A system for evaluating a parameter of a tool being driven by a three-phase brushless motor includes a rotor angle position estimation subsystem having one or more sensing elements and an electronic angle processor. A control subsystem that controls the speed and/or the torque of the motor includes one or more sensing elements and an electronic control processor. An electronic status processor is configured to receive measurements from the rotor angle position estimation subsystem and the control subsystem and is further configured to generate estimates of a tool parameter status. In an example embodiment the tool is a high-speed drill and the system evaluates parameters such as drill tip location and speed/torque characteristics indicative of runout, transitions between layers in drilling, etc.
The present invention generally relates to the field of motor driven equipment and in particular to sensing the status of equipment driven by three-phase brushless motors, for example, a variable-speed drill.

In some applications of a variable speed drill, for example drilling vias in multi-layer circuit boards, it is of importance that the drill bits be of high quality so as to drill precise holes. A worn drill bit can ruin many circuit boards, causing significant financial loss to the manufacturer. Currently, many manufacturers replace the drill bits in their machines based purely on time-of-use, where this scheduled maintenance is performed after a period of use that has been calculated to ensure that the drill bits will not be so worn that they damage the circuit boards.

On the other hand, the replacement cost of drill bits in these machines is high, so replacing the bits before their useful life is up is also a financial loss. Thus, there is a need for a system to detect the wear on an operating drill bit, at least on a threshold basis.

In other situations it is desirable to know when the tip of the drill has reached an interface between internal material layers in the object being drilled. For example, most printed circuit boards (PCB) are multi-layer boards comprised of alternating layers of conducting traces and insulating material. Vertical vias are drilled to connect certain conduct traces on one layer to certain other conducting traces on a different layer. Some vias in printed circuit boards are 'blind'; that is, they are only drilled part way through the total thickness of the board so as to avoid the conducting traces on lower level layers. Thus there is a need to know where the tip of a drill bit is within the thickness of a circuit board. Similarly, even for through vias (ones that pass completely through the circuit board) it is important to know where the tip of the drill bit is to prevent damage to the bit by running the drill into the supporting (metal) platen.

Previous approaches to measuring the status of a drill parameter, specifically for laminated workpieces, are unsuited to the high-speed, CNC controlled micro-drills used in PCB manufacture. For example, Alexander, in U.S. Patent No. 4,822,215, describes a thrust and torque sensitive drill, but this invention is applicable to pneumatic drills typically used in.
for example, large machine manufacture wherein the laminated object comprises, for example, an inch or more of titanium, an inch of aluminum, and which of stainless steel.

Similarly, Turrini et al, in U.S. Patent No. 7,523,678, describe a method for detecting and quantifying drilling anomalies but rely on an external, 3-axis force sensor attached to the workpiece to estimate to monitor the torque around the drill axis and the axial force with which the drill is bearing down on the workpiece. The method is specifically described as appropriate for metal machining operations and the anomalies they are detecting and quantifying include such gross problems as "a part being poorly clamped in a vied'.

Current PCB industry practice for determining the relative depth of a drill bit inside a printed circuit board comprises the combination of a "touch sensor" and an axial displacement sensor. The touch sensor determines when the tip of the drill bit touches the top surface of the work piece and the axial displacement sensor measures the movement of the drill bit into the work piece relative to the sensed top surface. This practice is deficient, however, because the touch sensor of choice is a capacitive sensor, which means the drill bit and work piece cannot be electrically grounded, creating a safety hazard, and because variations in the thicknesses and planarity of the layers of the circuit board confound the relationship between the measured physical depth of the drill bit and the exact position of the bit relative to a specific layer interface. Thus, