre **30** being installed onto the hub **20**.

Optionally, the module **400** is susceptible to including other types of sensor not described in detail above.

Optionally, the battery **700** is, at least in part, a rechargeable battery and provided with its own electro-magnetic recharging device actuated in response to rotation of the wheel **10** in operation, for example in a manner akin to an automatic wind-up mechanical wrist watch wherein wrist movement is operable to move an imbalance mass to provide watch-spring wind-up energy. Alternatively, or additionally, piezo-electric recharging of the battery **700** in response to rotation of the wheel **10** can be employed.

In operation, the computer processor **710** is operable to perform self-diagnostics and send a warning message via its wireless interface **730** in event of partial or total malfunction occurring within the module **400**, and a confirmatory message sent when the module **400** is fully functional; in an event that the module **400** malfunctions, its associated vehicle is not immobilized, but merely results in reduced functionality in respect of wheel and associated tyre monitoring. Beneficially, the driver of the vehicle can be informed via the electronic control unit (ECU) regarding reduced functionality and provided with a choice whether or not to continue driving despite malfunctioning of the module **400**.

In operation, when the computer processor **710** detects that the signals from the accelerometer **770** are substantially constant for more than a predefined time period, for example for a time period in a range from a few seconds up to 10 minutes, after cessation of a period of rotation of the wheel **10**, the computer processor **710** is beneficially operable to cause the module **400** to assume a hibernating mode to conserve power during which the wireless interface **730** is substantially de-energized. During the hibernating mode, the computer processor **710** is beneficially operable to periodically and momentarily activate the wireless interface **730** for short periods to detect "wake-up" commands from the electronic control unit (ECU) of the vehicle. As soon as the computer processor **710** detects that signals from the accelerometer **770** and/or the pressure sensor **760** are temporally varying, for example during a pre-defined time period, the processor **710** is operable to switch the module **400** to its active state, namely non-hibernating, with all its functional parts as shown in Figure 14 brought into operation. Alternatively, or additionally, the module **400** can be explicitly set in a hibernating mode on receipt of a specific hibernate instruction from the electronic control unit (ECU) **950**; beneficially, the specific instructions includes the identification code (ID) of the module **400** which is to assume such a hibernating state; similarly, the module **400** can be explicitly instructed to assume a functional active state, namely non-hibernating state, by receiving a specific wake-up instruction from the electronic control unit (ECU) **950**. Yet alternatively, or additionally, all the modules **400** included on the wheels **10** of the vehicle can be set to a hibernate state, or set to a functional active state, by a general explicit instruction wirelessly transmitted from the electronic control unit (ECU) **950**; the general explicit instruction is beneficially sent by the electronic control unit (ECU) **950** in response to the driver of the vehicle starting and stopping a combustion engine or an electric traction motor of the vehicle. Such an electric traction motor is relevant when the vehicle has a hybrid powertrain or an electric power train provided with electric power from fuel cells.

When considerable data processing is performed within the module **400** so as to distribute computing load around the vehicle, for example signal processing involving application of a Fast Fourier Transform (FFT) or similar signal processing algorithm, the module **400** is operable to receive a synchronization signal for its given associated wheel **10** derived from the aforementioned ABS sensor encoder **118** and its associated circuits associated with the given wheel **10**. Such a synchronization signal is beneficially provided from the aforementioned electronic control unit (ECU) **950** of the vehicle operating to provide a data communication hub for the vehicle. On account of the wheels **10** of the vehicle potentially revolving at mutually different rates, for example when the vehicle is turning or due to slight difference in outside diameters of the tyres **30**, each wheel **10** and its associated modules need to be individually synchronized in respect of their associated ABS sensor encoder **118**.

Data processing performed by the computer processor **710** is beneficially capable of reducing a volume of data to be communicated via the wireless interface **730** to the electronic control unit (ECU). Such local data processing is of benefit in that it is primarily the wireless interface **730** which consumes a majority of power from the battery **700** when the module **400** is in operation. Data flow can be further reduced in the module **400** by the processor **710** transmitting periodically at a beginning of time frames actual data values of sensor signals followed by data representing changes in the data values during each time frame. Other approaches for obtaining data compression can also optionally be employed to reduce power consumption at the wireless interface **730**. Beneficially, the module **400** is operable to transmit accelerometer signal data and pressure P data at a maximum sample rate in a range of 50 samples/second to 200 samples/second for each accelerometer axis and/or the pressure sensor **760** taking into consideration Nyquist sampling criteria. ,A lower rate of up to 1 sample per second for temperature T is optionally employed on account of the temperature T changing less rapidly in comparison to the acceleration A and pressure P.

Optionally, the module **400** is operable to perform Fourier analysis of its sensor input signals provided to the processor **710**, and the module **400** is operable to wirelessly communicate Fourier harmonic coefficients and optionally their relative phase relationship to the electronic control unit as an approach to reducing an quantity of data transfer occurring as well as conserving power in the battery **700** by using the wireless interface **730** sparingly. Such communication is referred to parameterized data compression performed by the module **400**.

The module **400** is also beneficially operable to permit software updates to be downloaded from the electronic control module (ECU) to the module **400**, for example via its wireless interface **730**, for upgrading or modifying its operation, for example in response to amended safety standards or policy adopted by an operator of the vehicle. Such software updates also enable new and improved data processing algorithms to be later employed, namely software upgrades.

As elucidated in the foregoing, the module **400** is programmed to have an identification code (ID) which is useable by the aforesaid electronic control unit (ECU) for distinguishing the module **400** from other similar modules **400** on the vehicle, and also from similar types of modules **400** on other vehicles which sporadically pass in near proximity, for example on an adjacent lane during motorway driving. The electronic control unit (ECU) is operable to use the identification code (ID) to identify from which portion of the vehicle data conveyed via the module **400** is derived. Such identification will be described in more detail later.

The computer processor **710** in combination with its wireless interface **730** is also operable to optionally provide a communication networking function. Beneficially, the computer processor **710** has a directly wired interface so that a first module **400** mounted at the location L1 on the wheel **10** is capable of being directly coupled via a wire or optical fibre communication link through the feed-through **310** as depicted in Figure 7 to a second module **400** mounted at the position L2 on the rim **90** within the volume **120** as depicted in Figure 15a. The processor **730** of the first module **400** located at the location L1 is thereby operable to:

(a) process signals generated by its array of sensors **750** and convey the processed signals as processed data to its wireless interface **730** of the first module **400** for communicating to the electronic control unit (ECU), as well as

(b) receiving processed signals output from the second module at the position L2 for conveying via the first module **400** and its wireless interface **730** to the electronic control unit (ECU).

Alternatively, data signals from the second module **400** at the location L2 can be:

(a) communicated via the wireless interface **730** of the second module at the location L2 to the wireless interface **730** of the first module at the location L1, and then

(b) the data signals can be relayed via the wireless interface **730** its associated computer processor **710** of the first module **400** to the electronic control unit (ECU).

Such a communication link is also susceptible to being used in reverse for conveying aforementioned ABS synchronization signals via the first module **400** at the location L1 to the second module **400** at the location L2 as depicted in Figure 15b.

In a similar manner, the second module **400** at the location L2 is able to function as a network relay for a third module **400** mounted at the location L3. Beneficially, the second module **400** at the location L2 is coupled by wire or optical fibre via the feed-through **310** to the first module **400** at the location L1, and the third module **400** at the location L3 is coupled by wireless to the second module **400** at the location L2 as depicted in Figure 15c. By such a configuration of Figure 15c, problems with the mesh **210** and rim **90** functioning as a Faraday screen are avoided. Wireless communication between the third module **400** at the location L3 to the second module **400** at the location L2 is beneficial in view of a potentially large number of times the third module **400** at the location L3 moves in respect of the second module **400** at the location L2 in response to flexure of the wall **230** of the tyre **30** as the wheel **10** rotates in operation; wires or similar direct connections linking the modules at the locations L2 and L3 would not only be prone to breakage due to work-hardening effects, but would also be impractical to attach once the tyre **30** has been installed onto the hub **20** on account of the volume **120** then being user-inaccessible.

In an alternative configuration, the third module **400** at the location L3 is electrically coupled to the mesh **210** of the tyre **30** which is used as a highly effective patch radio antenna for communicating by wireless to the electronic control unit (ECU). In such a configuration, the third module **400** at the location L3 is capable of function as a wireless relay node for communicating data from the second module **400** mounted at the location L2 on the rim **90**. Such a configuration is illustrated in Figure 15d.

Other network configurations for the modules **400** at the locations L1, L2 and L3 are also feasible. For example, the modules **400** are optionally operable to all communicate directly by wireless via their wireless interfaces **730** directly with the electronic control unit (ECU) as depicted in Figure 15e. Yet alternatively, the modules **400** are dynamically reconfigurable depending upon received wireless signal strength at the electronic control unit (ECU), for example between various network modes as elucidated in the foregoing with reference to Figures 15a to 15e. Such flexibility to reconfigure a communication network provided by the modules **400** is beneficial when wheels **10** are swapped around or changed on the vehicle. Such adaptability will be described in more detail later.

Beneficially, the first, second, third and fourth modules **400** mounted at the locations L1, L2, L3 and L4 respectively each are provided with their uniquely-defining identification codes (ID) which the modules **400** are operable to employ when communicating with the electronic control unit (ECU) for distinguishing their data from that of other modules **400**. Moreover, such identification codes (ID) are beneficial when the electronic control unit (ECU) sends synchronization signals derived from the ABS sensor encoders **118**, for example in a situation where considerable data processing is performed locally at the modules **400** to reduce a quantity of data to be communicated via their wireless interfaces **730** to the electronic control unit (ECU) in operation.

In the foregoing, components such as the wheel **10** and its associated one or more modules **400** and its electronic control unit (ECU) mounted on the vehicle have been described. These components form a part of a wheel- and tyre-monitoring system which will now be elucidated in greater detail with reference to Figure 16.

In Figure 16, there is shown in plan view the aforementioned vehicle indicated generally by **900**. The vehicle **900** is driven in operation by the aforesaid driver denoted by **910** in Figure 16. Moreover, the vehicle **900** comprises a front tractor unit **920** including a combustion engine **930** operable to provide motive force to a pair of steerable front wheels **10** beneficially implemented in a manner substantially as depicted in Figure 4. The combustion engine **930** is at least one of: a contemporary cylinder combustion engine, a combustion engine with turbocharger, an electric series or parallel hybrid engine, a gas turbine engine, a fuel cell system providing electrical power to associated electric motor traction. The vehicle **900** also comprises a trailer unit **940** having two sets of double rear wheels **10** as shown; the double rear wheels **10** are beneficially implemented in a manner as depicted in Figure 5 and are also optionally also steerable in a manner similar to the front wheels **10** of the front tractor unit **920**. Other configurations of wheels **10** for the vehicle **900** are possible and Figure 16 is merely one example for describing the present invention. The vehicle **900** is further provided with the aforementioned electronic control unit (ECU) denoted by **950**; the electronic control unit (ECU) **950** includes a computer processor together with data memory and one or more wireless interfaces and electrical interfaces, the computer processor being operable to execute one or more software products including executable software code. The electronic control unit (ECU) **950** is coupled in communication with a console **915** operated by the driver **910**. Optionally, the electronic control unit (ECU) **950** is also coupled in communication with the combustion engine **930** for performing engine management and monitoring functions, for example deliberately limiting a speed, or recommending to the driver a suitable speed, at which the driver **910** is able to drive the vehicle **900** in an event of the electronic control unit (ECU) **950** detecting a problem, or potential problem, with one or more wheels **10** of the vehicle **900**. Moreover, the electronic control unit (ECU) **950** is also wirelessly coupled to one or more modules **400** mounted on one or more of the wheels **10** of the vehicle **900** as elucidated in the foregoing.

The electronic control unit (ECU) **950** includes an antenna **960** for transmitting and receiving wireless signals as denoted by **970** for enabling the vehicle **900** to communicate with other facilities, for example a control centre **1000** of an enterprise organising logistics for a fleet of such vehicles **900**, or to a service facility **1010** whereat wheels **10** and their tyres **30** of the vehicle **900** can be serviced or replaced as depicted in Figure 16. Beneficially, the electronic control unit (ECU) **950** is operable to monitor operation of the wheels **10** of the vehicle **900** and automatically inform the control centre **1000** of a need to inform the driver **910** to drive the vehicle **900** into the service facility **1010** for servicing its wheels **10** and associated tyres **30**, for example as part of a delivery schedule planned for the vehicle **900**, thereby causing less disruption to a service provided by the enterprise to its customers. A visit to the service facility **1010** is optionally invoked in response to weather conditions or time, for example in connection with exchanging summer tyres **30** to winter tyres **30** in Northern Europe and North America.

Optionally, the electronic control unit (ECU) **950** is also wirelessly coupled to a global positioning system (GPS) **1020** for determining in operation a spatial position of the vehicle **900** upon the surface of the Earth. The GPS system **1020** is, for example, that managed by US Authorities or an equivalent European Galileo positioning system. Yet alternatively, or additionally, the GPS system **1020** is based on a mobile telephone, namely cell net, system known as GPRS or similar. In operation, the electronic control unit (ECU) **950** is operable to determine whereat the vehicle **900** is located and convey this positional information to the control centre **1000** so that the control centre **1000** is aware of the position of the vehicle **900**. Moreover, as elucidated in the foregoing, in an event that electronic control unit (ECU) **950** detects by way of one or more of the modules **400** that one or more of its wheels **10** are defective or needing maintenance, or are potentially likely to become defective or needing maintenance, the control centre **1000** can direct the vehicle **900** to a suitable geographically convenient service centre **1010**. Optionally, the control centre **1000** is also operable to arrange, based upon knowledge of the position of the vehicle **900**, for the tractor **920** to be decoupled from its trailer **940** at a suitable geographical location so that an alternative tractor can be rapidly coupled to the trailer **940** to haul the trailer **940** and its contents further promptly to its destination, for example to a customer; the tractor **920** can then be serviced without disrupting time-critical deliveries in the trailer **940** to the customer. Moreover, the service centre **1010** can also be warned in advance, either directly from the vehicle **900** or indirectly via the control centre **1010** or both, regarding arrival of the vehicle **900** together with an indication of a likely problem with one or more wheels **10** of the vehicle **900**. Such notification of problems regarding the vehicle **900** to the control centre **1000** and optionally to the service centre **1010** is susceptible to occurring automatically without the driver **910** needing to interpret messages and actively inform one or more of the control centre **1000**, the service centre **1010** or the customer. An improvement of service to the customer is thereby susceptible to being achieved.

In order that the vehicle **900** should not be immobilized in an event of its electronic control unit **950** detecting a problem with one or more of the wheels **10** of the vehicle **900**, or malfunction of one or more of its modules **400**, the electronic control unit (ECU) **950** is operable to generate various warning messages. In an event of malfunction of one or more of the modules **400**, the electronic control unit (ECU) **950** is operable to send a warning to at least one of the control centre **1000** and the driver **910** of such malfunction, but continue to monitor other wheels **10** whose modules **400** are continuing to function correctly. Such graceful decline in monitoring functionality of the modules **400** mounted on one or more of the wheels **10** is susceptible to improving operational robustness of the vehicle **900**, namely failure of one or more of the modules **400** does not immobilize the vehicle **900**. It is a decision then of the driver **900** and/or the control centre **1000** whether or not to continue driving the vehicle **900** in view of one or more of its module **400** becoming non-operational. A potential cause of one or more of the modules **400** failing is exhaustion of batteries **700** therein, or replacement of a tyre **30** for example.

As will be appreciated from the foregoing, the module **400** is employed when implementing the present invention in various configurations. When the module **400** includes the accelerometer **770** as depicted in Figure 14, the module **400** can be regarded as being a form of inertial navigation unit (INU). Moreover, it is elucidated in the foregoing that processing signals corresponding to radial, tangential and transverse accelerations, namely A_y, A_x and A_z as depicted in Figure 9, and resolving them to yield the vertical acceleration A_v as depicted in Figures 11 and 13 is found to be highly beneficial for deriving an indication of imbalance of the wheel **10**, a type of imbalance of the wheel **10**, whether or not the wheel **10** is skewed out of plane, whether or not the wheel **10** is loose on its fasteners, as well as monitoring flexural characteristics of the walls **230** of the tyre **30**. However, in a manner similar to inertial navigation units (INU) for steering vehicles such as rockets, helicopters, aircraft and so forth, it is conventionally found important that the inertial navigation units (INU) are mounted in accurate angular alignment with various reference axes of these vehicles. However, achieving such accurate angular alignment requires accuracy and precision which is potentially time consuming and costly to achieve. In a similar manner, pursuant to the present invention, it is highly desirable that the one or more modules **400** be mountable to the wheel **10**, for example at one or more of the locations L1 to L4, without a high degree of mounting precision and accuracy being necessary. By implementing the present invention such that the module **400** can be mounted in manner which does require its orientation to be precisely ensured, time and costs associated with furnishing the wheel with one or more of the modules **400** can be reduced. Such implementation of the present invention will now be elucidated with reference to example embodiments of the invention.

For a given wheel **10** correctly mounted to its axle **110**, it is beneficial to refer to:

(a) a lateral direction as being the z-axis parallel to the axis **B-B**;

(b) a radial direction from the axis B-B, and thus from the axle **110**, as being the y-axis; and

(c) a tangential axis at a given position on the wheel **10** as being the x-axis, as illustrated in Figure 17.

The z-axis and the y-axis are pertinent at the locations L1 to L4. The x-axis is dependent upon a radius *r* at which the point is from the axis B-B. Figure 17 corresponds to Figure 9 for the inclination angle ϕ being substantially zero. As elucidated earlier, the acceleration A_z is especially useful, as depicted in Figure 10, for monitoring flexural characteristics of the tyre **30** as well as detecting whether or not the wheel **10** is at a skewed angle relative to its axle **110**. Moreover, the vertical acceleration A_v resolved from A_x and A_y acceleration components measured at a given module **400** is beneficial for monitoring imbalance in the wheel **10** and also a type of imbalance involved. However, as shown in Figure 17, the module **400** is potentially mounted in an angularly misaligned position on the wheel **10** such that its local orthogonal axes denoted by x', y', z' do not align with true axes x, y, z required for generating highly useful A_x, A_y, A_z acceleration signals.

Accelerations A_x', A_y', A_z' correspond to measurements of accelerations along the local orthogonal axes x', y', z' respectively. It is feasible to resolve the accelerations A_x', A_y', A_z' in respect of the true axes x, y, z as provided by a matrix mapping as defined by Equation 10 (Eq. 10):

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix} = \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix} \qquad \text{Eq. 10}$$

wherein angles α and β are resolving angles mapping the axes x', y', z' onto the true axes x, y, z.

A special condition arises when the wheel 10 rotates at a constant angular velocity ω, for example as determinable by the electronic control unit (ECU) **950** from signal generated from ABS sensor encoders **118**, the vehicle **900** is driving straight ahead and not turning, for example as determined from an angular sensor coupled to the steering wheel at the console **915**, and a plane of the wheel **10** is orthogonal to the axis B-B and hence to the axle **110** in that:

(a) the lateral acceleration A_z is substantially zero as define by Equation 11 (Eq. 11);

(b) the tangential acceleration A_x is substantially zero when integrated over a complete 2π change in the rotation angle θ of the wheel **10**.

$$\int_{\theta_1}^{\theta_2} A_z = 0 \qquad \text{Eq. 11}$$

wherein θ_1 and θ_2 are lower and upper integration limits corresponding to first and second angular rotation angles θ of the wheel **10**.

$$\int_{\gamma}^{\gamma+2n\pi} A_x = 0 \qquad \text{Eq. 12}$$

wherein γ is an offset angle and n is an integer such that n = 1, 2, 3, ...

Suitable values for the angles α and β are susceptible to being computed in an iterative manner so that Equations 11 and 12 can be substantially achieved, or at least a minimized condition in respect of the angles α and β is susceptible to being achieved. For example, spurious road surface noise present in the accelerations A_x', A_y', A_z' potentially requires a minimum condition to be searched for as a best approximation for satisfying Equations 11 and 12.

Optimal values for the angles α and β can either be found from an explicit solution for Equations 10, 11 and 12, or iteratively by recomputing for various combinations of the angles α and β for a sample of signals representative of the accelerations A_x', A_y', A_z' until a nearest approximation to Equations 11 and 12 is achieved.

Computation of the angles α and β is beneficially performed at the electronic control unit (ECU) **950**. Alternatively, distributed computing performed at the module **400** can also be employed for computing the angles α and β. Once the angles α and β have been computed for a minimized condition or a zero condition as given in Equations 11 and 12, application of these angles α and β pursuant to Equation 10 to obtain the accelerations A_x, A_y, A_z for monitoring operation of the wheel **10**, for example as depicted in Figures 11 and 13, is susceptible to being implemented at the electronic control unit (ECU) **950** or at the module **400**, or distributed between both the electronic control unit (ECU) **950** and the computer processor **710** of the module **400** to spread computational load.

Equations 10 to 12 are an example of auto-resolving accelerations sensed by the accelerometer **770** of the module **400** to generate corresponding acceleration signals suitable for processing as depicted in Figure 11 and 13 with associated description in the foregoing. Although auto-resolving for a three-axis accelerometer **770** is described, such approximate auto-resolving can be also be employed when the accelerometer **770** is a two-axis accelerometer for example in simplified form. Auto-resolving is also susceptible to being referred to as auto-alignment.

Auto-resolving, for example as described in Equations 10 to 12, is of benefit in that the one or more modules **400** mounted one or more of the locations L1 to L4 do not need to be mounted onto the wheel **10** pursuant to highly precise angular alignment, thereby simplifying mounting of the one or more modules **400** to the wheel **10** and potentially reducing assembly and mounting costs.

When auto-resolving pursuant to Equations 10 to 12 is employed in the apparatus **600**, a corresponding apparatus as indicated generally by **2200** in Figure 18 wherein an auto-resolver is denoted by **2210**. The apparatus **2200** includes at least one module **400** whose accelerometer **770** is operable to generate the acceleration signals A_x', A_y', A_z' which are firstly auto-resolved in the auto-resolver **2210** to generate corresponding resolved acceleration data for the accelerations A_x, A_y, A_z. The resolved accelerations A_x, A_y, A_z are then further resolved in the resolver **620** in respect of the rotation angle θ of the wheel **10** as sensed by the ABS sensor encoder **118** to generate corresponding vertical acceleration A_v signal data and also acceleration A_z signal data. The acceleration A_v, A_z signal data are then subject to harmonic analysis in the harmonic analyzer **630** to generate corresponding series of harmonic coefficients $Q_v(m)$ and $Q_z(m)$ respectively in relation the angular frequency ω of rotation of the wheel **10**. The harmonic coefficients $Q_v(m)$ and $Q_z(m)$ are then optionally subject to harmonic scaling in the scaler **640** to generate corresponding scaled harmonic coefficients $y_v(m).Q_v(m)$ and $y_z(m).Q_z(m)$ which are then subject to analysis in terms of absolute magnitude and relative magnitude to determine whether or not:

(a) the wheel **10** is imbalanced;

(b) a type of imbalance present in the wheel **10**;

(c) the wheel **10** is skewed in relation to the axle **110**;

(d) the wheel **10** is loose and wobbling about on its fasteners;

(e) the tyre **30** has defects in its flexural characteristics, for example its mesh **210** has become damaged;

(f) the tyre **30** is insufficiently inflated;

(g) the tyre **30** is over-inflated;

(h) the tyre **30** is oval or has a higher-order lobed distortion;

(i) there is a mass imbalance in the wheel **10**;

(j) wheel bearings associated with the axle **110** are vibrating or rattling in an unexpected manner indicative of a fault, or potentially developing fault,

to mention a few alternative types of analysis which are executable using the apparatus **2200**.

When harmonic scaling in the scaler **640** is optionally not required, its scaling values are beneficially set to a uniform value, for example $y_v(m) = 1$, $y_z(m) = 1$ unity value, or the scaler **640** simply bypassed. Moreover, for the apparatus **2200**, one or more modules **400** can be optionally mounted at one or more of the locations L1, L2, L3 and L4. The apparatus **2200** is susceptible to being implemented in hardware, in software executable on computing hardware, or a combination of such hardware and software. Moreover, the apparatus **2200** is susceptible to being implemented substantially in the electronic control unit (ECU) **950**, on the module **400**, or on both the module **400** and electronic control unit (ECU) **950** in combination. The software is optionally supplied as one or more software products on one or more data carriers. Moreover, the software is optionally dynamically reconfigurable depending on potentially changing configurations of one or more modules **400** included on the wheel **10**.

The apparatus **2200** illustrated in Figure 18 is susceptible to being modified in a manner akin to the apparatus **690** illustrated in Figure 13, namely concurrently or alternately being operable to harmonically analyze a sampled signal representative of the pressure P in the volume **120** of the tyre **30**.

The auto-resolver **2210** requires calibrating in order to determine its correction angles α and β as elucidated in the foregoing. Such calibration is beneficially implemented as part of the aforesaid methods of "calibrating" the modules **400**, namely enabling the electronic control unit (ECU) **950** to identify which modules **400** with which it is required to communicate on the vehicle **900**, wherein the modules **400** are mounted at various locations on wheels **10** of the vehicle **900**, with potentially mutually different operating characteristics of the modules **400**; as elucidated earlier, a situation potentially arises in operation where certain wheels **10** of the vehicle **900** are provided with a more comprehensive set of modules **400** in comparison to other wheels of the vehicle **900**, in a potentially temporally dynamically changing manner. Auto-resolving in the auto-resolver **2210** has an effect with regard to the module **400** mounted at the location L3 to effectively set the offset angle ϕ_0 in Equation 6 (Eq. 6) to substantially a null value, namely $\phi_0 = 0$, and thereby potentially simplifies associated signal processing in operation for monitoring flexural characteristics of the tyre **30**.

In year 2007, it is estimated from studies undertaken by the International Panel of Climate Change (IPCC) that 13.5% of all carbon dioxide emissions resulting from androgenic activity are associated with transport. In view of the future potential threat that climate change is believed to represent to human civilization, including sudden climate change resulting from release of methane from gas hydrate deposits, vehicle manufacturers are presently striving to improve operating efficiency of their road vehicles, for example heavy commercial vehicles, to reduce their carbon dioxide output. Such efficiencies are also of considerable interest to enterprises operating such heavy commercial vehicles to improve their profit margins and/or improve their competitiveness. Rolling resistances of tyres on heavy commercial vehicles have energy dissipation associated therewith which is potentially susceptible to being reduced by employing tyres based upon alternative technology. As a more radical alternative to the inflated tyre **30**, airless tyres have been proposed and some practical examples have been demonstrated, for example in the form of Michelin's "Tweel" tyre. A schematic illustration of an airless tyre is shown in Figure 19.

In Figure 19, there is shown a wheel indicated generally by **2500**. The wheel **2500** includes a hub **2510** including a central flange **2520** with holes **2530** for receiving fasteners for attaching the hub **2510** an end of the axle **110** of the vehicle **900** in a similar manner to the wheel **10**. Instead of including the tyre **30**, the wheel **2500** is provided with a spring matrix **2540** radially surrounding a perimeter of the hub **2510**. The spring matrix **2540** is circularly symmetrical as shown and has a circular periphery onto which a circular flexible rim **2550** is attached; the circular flexible rim **2550** is fabricated from solid material, for example reinforced vulcanized rubber. The spring matrix **2540** includes a configuration of interconnecting leaf springs **2560** arranged to provide a relatively high transverse stiffness and a radial stiffness comparable to that provided by the tyre **30** of the wheel **10** when in a correctly inflated state. The leaf springs **2560** are fabricated from a material which exhibits a low susceptibility to work hardening; a polymer material such a nylon or polypropylene has been proposed, although other plastics material and/or metal alloys can be potentially employed. If required, lateral sides of the spring matrix **2540** can be protected by a membrane (not shown) to prevent snow and objects, for example stones and lumps of rock, becoming trapped between the leaf springs **2560** of the spring matrix **2540** and causing mass imbalance. The wheel **2500** is of advantage in that it is not susceptible to being punctured. Moreover, on account of the leaf springs **2560** undergoing elastic flexure in operation, rolling resistance is susceptible to being reduced in comparison to the wheel **10**.

However, the wheel **2500** has a potential failure mode involving one or more of the leaf springs **2560** fracturing on account of excess stress being applied thereto or by eventual work-hardening after a long period of use. Moreover, the leaf-springs **2560** are susceptible to acquiring permanent deformation after a long period of use or storage causing symmetrical and/or asymmetrical flexural imbalances in the wheel **2500**.

The present invention as described in the foregoing in relation to the wheel **10** is also susceptible to being used in conjunction with the wheel **2500**, with a modification that sensing the pressure P is no longer relevant for the wheel **2500**. The module **400** is susceptible to being mounted close to a central axis of the wheel **2500** at a location U1, at a periphery of the hub **2510** at a location U2, or on an inside of the flexible rim **2550** at a position U3. The modules **400** mounted at the position U1 or U2 on the wheel **2500** are susceptible to functioning in a substantially similar manner to the modules **400** mounted at the locations L1 and L2 on the wheel **10**.

In operation, when the wheel **2500** rotates, a portion of the flexible rim **2550** at which the module **400** is mounted at the location U3 periodically contacts a road surface resulting in a sudden y-axis radial acceleration A_y to be experienced by the module **400** which generates a signal of a general form as illustrated in signal V1 in Figure 10; in such case, the ordinate axis is to be interpreted to represent the acceleration A_y rather than the angle ϕ. Harmonic analysis of a sampled signal corresponding to the radial acceleration A_y in the apparatus **600, 2200** is highly informative regarding operation of the spring matrix **2540** of the wheel **2500**. In an event of the peaks of a type as shown in curve V1 in Figure 10 changing shape for the wheel **2500**, for example broadening out with time as depicted for signal V2, or becoming asymmetrical in respect of the rotation angle θ as illustrated in curves V3 and V4 in Figure 10, such a change is an indication that the spring matrix **2540** has suffered damage or has some form of problem. Both occlusion of voids between the leaf springs **2560** or potential cracking of the leaf springs **2560** can thereby be detected and a warning provided to the driver **910** of the vehicle **900**.

The wheel **2500** is of benefit that the module **400** at locations U1 to U3 is not occluded by metal components such that wireless communication to the electronic control unit (ECU) **950** is more easily achieved than potentially is possible from within the tyre **30** for the wheel **10**.

A hybrid wheel derived from the wheels **10, 2500** is also possible as shown in Figure 20 and indicated generally by **3000**. The wheel **3000** has both a hollow inflatable circular air-tight cavity **3010** provided with flexible walls, for example side walls in a generally similar manner to the aforementioned walls **230**, wherein the cavity **3010** is inflated in operation to the pressure P via its valve akin to the aforementioned valve **80**. Moreover, the wheel **3000** further comprises a spring matrix **3020** in a generally similar manner to the tyre **2500**. The spring matrix **3020** is beneficially interposed between the circular cavity **3010** and an exterior flexible rim **3030** of the wheel **3000**. At a centre of the wheel **3000**, there is provided a hub **3040** abutting onto the circular cavity **3010** and having a flange **3050** mountable using fasteners **3060**, for example bolts, to the axle **110**. The wheel **3000** is of advantage in that sharp objects penetrating the flexible rim **3020** are contained within the matrix **3020** and are thereby preventing from puncturing the cavity **3010**. The present invention with its modules **400** as described in the foregoing is also susceptible to being employed with the wheel **3000**, for example mounted upon the hub **3030**, within the circular cavity **3010** and also onto the flexible rim **3020**.

The wheel **3000** is of benefit, apart from the spring matrix **3020** protecting the cavity **3010** from being punctured by objects penetrating the rim **3030**, that partial failure of leaf springs **2560** in the matrix **3020** does not cause the wheel **3000** to become immediately non-functional, as occurs with puncturing of the tyre **30** of the wheel **10**, because the cavity **3010** continues to provide elastic support in a manner akin to the tyre **30**; however, partial failure of the leaf springs **2560** can be readily detected using the modules **400** pursuant to the present invention. Conversely, in a rare situation of the cavity **3010** becoming punctured, the spring matrix **3020** continues to provide elastic support in operation. In consequence, sudden loss of overall functionality of the wheel **3000** would be extremely rare in practice and any problems with the wheel **3000** would develop gradually in a manner that is readily detected by one or more of the modules **400** mounted on the wheel **3000** in conjunction with their electronic control unit (ECU) **950**. Such gradual development of any operating problems enables the enterprise **1000** to divert the vehicle **900** equipped with such wheels **3000** to the service centre **1020** for attention without the vehicle **900** becoming in any way totally immobilized en route to the service centre **1020**. The enterprise **1000** is thereby capable of providing a more reliable service to its customers. Moreover, the wheel **3000** is also potentially capable of exhibiting a lower rolling resistance in comparison to the wheel **10** and is thereby potentially more energy efficient which assists in respect of excess carbon dioxide emissions believed by the International Panel on Climate Change (IPCC) to be responsible for climate change associated with global warming. The wheel **3000** also potentially represents a considerable increase in safety on account of its enhanced reliability.

Although use of the present invention in relation to heavy commercial vehicles is described in the foregoing, it will be appreciated that the invention is also applicable to other types of vehicle, for example on wheels of aircraft, on wheels of automobiles, wheels of motorcycles and bicycles, on heavy construction equipment, on the wings of electricity wind turbines to identify potential structural problems, and so forth.

Expressions such as "has", "is", "include", "comprise", "consist of", "incorporates" are to be construed to include additional components or items which are not specifically defined; namely, such terms are to be construed in a non-exclusive manner. Moreover, reference to the singular is also to be construed to also include the plural. Furthermore, numerals and other symbols included within parentheses in the accompanying claims are not to be construed to influence interpreted claim scope but merely assist in understanding the present invention when studying the claims.

Modifications to embodiments of the invention described in the foregoing are susceptible to being implemented without departing from the scope of the invention as defined by the appended claims.

For example, use of the ABS sensor encoder **118** for sensing rotation of the wheels **10, 2500, 3000** has been described in the foregoing. However, additionally or alternatively, a measure of the angular orientation θ of the wheel **10, 2500, 3000** can also be computed, as elucidated in the foregoing, on a basis of the gravitational force g acting upon the accelerometer **770** of the module **400**. The gravitation force g is manifested in operation in the acceleration components A_x, A_y and is superimposed on any acceleration experienced at the wheel **10, 2500, 3000** due to general acceleration or deceleration of the vehicle **900**. On account of a typical time scale in which cyclical fluctuations of the gravitational force g as observed in the acceleration components A_x, A_y being generally more rapid than effects due to such general acceleration or deceleration, it is feasible to filter out or compensate for such components in the acceleration components A_x, A_y as a weight of the vehicle **900** and a motive power output from the engine or motor **930** of the vehicle **900** can be estimated or measured. When the angular orientation θ of the wheel **10, 2500, 3000** is derived from the acceleration components A_x, A_y, in addition to or as an alternative to the ABS encoder sensor **118**, such derivation does not preclude the use of aforementioned auto-alignment of the axes x', y', z' of the module **400** to the true x, y, z axes of the wheel **10, 2500, 3000** representative of orthogonal tangential and lateral axes respectively, see Figure 9. Such derivation of the angular orientation θ enables the present invention to be, for example, applied to vehicles which are not equipped with ABS braking or partially equipped with ABS braking on only certain of their wheels. Moreover, such derivation enables the present invention to be retrofitted in certain situations to older vehicles which are not provided with ABS braking.

Flexure of the side-wall **230** of the tyre **30** is also susceptible to being sensed by a first module **400** mounted at the location L3 moving in respect of a second module **400** mounted at the location L2 in close spatial proximity to the first module **400**. In operation, flexure of the side-wall **230** causes a relative spatial distance between the first and second modules **400** to vary correspondingly.

In a first configuration, the first module **400** is provided with a source of radiation, and the second module **400** is operable to monitor a magnitude of a portion of the radiation received thereat and convey a corresponding signal by wireless to the electronic control unit (ECU) **950**. The signal is representative of a change of spatial separation between the first and second modules **400** as a function of their wheel **10** rotating.

In a second configuration, the second module **400** is provided with a source of radiation, and the first module **400** is operable to monitor a magnitude of a portion of the radiation received thereat and convey a corresponding signal by wireless, for example using the mesh **210** of the tyre **30** as a wireless patch antenna, to the electronic control unit (ECU) **950**. The signal is representative of a change of spatial separation between the first and second modules **400** as a function of their wheel **10** rotating.

The radiation can be at least one of: a substantially constant magnetic field generated by a permanent magnet, an alternating magnetic field, ultrasonic radiation, wireless radiation, pulsed optical radiation, capacitively electrostatically-coupled radiation to mention a few examples. Ultrasonic radiation is beneficially generated and received using piezo-electric transducers.

CLAIMS

1. A wheel-monitoring apparatus (600, 680, 690, 2200) for monitoring operation of at least one wheel (10, 2500, 3000) of a vehicle (900), said apparatus (600, 680, 690, 2200) including one or more sensor modules (400) operatively mounted to revolve with said at least one wheel (10, 2500, 3000), said one or more modules (400) being operatively coupled in communication with a processing arrangement (710, ECU 950) of said vehicle (900), said one or more modules (400) being operable to sense at least one physical parameter of said wheel (10, 2500, 3000) and to generate at least one corresponding sensor signal for said processing arrangement (950), said processing arrangement (710, ECU 950) being operable to process said at least one sensor signal to compute information indicative of operation of said at least one wheel (10, 2500, 3000), said apparatus (600, 680, 690, 2200) including a sensor arrangement (118) for sensing an angular frequency of rotation (ω) of said at least one wheel (10, 2500, 3000),

characterized in that

said processing arrangement (710, ECU 950) is operable to process said at least one sensor signal in respect of said an angular frequency (ω) of rotation and/or an angular orientation (θ)of said at least one wheel (10, 2500, 3000); and

said processing arrangement being are operable to detect harmonic components occurring in said at least one physical parameter within one or more revolutions of said at least one wheel (10, 2500, 3000) as communicated in said at least one sensor signal to said processing arrangement (710, ECU 950) for computing said information indicative of operation of said at least one wheel (10, 2500, 3000).

2. A wheel monitoring apparatus according to claim 1, characterised an that processing arrangement being are operable to detect harmonic components of the first and further orders of the angular frequency of said at least one wheel.

3. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claims 1 or 2, wherein said at least one physical parameter includes at least one of:

(a) a pressure (P) within a tyre (30) or inflatable cavity (3010) of said at least one wheel (10, 2500, 3000) as measured at said one or more modules (400);

(b) an acceleration (A_x, A_y, A_z) as measured substantially at said one or more modules (400);

wherein said processing arrangement (710, ECU 950) is operable to apply an harmonic analysis to signals corresponding to said pressure (P) and/or said acceleration (A_x, A_y, A_z), said harmonic analysis being operable to identify harmonic components in respect of angular frequency (ω) corresponding to a temporal rate of change of said angular orientation (θ) of said at least one wheel (10, 2500, 3000).

4. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claim 3, wherein said harmonic analysis applying computation to at least one of:

(a) magnitudes of the harmonic components; and

(b) relative phase relationships between the harmonic components.

5. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any of claims 1 - 4, wherein said processing arrangement (710, ECU 950) is operable to employ said harmonic analysis for identifying an occurrence of at least one of:

(a) said at least one wheel (10, 2500, 3000) is imbalanced;

(b) a specific type of imbalance is present in said at least one wheel (10);

(c) said at least one wheel (10) is skewed in relation to its axle (110);

(d) said at least one wheel (10) is loose and wobbling about on its fasteners;

(e) a tyre (30), an inflatable cavity (3010) and/or a spring matrix (2560, 3020) of said at least one wheel (10, 2500, 3000) has defects in its flexural characteristics;

(f) a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000) is insufficiently inflated;

(g) a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000) is over inflated;

(h) a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000) is oval or has a higher-order lobed distortion;

(i) said at least one wheel (10) has a mass imbalance therein; and

(j) wheel bearings associated with an axle rotationally supporting said at least one wheel (10, 2500, 3000) in operation are vibrating or rattling in an unexpected manner indicative of a fault, or a potentially developing fault.

6. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any of claims 1 - 5, wherein said processing arrangement (710, ECU 950) is operable to perform said analysis of said harmonic components by applying:

(a) a rule-based algorithm for identifying one or more faults or potential faults from the harmonic components;

(b) a neural network pre-programmed to identify one or more faults or potential faults when presented with data describing said harmonic components; and/or

(c) an harmonic filter for highlighting a specific combination of one or more harmonic components which are indicative of one or more faults or potential faults with said at least one wheel (10).

7. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said processing arrangement (ECU 950) is provided with a predetermined list of types of wheel (10, 2500, 3000) susceptible to being employed with said vehicle (900) and associated expected characteristics, and said one or more modules (400) are operable to communicate information to said processing arrangement (ECU 950) regarding an identification of a type of wheel (10, 2500, 3000) onto which the one or more modules (400) are mounted, and said processing arrangement (ECU 950) is operable to compare measured signals provided from said one or more modules (400) with signals that would be expected from said one or more modules (400) as simulated from said predetermined list, and wherein a disparity between said measured signals and said simulated signals is indicative of one or more faults or potential faults.

8. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said one or more modules (400) include one or more processors (710) therein, and computation effort executed in operation for identifying one or more faults or potential faults in said at least one wheel (10, 2500, 3000) is shared between said one or more processors (710) and said processing arrangement (ECU 950).

9. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said processing arrangement (ECU 950) is operable to send a message requesting said one or modules (400) to respond back to said processing arrangement (ECU 950) for declaring their identification codes (ID) to said processing arrangement (ECU 950) for enabling said processing arrangement to identify its configuration of one or more modules (400), and for identifying any changes in said configuration of one or more modules (400) occurring.

10. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claim 9, wherein said one or more modules (400) are operable to also respond with data indicative of expected characteristics of said at least one wheel (10, 2500, 3000) to which said one of more modules (400) are mounted.

11. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said processing arrangement (ECU 950) is operable to compare rotation measurements from said sensor arrangement (118) for sensing said angular orientation (θ) of said at least one wheel (10, 2500, 3000) against signals supplied from said one or more corresponding modules (400) for checking functional operation of said sensor arrangement (118) and/or said one or more modules (400).

12. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claim 36, wherein said sensor arrangement (118) is an ABS wheel angular orientation sensor associated with brakes of said vehicle (900).

13. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any of the preceding claims, wherein said one or more modules (400) include at least one of:

(a) a pressure sensor (760) operable to sense a pressure (P) existing within a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000), said one or more modules (400) being operable to communicate a signal indicative of said pressure (P) to said processing arrangement (710, ECU 950) for use in computing said information indicative of operation of said at least one wheel (10, 2500, 3300);

(b) a strain gauge sensor (780) for measuring flexure of said tyre (30) or said inflatable cavity (3010) of said at least one wheel (10, 3000), said module (400) being operable to communicate a signal indicative of said flexure to said processing arrangement (710, ECU 950) for use in computing said information indicative of operation of said at least one wheel (10, 2500, 3300);

(c) an accelerometer (770) for measuring acceleration (A_x, A_y,) in at least one axis at a mounting location (L1, L2, L3, L4) of said one or more modules (400) on said at least one wheel (10, 2500, 3000), said one or more modules (400) being operable to communicate a signal indicative of said acceleration (A_x, A_y,) to said processing arrangement (710, ECU 950) for use in computing said information indicative of operation of said at least one wheel (10, 2500, 3300); and

.

14. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claim 13, wherein said accelerometer (775) is a multi-axis accelerometer operable to measure components of acceleration (A_x, $A_{y,}$) in at least one of radial, and tangential axes in respect of rotations of said at least one wheel (10, 2500, 3000).

15. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claim 14, wherein said accelerometer (775) is a silicon micromachined device.

16. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said one or more modules (400) are mounted at one or more locations (L1, L2, L3, L4) on said at least one wheel (10, 2500, 3000), said one or more locations including:

(a) on a hub (20) of said at least one wheel (10, 2500, 3000) substantially at an axis (B-B) of rotation of said at least one wheel (10, 2500, 3000);

(b) on a hub (20) of said at least one wheel (10, 2500, 3000) at a radial distance from said axis of rotation (B-B) of said at least one wheel (10, 2500, 3000);

(c) on a hub (20) of said at least one wheel (10, 2500, 3000) in fluid communication with a filling valve (80) of a tyre (30) or a filling valve of an inflatable cavity (3010) of said wheel (10, 3000) for sensing a pressure (P) within said tyre (30) or said cavity (3010);

(d) within a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000) for sensing a pressure (P) within said tyre (30) or said cavity (3010), said at least one module (400) being mounted to a peripheral surface (90) of a hub (20, 3040) of said at least one wheel (10, 3000);

(e) within a tyre (30) or an inflatable cavity (3010) of said wheel (10, 3000) for sensing a pressure (P) within said tyre (30) or said cavity (3010), said one or more modules (400) being mounted to an inside side-wall surface (230) of said tyre (30) or said cavity (3010) for measuring flexural characteristics of said side-wall (230); and

(f) on an inside surface of a peripheral rim (2550, 3030) of said at least one wheel (10, 2500, 3000) for measuring acceleration thereat.

17. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said one or more modules (400) include at least one wireless interface (730) for communicating between said one or more modules (400) and said processing arrangement (ECU 950), said one or more modules (400) forming a wireless network wherein certain of said one or more modules (400) are operable to function as one or more relay nodes for conveying signal exchange between said processing arrangement (ECU 950) and other of said one or more modules (400).

18. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said one or more modules (400) are each provided with a corresponding identification code for communicating to said processing arrangement (ECU 950) so that said processing arrangement (ECU 950) is able to recognize from which module (400) corresponding signal data has been sent.

19. A wheel-monitoring apparatus (600, 680, 690, 2000) as claimed in any one of the preceding claims, wherein said one or more modules (400) are radially distributed around said at least one wheel (10, 2500, 3000) for sensing operation of said at least one wheel (10, 2500, 3000) at a plurality of angular locations therearound.

20. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said apparatus (600, 680, 690, 2200) includes a display (915) coupled in communication with said processing arrangement (ECU 950) for presenting information to a driver of said vehicle (900) indicating at least one of:

(a) an operating status of said one or more modules (400);

(b) a condition of said at least one wheel (10, 2500, 3000);

(c) one or more faults or potential faults associated with said at least one wheel (10, 2500, 3000);

(d) information regarding one or more actions to be taken by a driver (910) of said vehicle (900) in an event of one or more faults or potential faults associated with said at least one wheel (10, 2500, 3000) being identified; and

(e) an indication of whether or not at said at least one wheel (10, 2500, 3000) of said vehicle (900) has been modified or tampered with.

21. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said processing arrangement (ECU 950) is provided with a wireless interface (960) for communicating with a service facility (1000, 1010, 2000, 2010) remote from said vehicle (900), said processing arrangement (ECU 950) being operable to communicate information indicative of functionality of said at least one wheel (10, 2500, 3000), said information being indicative of one or more faults or potential faults associated with said at least one wheel (10, 2500, 3000) as computed from signals provided from said one or more modules (400), and for receiving instructions from said service facility regarding actions for addressing said one or more faults or potential faults.

22. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in any one of the preceding claims, wherein said one or more modules (400) include a processor (710) coupled to an associated data memory (720), said one or more modules (400) via their pressure sensors (760) being operable to record a pressure (P) within a tyre (30) or inflatable cavity (3010) of said at least one wheel (10, 3000) in relation to time (t) as determined by a clock arrangement (CLK 710) included within said one or more modules (400), and said processor (710) is operable to monitor changes in said pressure (P) with time (t) to identify one or more of:

(a) a gradual leak of air or gas from said tyre (30) or inflatable cavity (3010) indicative of a need to recharge said tyre (30) or inflatable cavity (3010) with air or gas; and

(b) any abrupt depressurization of said tyre (30) or inflatable cavity (3010) indicative of a puncturing or rapid deflation event having occurred, or said tyre (30) or inflatable cavity (3010) having been exchanged.

23. A wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claim 21, wherein said one or more modules (400) are operable to communicate to said processing arrangement (950) a message that sensed data pertaining to said tyre (30) or inflatable cavity (3010) of said at least one wheel (10, 3000) being potentially unreliable due to said abrupt depressurization.

24. A method for monitoring operation of at least one wheel (10, 2500, 3000) of a vehicle (900) using a wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claim 1, said apparatus (600, 680, 690, 2200) including one or more sensor modules (400) operatively mounted to revolve with said at least one wheel (10, 2500, 3000), said one or more modules (400) being operatively coupled in communication with a processing arrangement (710, ECU 950) of said vehicle (900),

said method including steps of:

(a) sensing using said one or more modules (400) at least one physical parameter of said at least one wheel (10, 2500, 3000) and generating at least one corresponding sensor signal for said processing arrangement (950);

(b) sensing an angular frequency of rotation (ω) of said at least one wheel (600, 680, 690, 2200) using a sensor arrangement (118) of said apparatus (600, 680, 690, 2200);

(c) processing in said processing arrangement (710, ECU 950) said at least one sensor signal to compute information indicative of operation of said at least one wheel (10, 2500, 3000),

characterized in that

said processing arrangement (710, ECU 950) is operable to process said at least one sensor signal in respect of said an angular frequency (ω) of rotation and/or angular orientation (θ) of said at least one wheel; and

said processing arrangement is operable to detect harmonic components occurring in said at least one physical parameter within one or more revolutions of said at least one wheel (10, 2500, 3000) as communicated in said at least one sensor signal to said processing arrangement (710, ECU 950) for computing said information indicative of operation of said at least one wheel (10, 2500, 3000).

25. A method according to claim 24, characterised an that said processing arrangement is operable to detect harmonic components of the first and further orders of the angular frequency of said at least one wheel.

26. A method as claimed in claim 24 or 25, wherein said harmonic analysis includes computations pertaining to at least one of:
(a) magnitudes of the harmonic components; and
(b) relative phase relationships between the harmonic components.

27. A method as claimed in claim 24, 25 or 26, wherein said processing arrangement (710, ECU 950) is operable to employ said harmonic analysis for identifying an occurrence of at least one of:
(a) said at least one wheel (10, 2500, 3000) is imbalanced;
(b) a specific type of imbalance present in said at least one wheel (10);
(c) said at least one wheel (10) is skewed in relation to its axle (110);
(d) said at least one wheel (10) is loose and wobbling about on its fasteners;
(e) a tyre (30), an inflatable cavity (3010) and/or a spring matrix (2560, 3020) of said at least one wheel (10, 2500, 3000) has defects in its flexural characteristics;
(f) a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000) is insufficiently inflated;

(g) a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000) is over inflated;

(h) a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000) is oval or has a higher-order lobed distortion;

(i) said at least one wheel (10) has a mass imbalance therein; and

(j) wheel bearings associated with an axle rotationally supporting said at least one wheel (10, 2500, 3000) in operation are vibrating or rattling in an unexpected manner indicative of a fault, or a potentially developing fault.

28. A method as claimed in any of claimw 24, - 27, wherein said processing arrangement (710, ECU 950) is operable to perform said analysis of said harmonic components by applying:

(a) a rule-based algorithm for identifying one or more faults or potential faults from the harmonic components; and/or

(b) a neural network pre-programmed to identify one or more faults or potential faults when presented with data describing said harmonic components; and/or

(c) a harmonic filter for highlighting a specific combination of one or more harmonic components which are indicative of one or more faults or potential faults with said at least one wheel (10).

29. A method as claimed in any one of claims 24 to 28, wherein said processing arrangement (ECU 950) is provided with a predetermined list of types of wheel (10, 2500, 3000) susceptible to being employed with said vehicle (900) and associated expected characteristics, and said one or more modules (400) are operable to communicate information to said processing arrangement (ECU 950) regarding an identification of a type of wheel (10, 2500, 3000) onto which the one or more modules (400) are mounted, and said processing arrangement (ECU 950) is operable to compare measured signals provided from said one or more modules (400) with signals that would be expected from said one or more modules (400) as simulated from said predetermined list, and wherein a disparity between said measured signals and said simulated signals is indicative of one or more faults or potential faults.

30. A method as claimed in any one of claims 24 to 29, wherein said one or more modules (400) include one or more processors (710) therein, and computation effort executed in operation for identifying one or more faults or potential faults in said at least one wheel (10, 2500, 3000) is shared between said one or more processors (710) and said processing arrangement (ECU 950).

31. A method as claimed in any one of claims 24 to 30, wherein said processing arrangement (ECU 950) is operable to send a message requesting said one or more modules (400) to respond back to the processing arrangement (ECU 950) for declaring their identification codes (ID) to said processing arrangement (ECU 950) for enabling said processing arrangement to identify its configuration of one or more modules (400), and for identifying any changes in said configuration of one or more modules (400) occurring.

32. A method as claimed in claim 30, wherein said one or more modules (400) are operable to also respond with data indicative of expected characteristics of said at least one wheel (10, 2500, 3000) to which said one of more modules (400) are mounted.

33. A method as claimed in any one of claims 24 to 32, wherein said processing arrangement (ECU 950) is operable to compare rotation measurements from said sensor arrangement (118) for sensing said angular orientation (θ) of said at least one wheel (10, 2500, 3000) against signals supplied from said one or more corresponding modules (400) for checking functional operation of said sensor arrangement (118) and/or said one or more modules (400).

34. A method as claimed in claim 33, wherein said sensor arrangement (118) is an ABS sensor associated with brakes of said vehicle (900).

35. A method as claimed in any of claims 24 or 34, wherein said one or more modules (400) include at least one of:

(a) a pressure sensor (760) operable to sense a pressure (P) existing within a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000), said one or more modules (400) being operable to communicate a signal indicative of said pressure (P) to said processing arrangement (710, ECU 950) for use in computing said information indicative of operation of said at least one wheel (10, 2500, 3300);

(b) a strain gauge sensor (780) for measuring flexure of said tyre (30) or said inflatable cavity (3010) of said at least one wheel (10, 3000), said one or more modules (400) being operable to communicate a signal indicative of said flexure to said processing arrangement (710, ECU 950) for use in computing said information indicative of operation of said at least one wheel (10, 2500, 3300);

(c) an accelerometer (770) for measuring acceleration (A_x, A_y,) in at least one axis at a mounting location (L1, L2, L3, L4) of said one or more modules (400) on said at least one wheel (10, 2500, 3000), said one or more modules (400) being operable to communicate a signal indicative of said acceleration (A_x, A_y,) to said processing arrangement (710, ECU 950) for use in computing said information indicative of operation of said at least one wheel (10, 2500, 3300); and

(d) a magnetic sensor (775) for measuring a magnetic field applied to said one or more modules (400), said one or more modules (400) being operable to communicate a signal indicative of said applied magnetic field to said processing arrangement (710, ECU 950) for use in controlling operation of said apparatus (600, 680, 690, 2200).

36. A method as claimed in claim 35, wherein said accelerometer (775) is a multi-axis accelerometer operable to measure components of acceleration (A_x, A_y,) in at least one of radial, and tangential axes in respect of rotations of said at least one wheel (10, 2500, 3000).

37. A method as claimed in claim 36, wherein said accelerometer (775) is a silicon micromachined device.

38. A method as claimed in any one of claims 24 to 37, wherein said one or more modules (400) are mounted at one or more locations (L1, L2, L3, L4) on said at least one wheel (10, 2500, 3000), said one or more locations including:

(a) on a hub (20) of said at least one wheel (10, 2500, 3000) substantially at an axis (B-B) of rotation of said at least one wheel (10, 2500, 3000);

(b) on a hub (20) of said at least one wheel (10, 2500, 3000) at a radial distance from said axis of rotation (B-B) of said at least one wheel (10, 2500, 3000);

(c) on a hub (20) of said wheel (10, 2500, 3000) in fluid communication with a filling valve (80) of a tyre (30) or a filling valve of an inflatable cavity (3010) of said at least one wheel (10, 3000) for sensing a pressure (P) within said tyre (30) or said cavity (3010);

(d) within a tyre (30) or an inflatable cavity (3010) of said at least one wheel (10, 3000) for sensing a pressure (P) within said tyre (30) or said cavity (3010), said one or more modules (400) being mounted to a peripheral surface (90) of a hub (20, 3040) of said at least one wheel (10, 3000);

(e) within a tyre (30) or an inflatable cavity (3010) of said wheel (10, 3000) for sensing a pressure (P) within said tyre (30) or said cavity (3010), said one or more modules (400) being mounted to an inside side-wall surface (230) of said tyre (30) or said cavity (3010) for measuring flexural characteristics of said side-wall (230); and

(f) on an inside surface of a peripheral rim (2550, 3030) of said at least one wheel (10, 2500, 3000) for measuring acceleration thereat.

39. A method as claimed in any one of claims 24 to 38, wherein said one or more modules (400) include at least one wireless interface (730) for communicating between said one or more modules (400) and said processing arrangement (ECU 950), said one or more modules (400) forming a wireless network wherein certain of said one or more modules (400) are operable to function as one or more relay nodes for conveying signal exchange between said processing arrangement (ECU 950) and other of said one or more modules (400).

40. A method as claimed in any one of claims 24 to 39, wherein said one or more modules (400) are each provided with a corresponding identification code (ID) for communicating to said processing arrangement (ECU 950) so that said processing arrangement (ECU 950) is able to recognize from which module (400) corresponding signal data has been sent.

41. A method as claimed in any one of claims 24 to 40, wherein said one or more modules (400) are radially distributed around said at least one wheel (10, 2500, 3000) for sensing operation of said at least one wheel (10, 2500, 3000) at a plurality of angular locations therearound.

42. A method as claimed in any one of claims 24 to 41, wherein said apparatus (600, 680, 690, 2200) includes a display (915) coupled in communication with said processing arrangement (ECU 950) for presenting in formation to a driver (910) of said vehicle (900) indicating at least one of:

(a) an operating status of said one or more modules (400);
(b) a condition of said at least one wheel (10, 2500, 3000);
(c) one or more faults or potential faults associated with said at least one wheel (10, 2500, 3000);
(d) information regarding actions to be taken by a driver (910) of said vehicle (900) in an event of one or more faults or potential faults associated with said at least one wheel (10, 2500, 3000) being identified; and
(e) an indication of whether or not one or more wheels (10, 2500, 3000) of the vehicle (900) have been modified.

43. A method as claimed in any one of claims 24 to 42, wherein said processing arrangement (ECU 950) is provided with a wireless interface (960) for communicating with a service facility (1000, 1010, 2000, 2010) remote from said vehicle (900), said processing arrangement (ECU 950) being operable to communicate information indicative of functionality of said at least one wheel (10, 2500, 3000), said information being indicative of

one or more faults or potential faults associated with said at least one wheel (10, 2500, 3000) as computed from signals provided from said one or more modules (400), and for receiving instructions from said service facility regarding actions for addressing said one or more faults or potential faults.

44. A method as claimed in any one of claims 24 to 43, wherein said one or more modules (400) include a processor (710) coupled to an associated data memory (720), said one or more modules (400) via their pressure sensors (760) being operable to record a pressure (P) within a tyre (30) or inflatable cavity (3010) of said at least one wheel (10, 3000) in relation to time (t) as determined by a clock arrangement (CLK 710) included within said one or more modules (400), and said processor (710) is operable to monitor changes in said pressure (P) with time (t) to identify one or more of:

(a) a gradual leak of air or gas from said tyre (30) or inflatable cavity (3010) indicative of a need to recharge said tyre (30) or inflatable cavity (3010) with air or gas;

(b) any abrupt depressurization of said tyre (30) or inflatable cavity (3010) indicative of a puncturing event or a rapid deflation event having occurred, or said tyre (30) or inflatable cavity (3010) having been exchanged.

45. A method as claimed in claim 44, wherein said one or more modules (400) are operable to communicate to said processing arrangement (950) a message that sensed data pertaining to said tyre (30) or inflatable cavity (3010) of said at least one wheel (10, 3000) being potentially unreliable on account of said abrupt depressurization of said tyre or cavity.

46. A method as claimed in any one of claims 24 to 45, wherein said at least one physical parameter includes at least one of:

(a) a pressure (P) within a tyre (30) or inflatable cavity (3010) of said at least one wheel (10, 2500, 3000) as measured at said one or more modules (400); and

(b) an acceleration (A_x, A_y, A_z) as measured substantially at said one or more modules (400);

wherein said processing arrangements (710, ECU 950) is operable to apply a harmonic analysis to signals corresponding said pressure (P) and/or said acceleration (A_x, A_y, A_z), said harmonic analysis being operable to identify harmonic components in respect of angular frequency (ω) corresponding to a temporal rate of said angular orientation (θ) of said at least one wheel (10, 2500, 3000).

47. A vehicle (900) including a wheel-monitoring apparatus (600, 680, 690, 2200) as claimed in claim 1 operable to monitor operation of at least one wheel (10, 2500, 3000) of said vehicle (900).

48. A wheel (10, 2500, 3000) including one or more modules (400) mounted thereonto, said one or more modules (400) operable to function with a wheel-monitoring apparatus as claimed in claim 1.

49. A module (400) for mounting onto a wheel (10, 2500, 3000) operable to function with a wheel-monitoring apparatus as claimed in claim 1.

50. A tyre (30) including a module (400) as claimed in claim 49.

51. A tyre (30) as claimed in claim 50, wherein said module (400) is mounted to a side wall (230) of said tyre (30).

52. A software product recorded on a data carrier, said product being executable on computing hardware for executing a method as claimed in any one of claims 24 to 46.

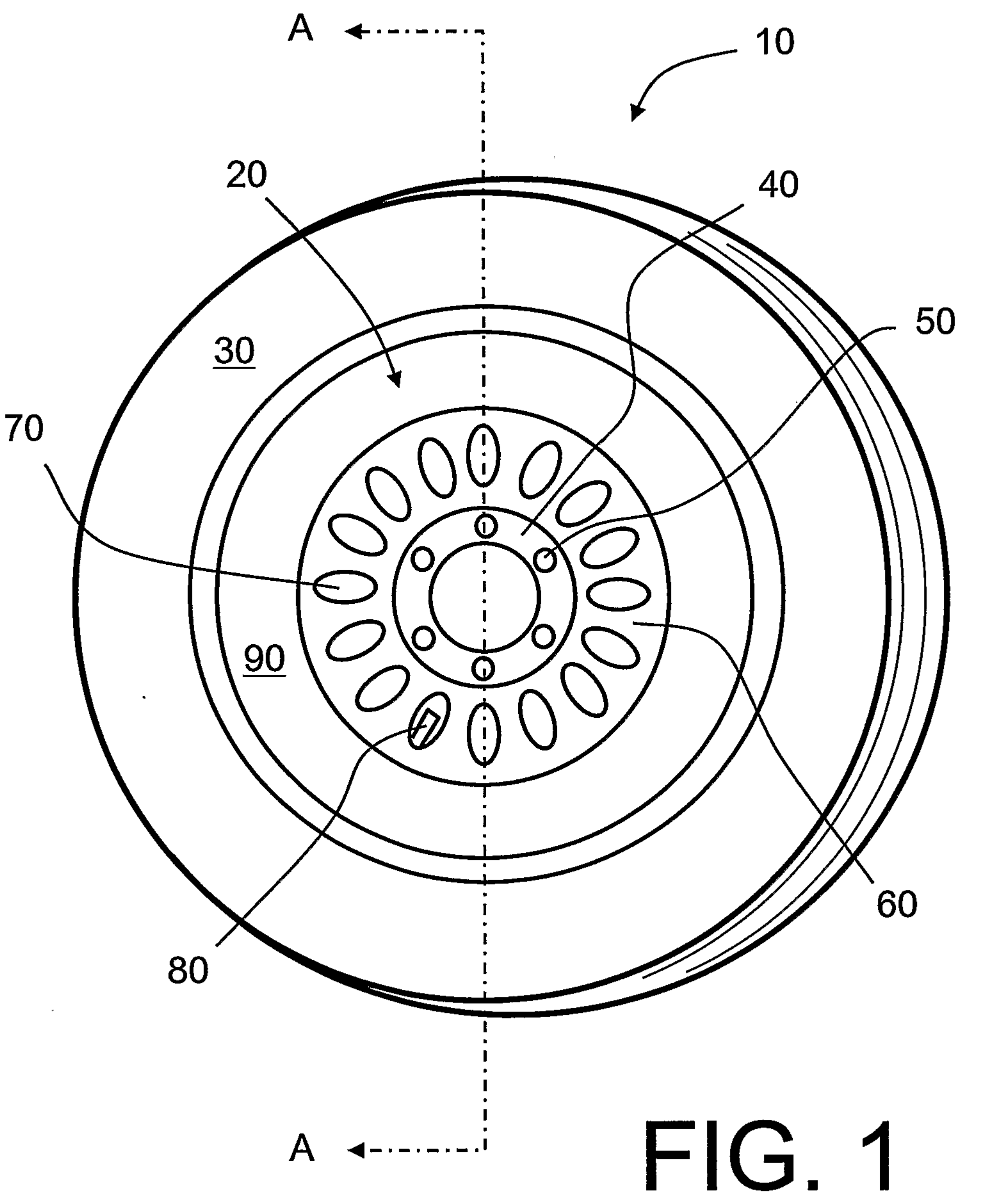


FIG. 1

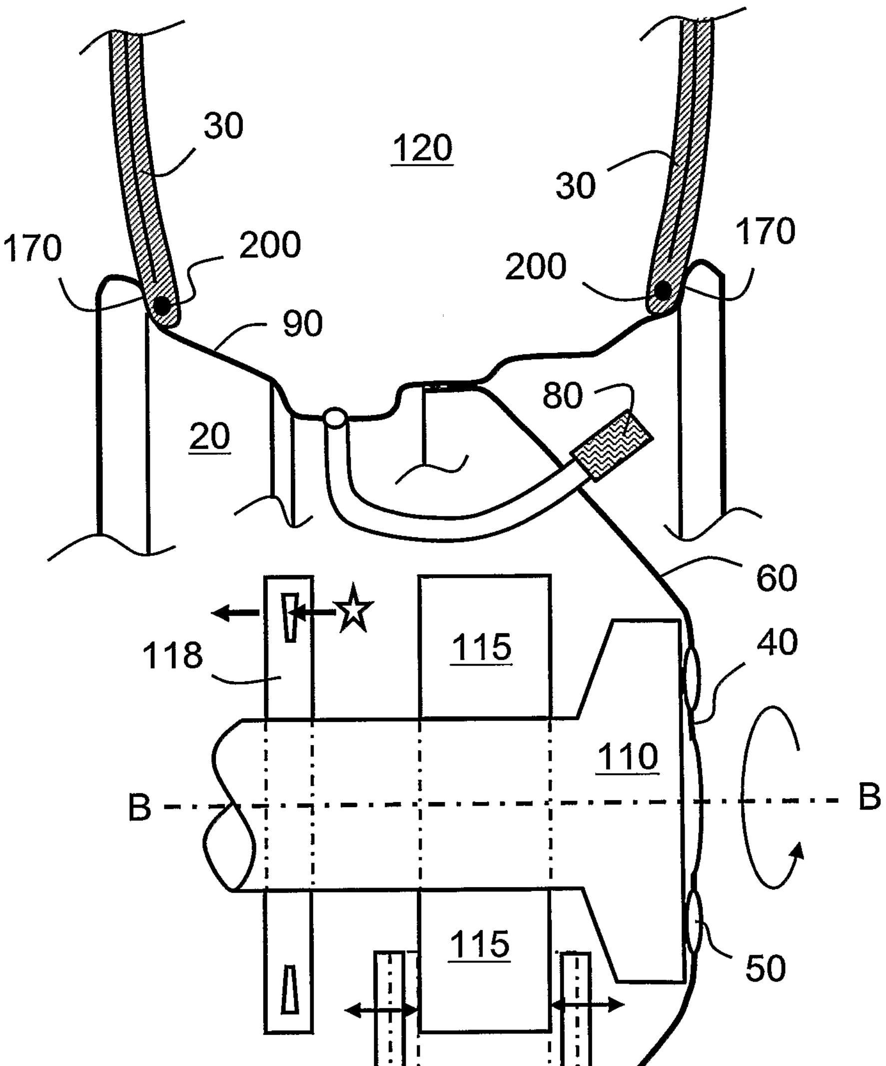


FIG. 2

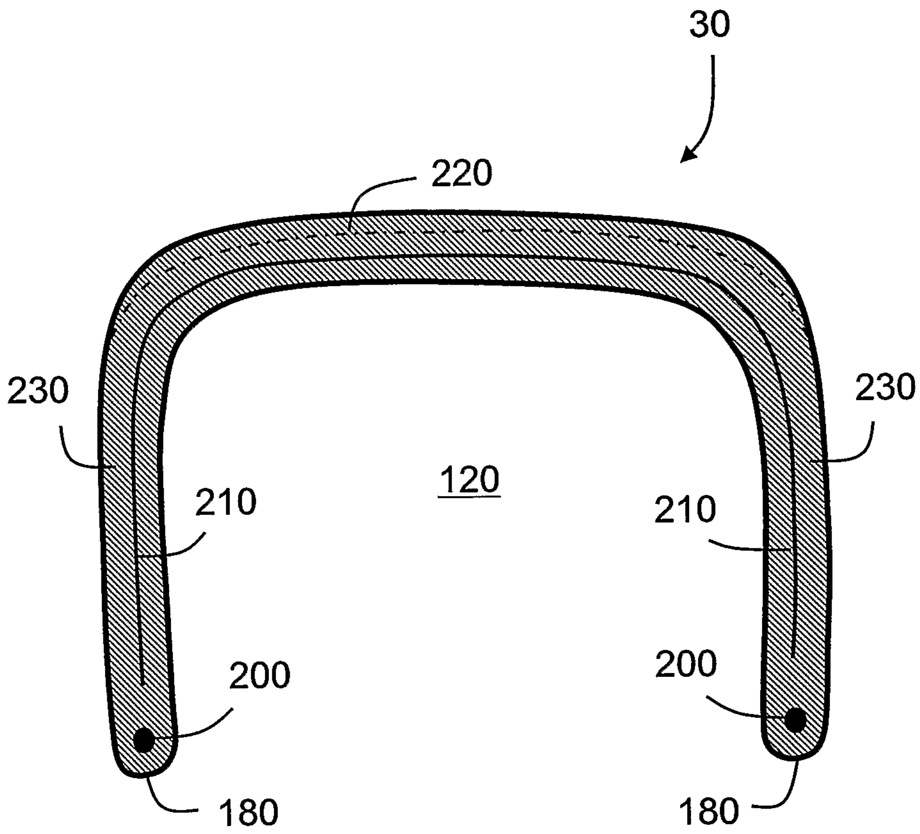


FIG. 3

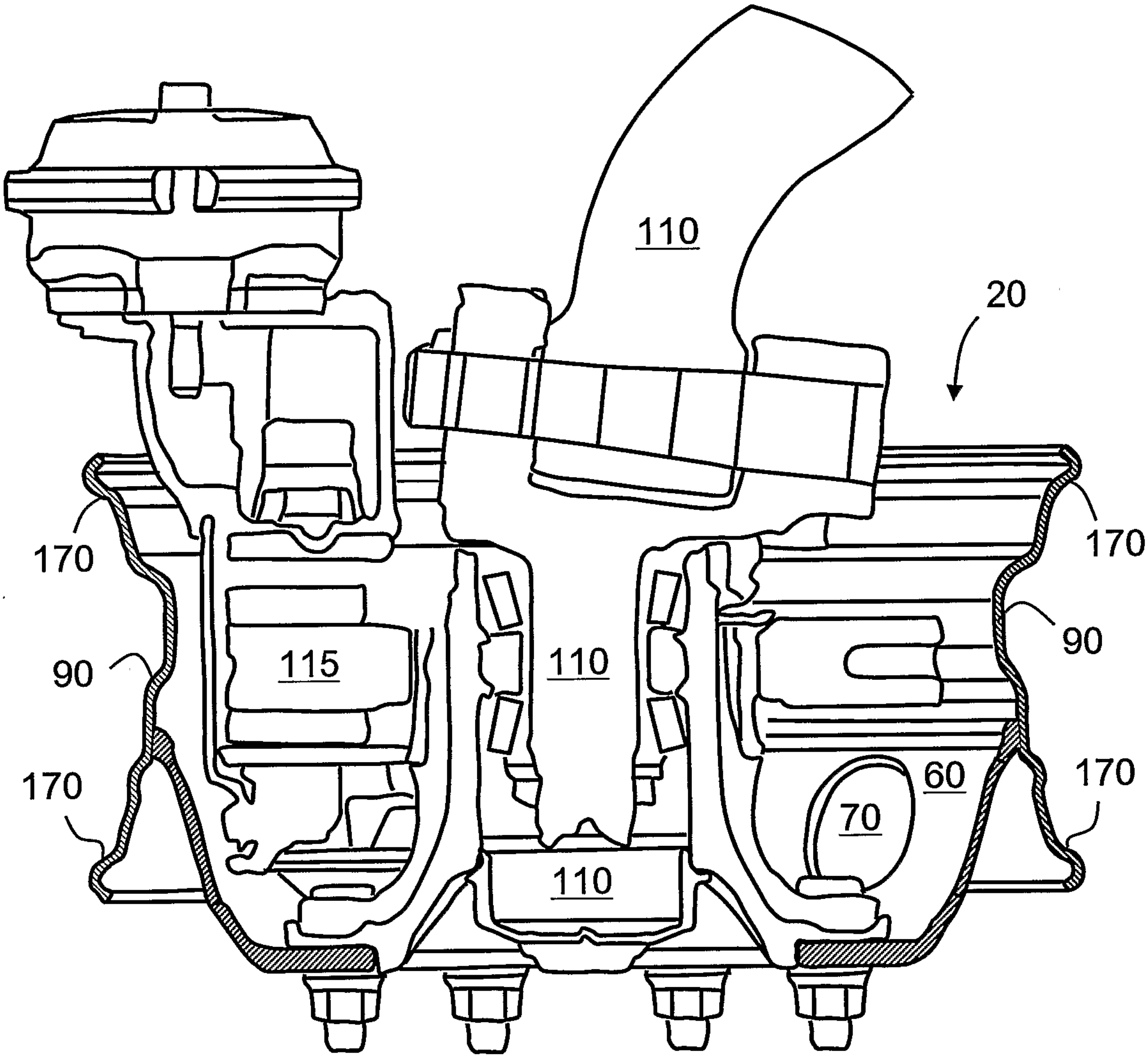


FIG. 4

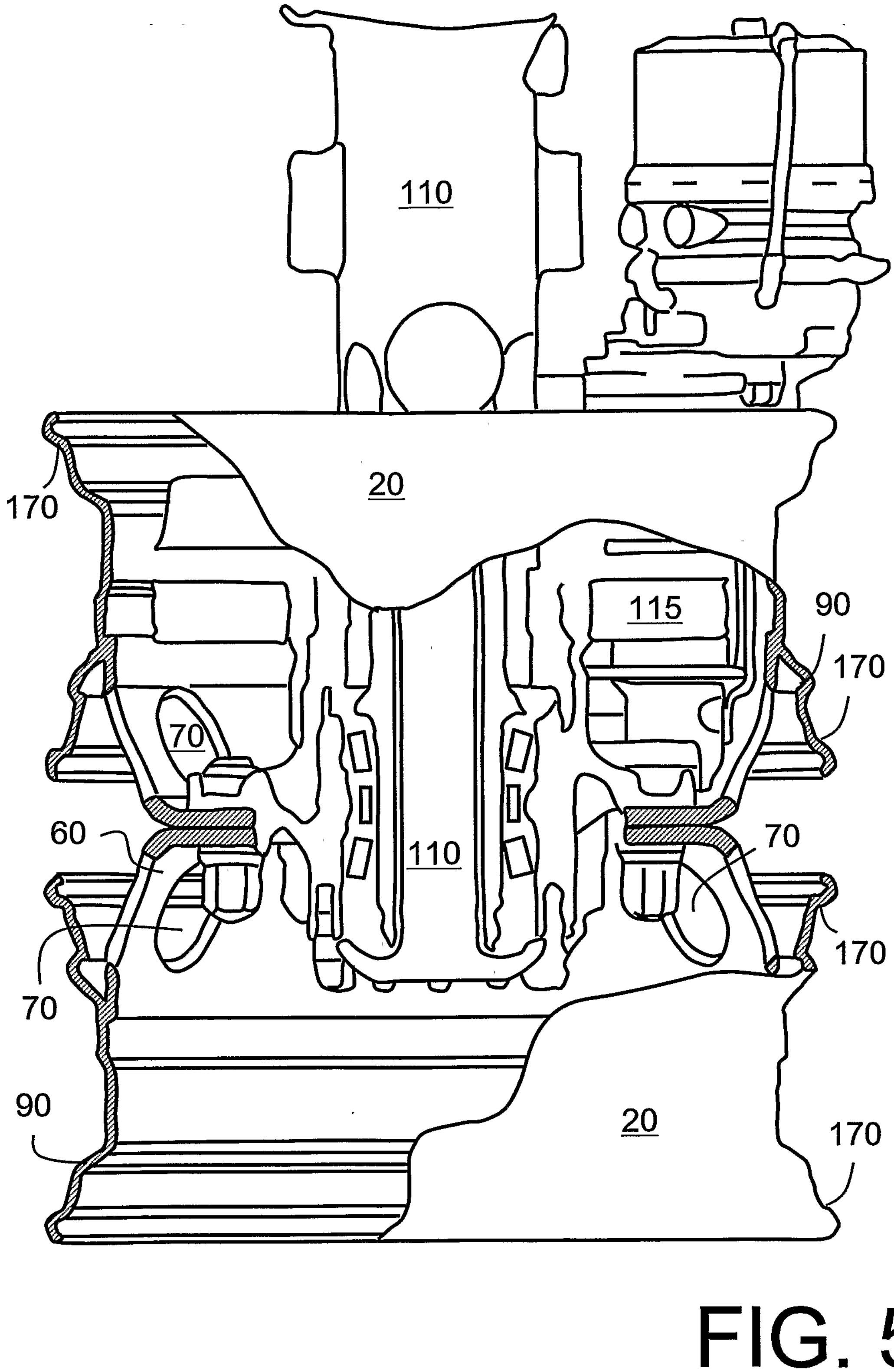


FIG. 5

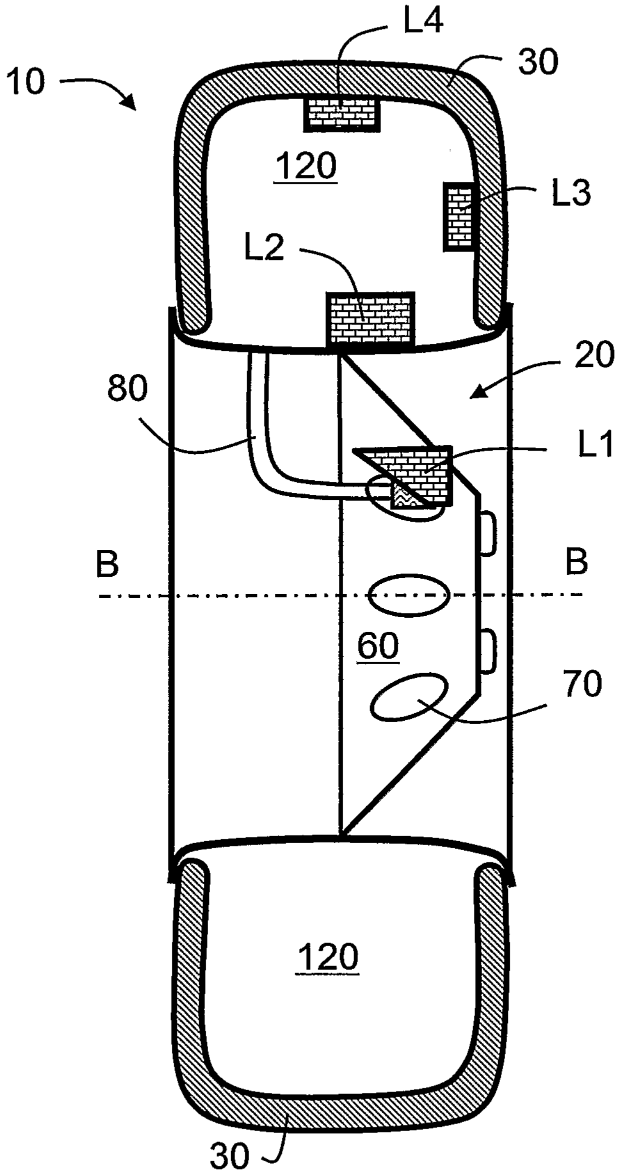


FIG. 6

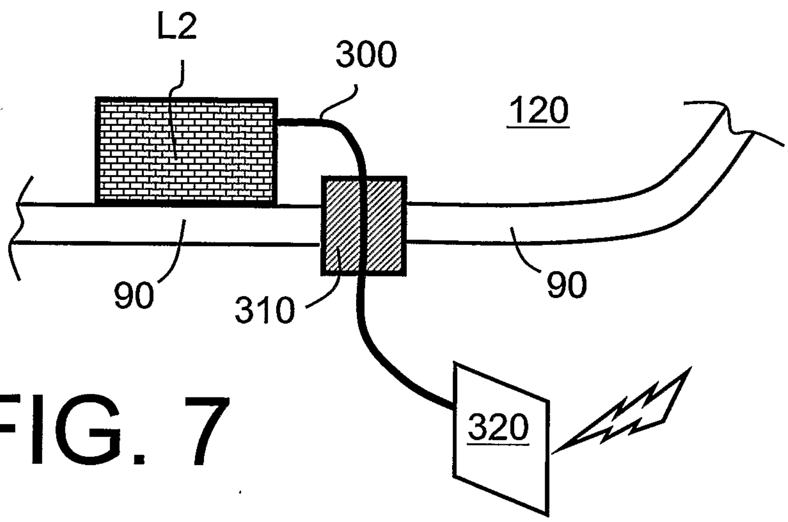


FIG. 7

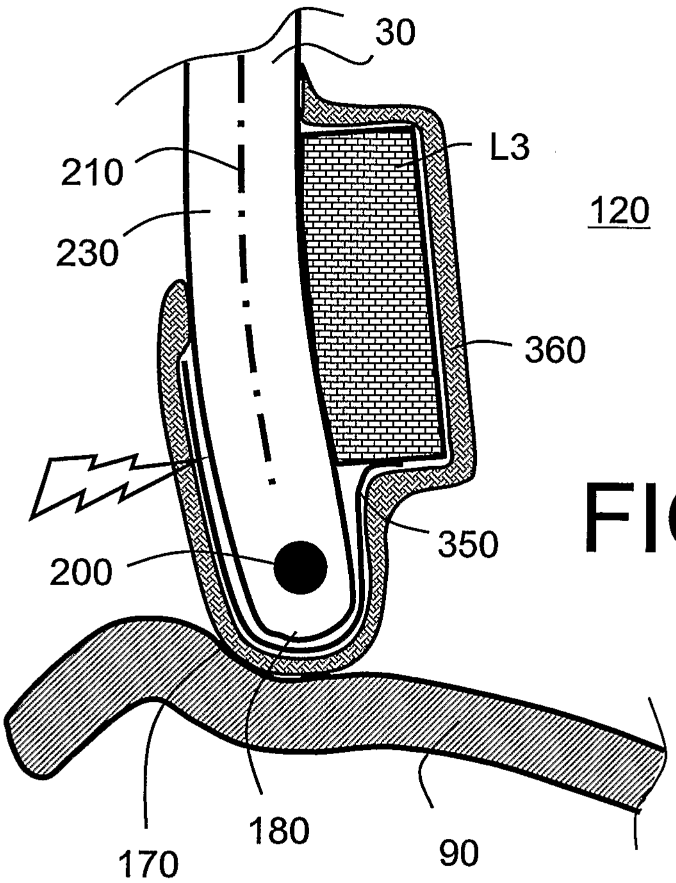


FIG. 8

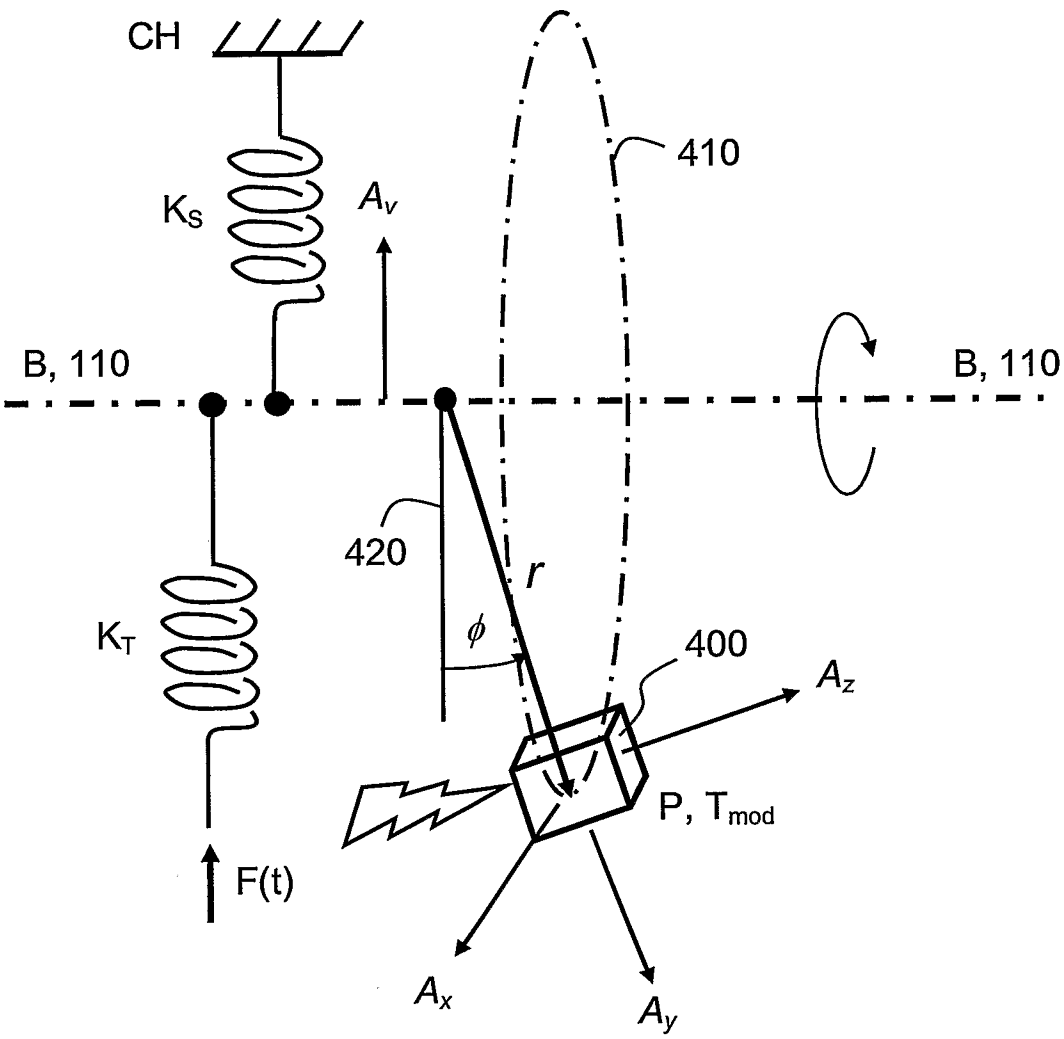


FIG. 9

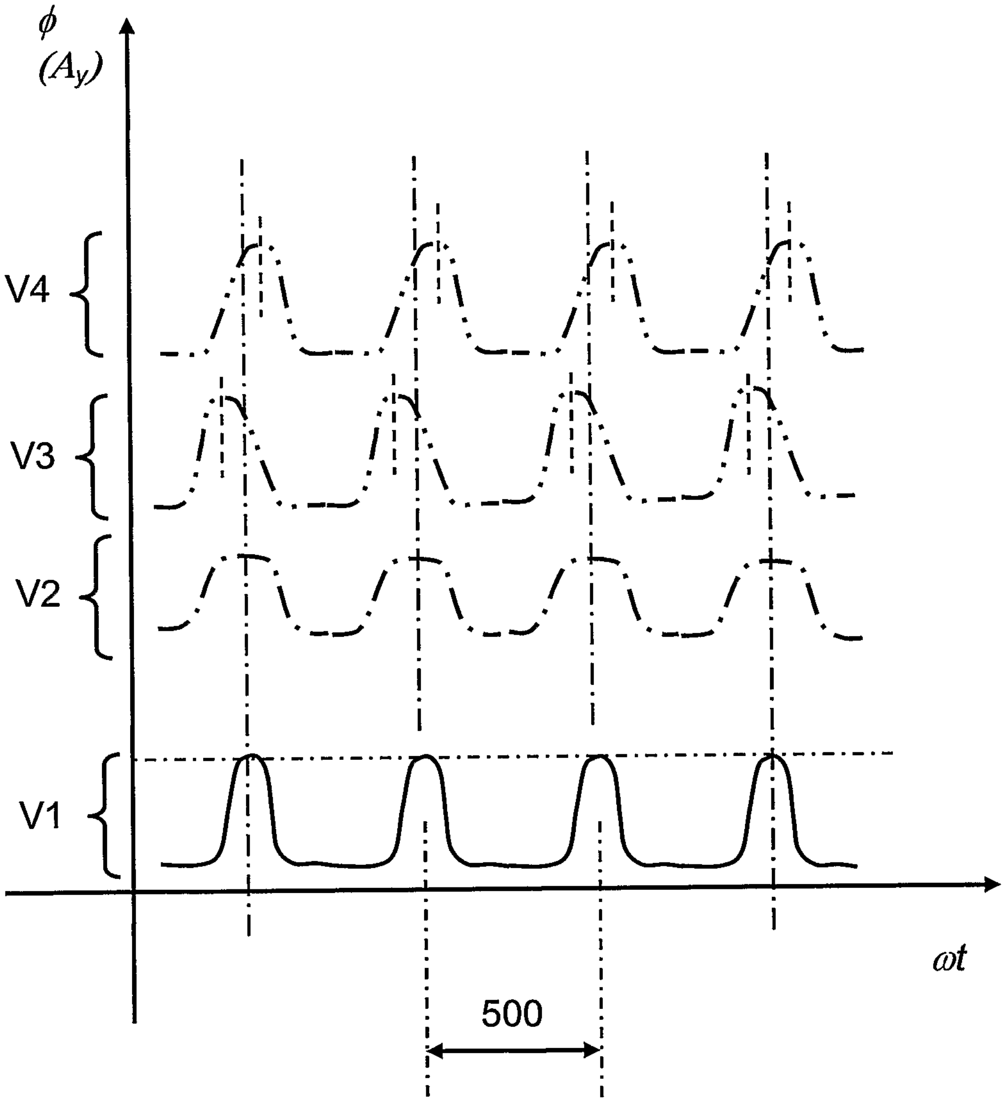
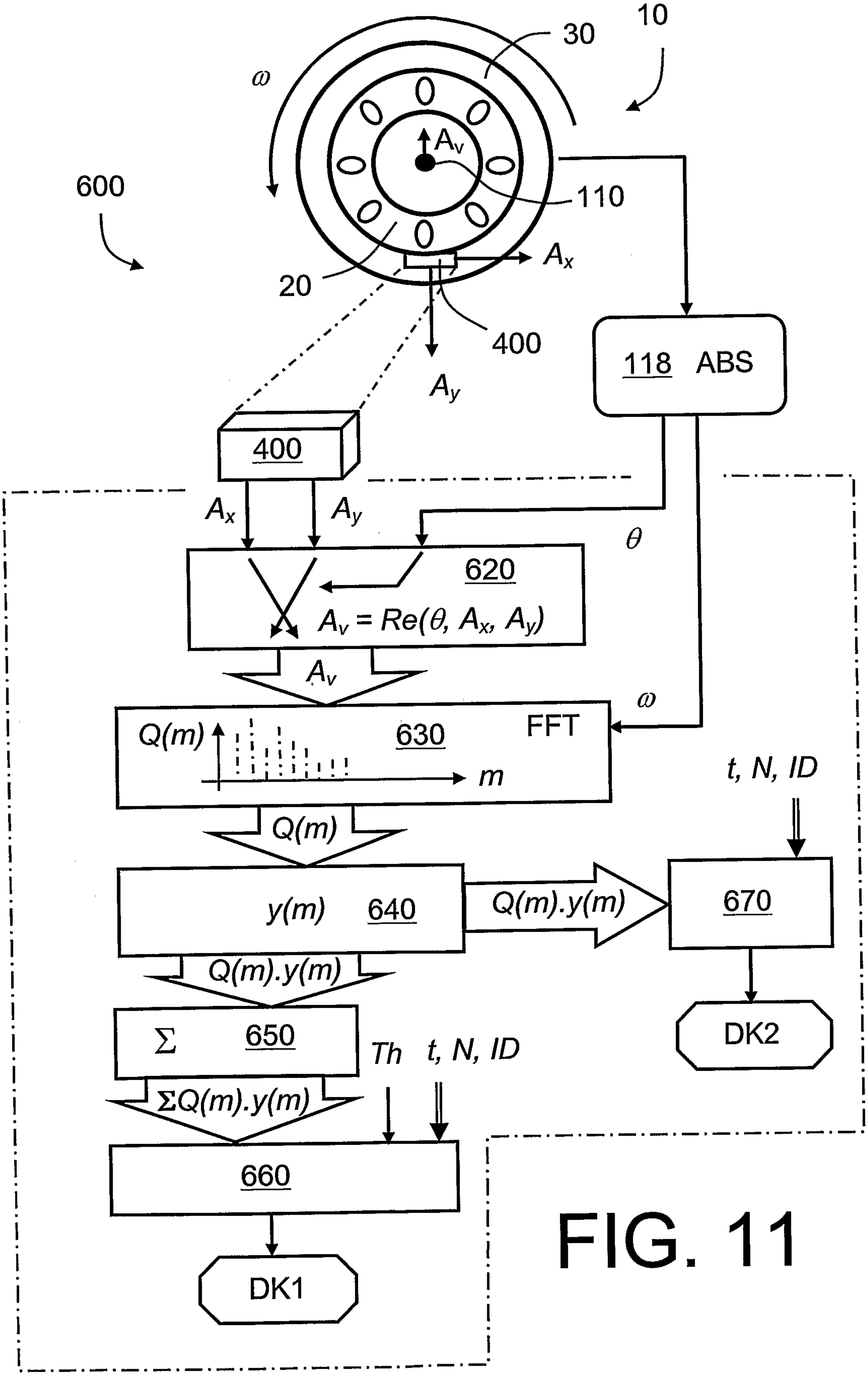
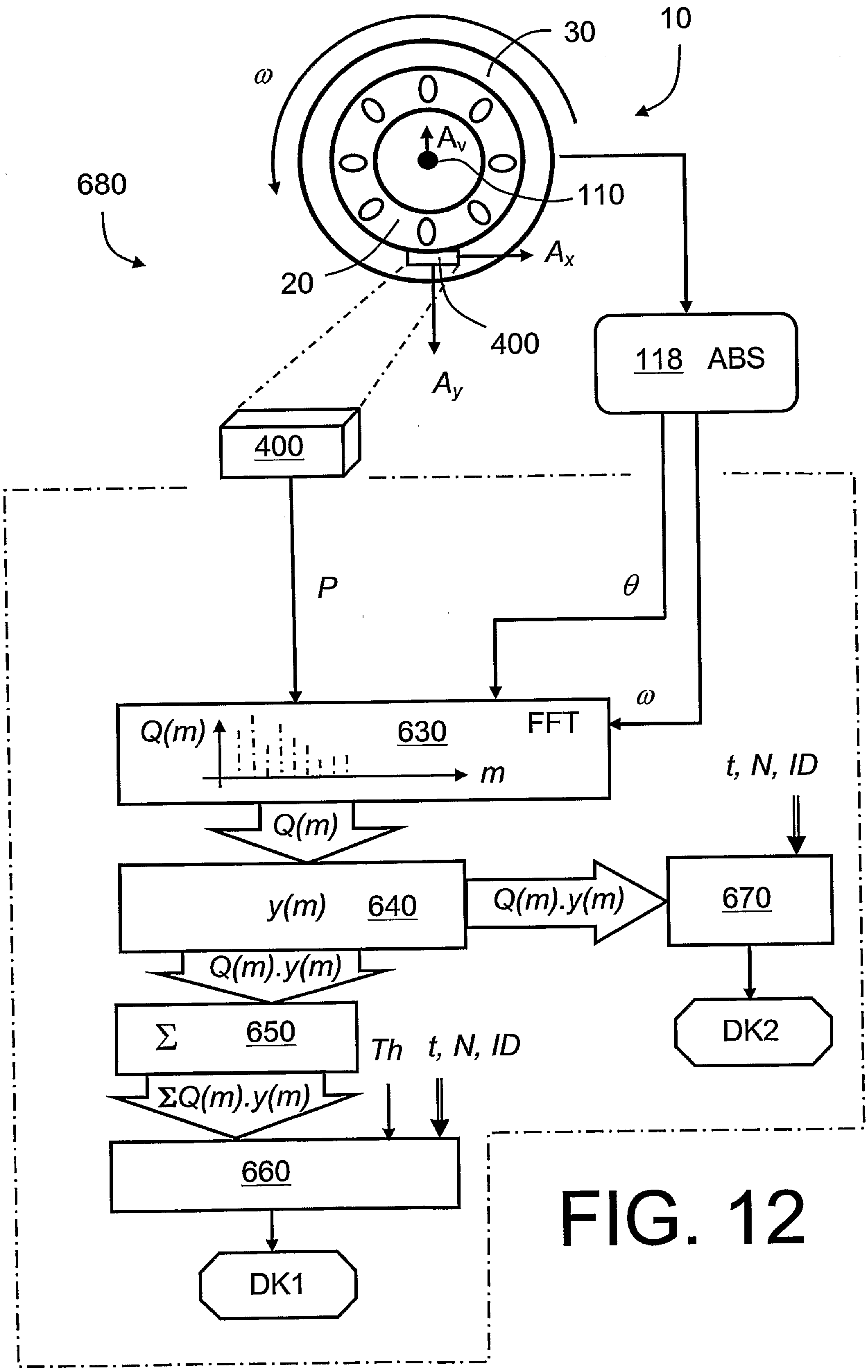


FIG. 10



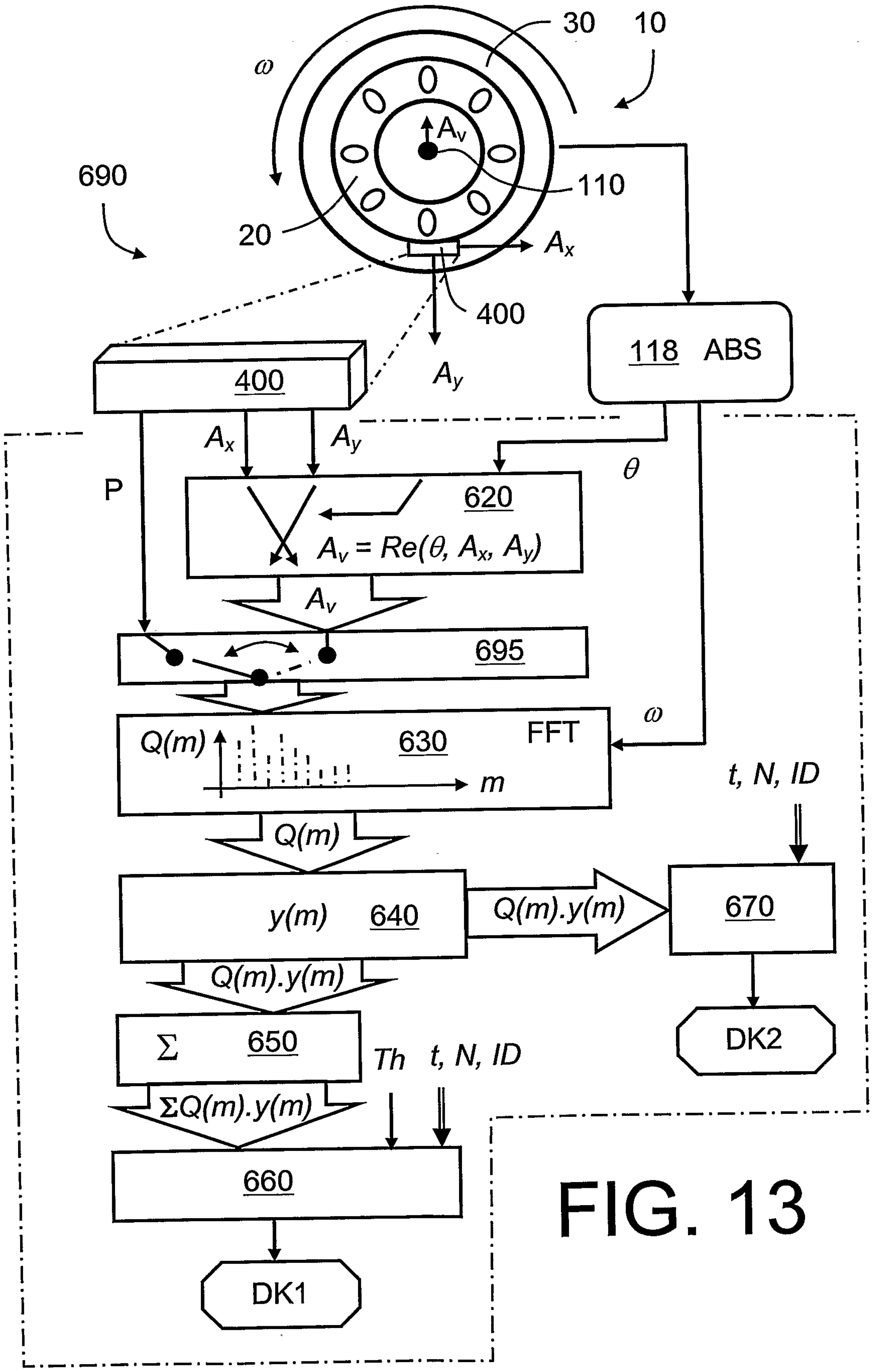
10
30
ω
A_v
110
600
20
A_x
400
A_y
118 ABS
400
A_x
A_y
θ
620
$A_v = Re(θ, A_x, A_y)$
A_v
ω
Q(m)
630
FFT
m
t, N, ID
Q(m)
y(m) 640
Q(m).y(m)
670
Q(m).y(m)
Σ 650
Th
t, N, ID
DK2
ΣQ(m).y(m)
660
DK1

FIG. 11



30
10
ω
A_v
110
680
20
A_x
400
A_y
118 ABS
400
P
θ
ω
Q(m)
630
FFT
m
t, N, ID
Q(m)
y(m) 640
Q(m).y(m)
670
Q(m).y(m)
Σ 650
Th
t, N, ID
DK2
ΣQ(m).y(m)
660
DK1

FIG. 12



30
10
ω
A_v
690
110
20
A_x
400
400
A_y
118 ABS
A_x
A_y
P
θ
620
$A_v = Re(\theta, A_x, A_y)$
A_v
695
ω
Q(m)
630
FFT
m
t, N, ID
Q(m)
y(m)
640
Q(m).y(m)
670
Q(m).y(m)
DK2
Σ
650
Th
t, N, ID
ΣQ(m).y(m)
660
DK1

FIG. 13

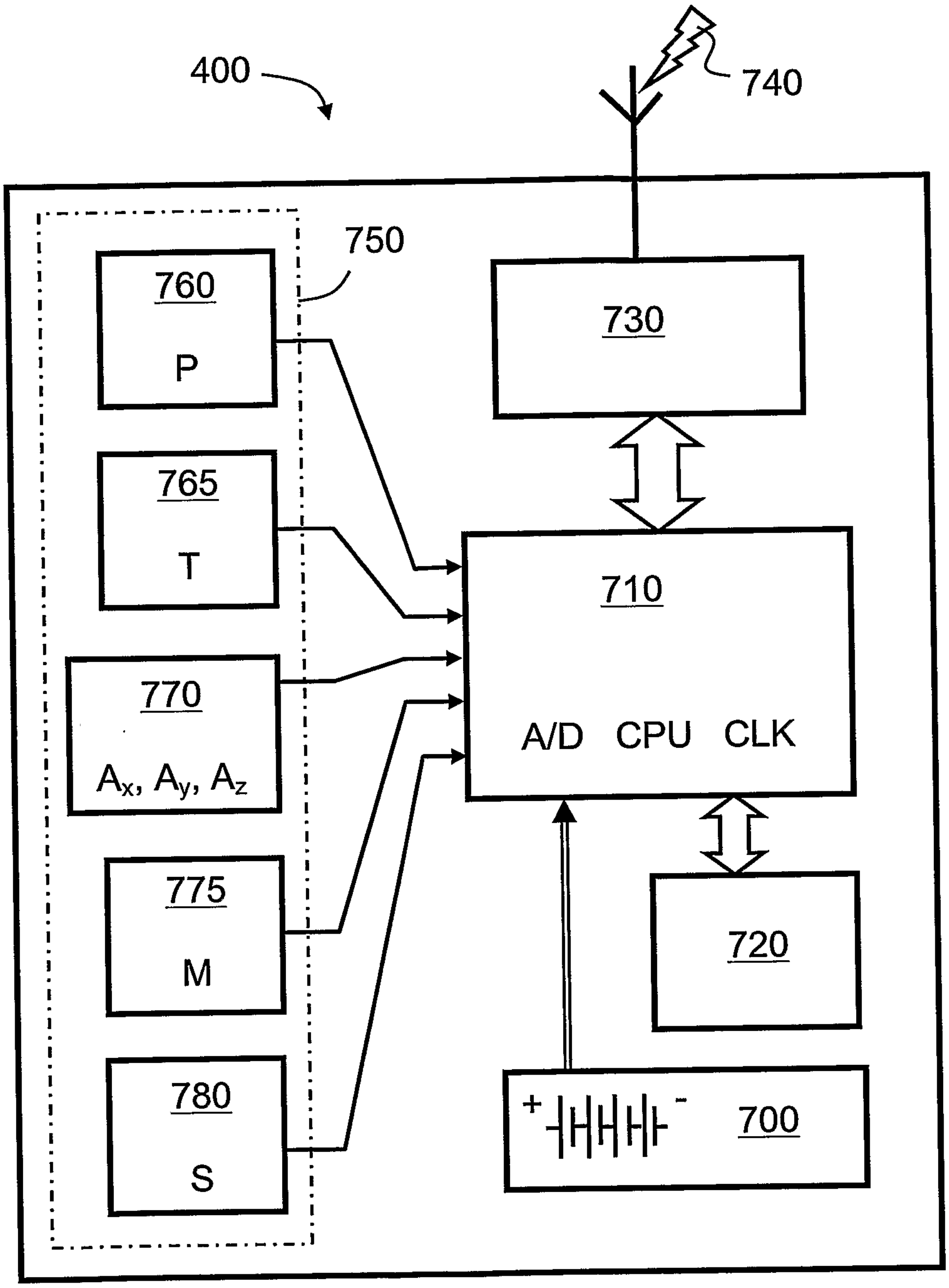

400
740
750
760
P
765
T
770
A_x, A_y, A_z
775
M
780
S
730
710
A/D CPU CLK
720
+
-
700

FIG. 14

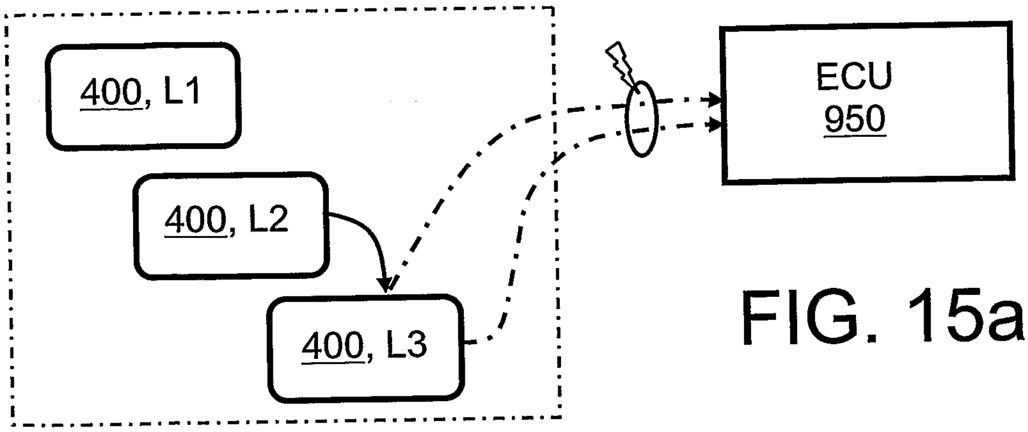


FIG. 15a

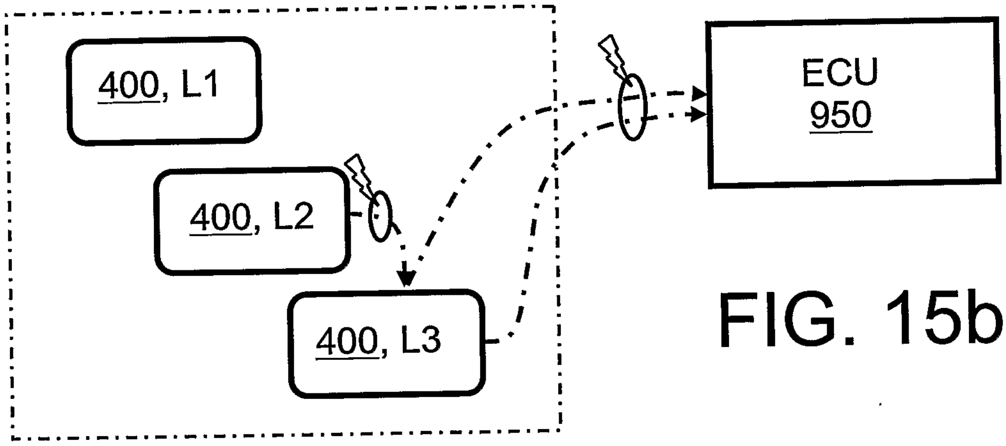


FIG. 15b

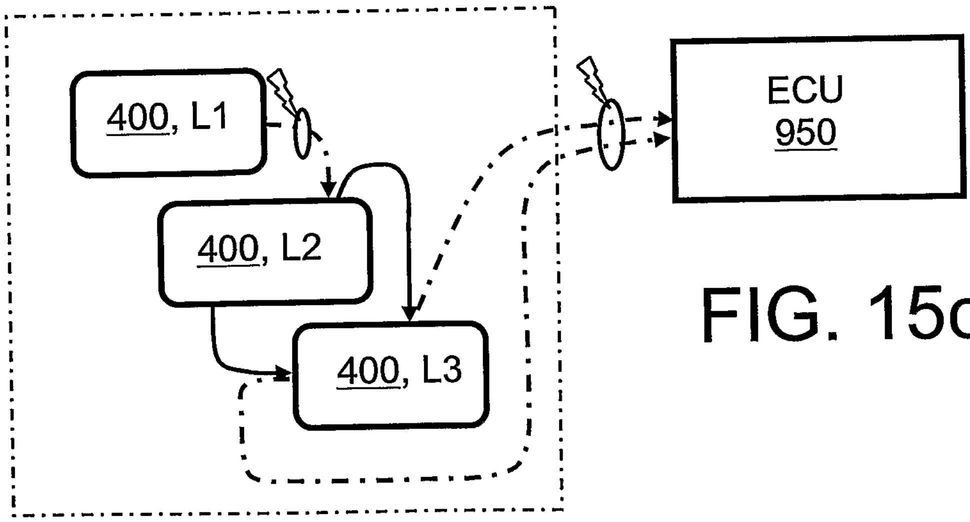


FIG. 15c

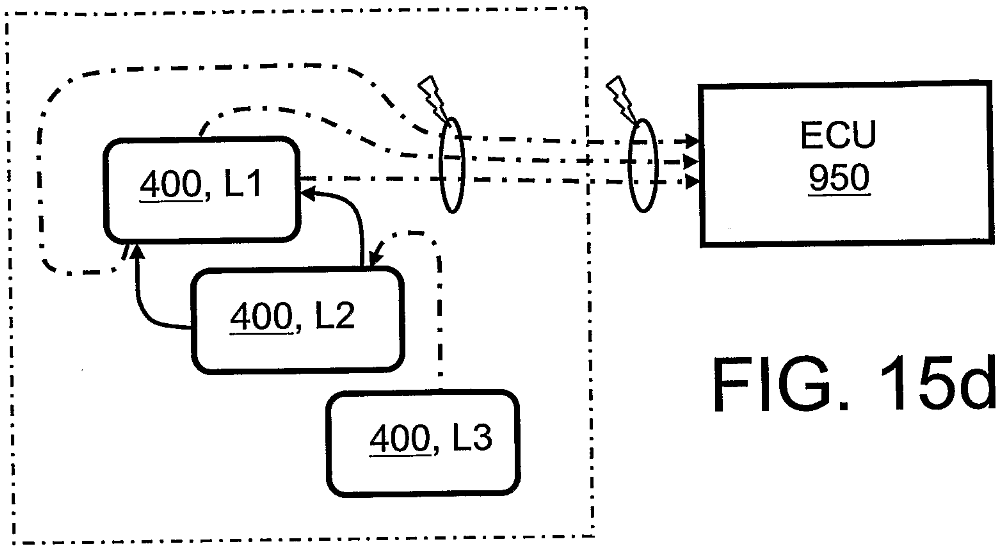


FIG. 15d

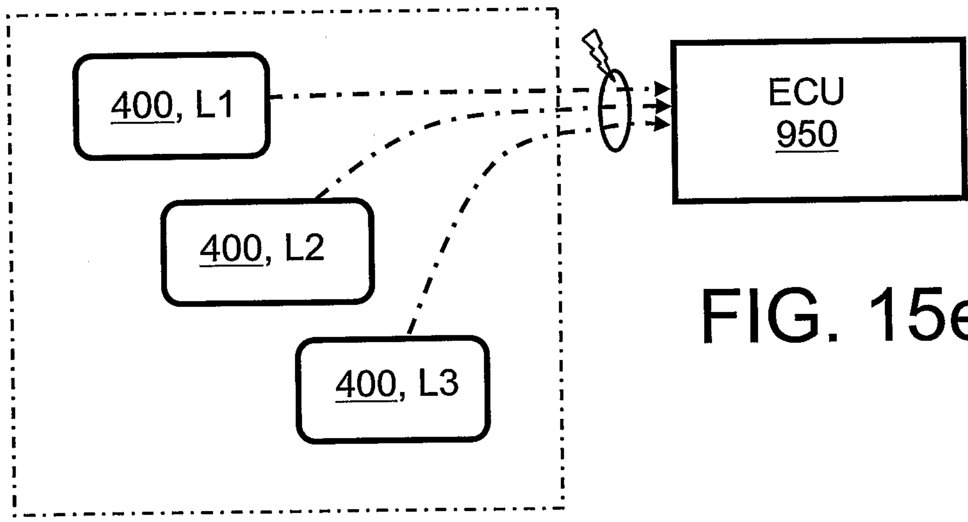


FIG. 15e

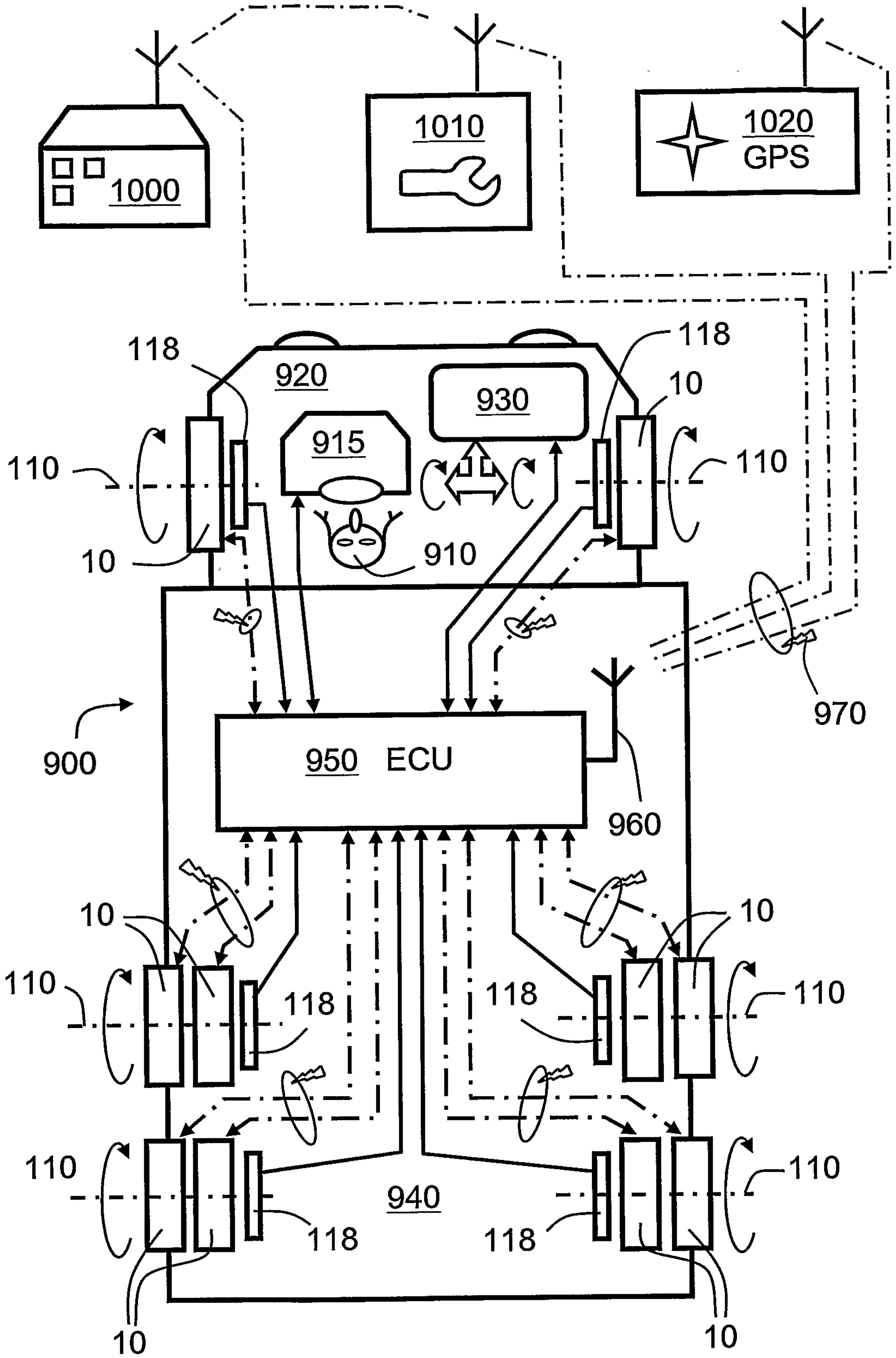

1000
1010
1020
GPS
118
920
930
10
915
110
910
970
900
950 ECU
960
940

FIG. 16

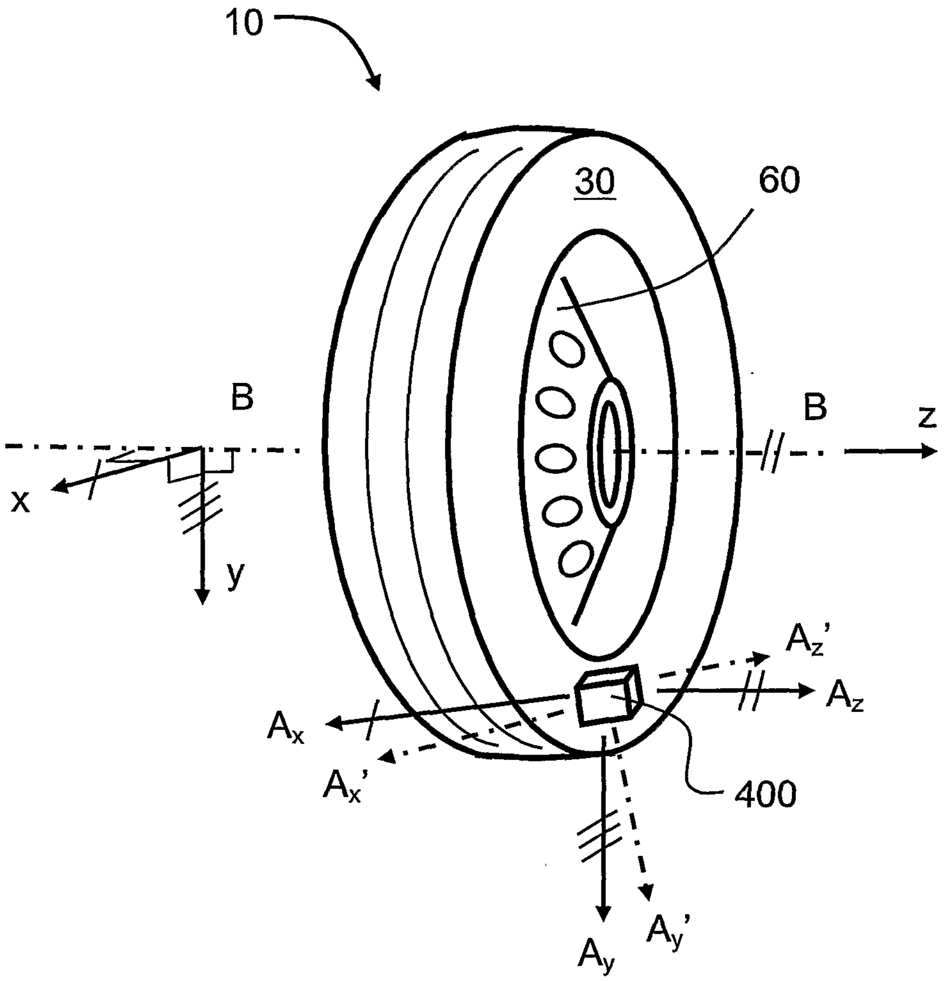
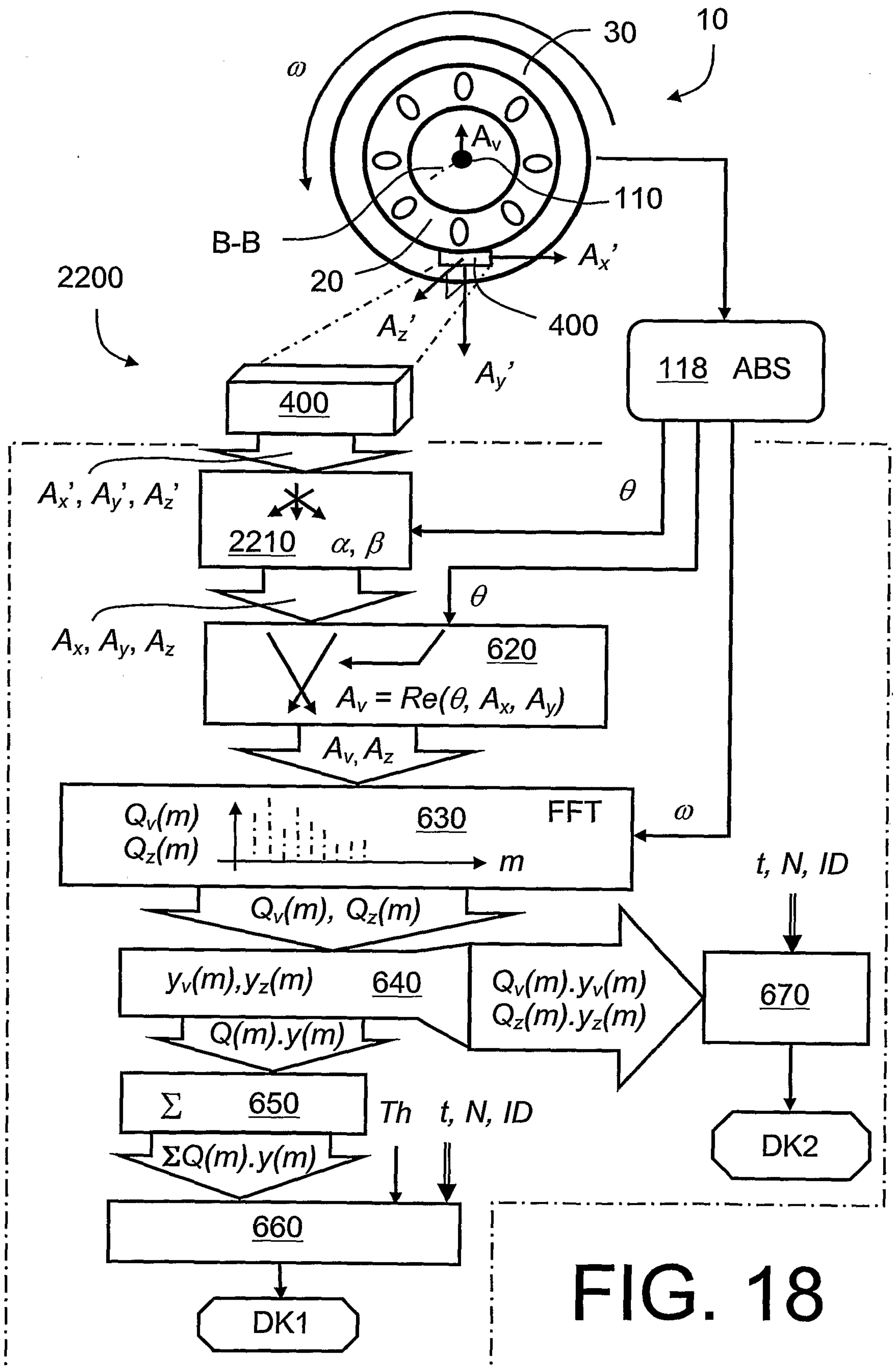


FIG. 17



30
10
ω
Av
110
B-B
20
Ax'
2200
Az'
400
Ay'
118 ABS
400
θ
Ax', Ay', Az'
2210 α, β
θ
Ax, Ay, Az
620
Av = Re(θ, Ax, Ay)
Av, Az
Qv(m)
Qz(m)
630
FFT
ω
m
t, N, ID
Qv(m), Qz(m)
yv(m),yz(m)
640
Qv(m).yv(m)
Qz(m).yz(m)
670
Q(m).y(m)
Σ
650
Th
t, N, ID
ΣQ(m).y(m)
DK2
660
DK1

FIG. 18

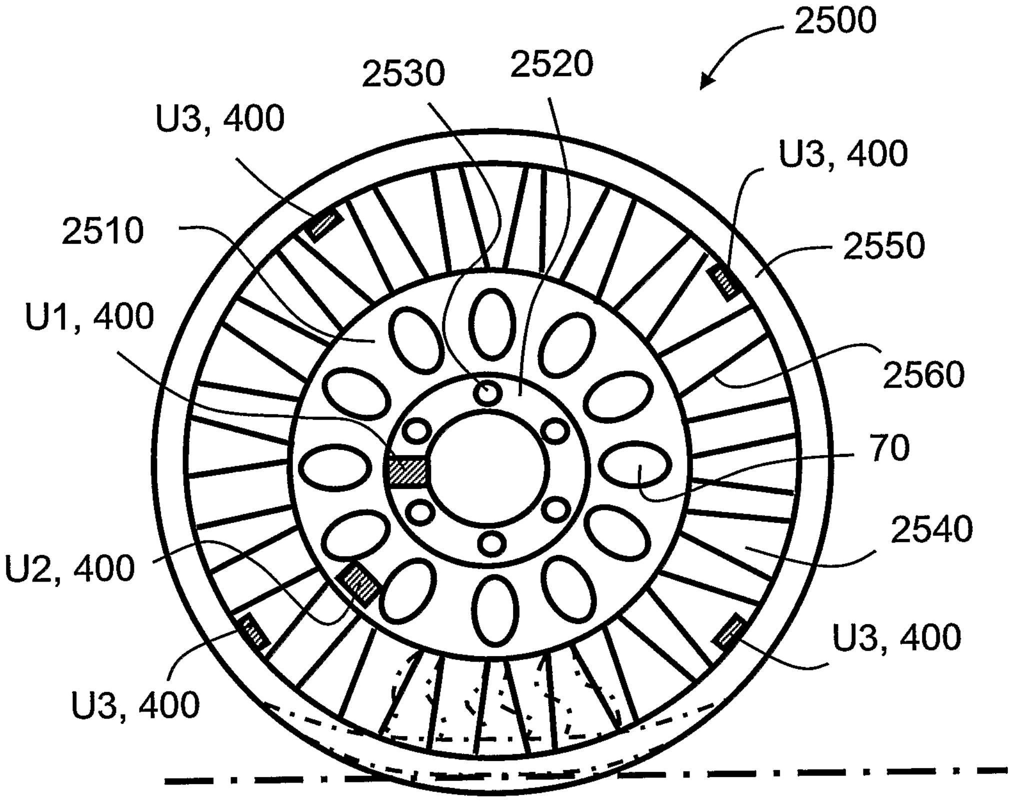

2500
2530
2520
U3, 400
U3, 400
2510
2550
U1, 400
2560
70
2540
U2, 400
U3, 400
U3, 400

FIG. 19

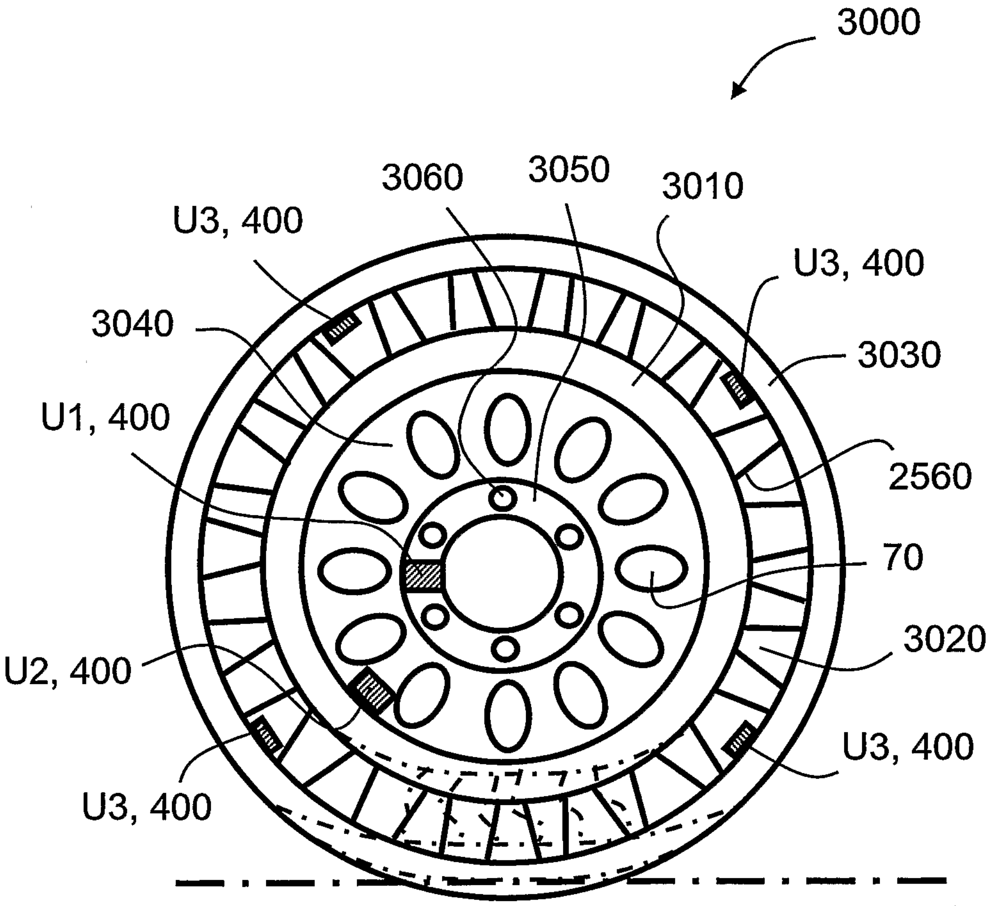

3000
3060
3050
3010
U3, 400
U3, 400
3040
3030
U1, 400
2560
70
3020
U2, 400
U3, 400
U3, 400

FIG. 20

INTERNATIONAL SEARCH REPORT 1

International application No.
PCT/SE2007/001066

A. CLASSIFICATION OF SUBJECT MATTER

IPC: see extra sheet

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: G01M, G01L, B60C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-INTERNAL, WPI DATA, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 20040246115 A1 (OGAWA, A), 9 December 2004 (09.12.2004), figures 2,8, abstract, paragraphs [0033]; [0054]-[0060] --	1-52
A	WO 2007030037 A1 (VOLVO LASTVAGNAR AB), 15 March 2007 (15.03.2007), abstract --	1-52
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INTERNATIONAL SEARCH REPORT

International application No.
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International patent classification (IPC)
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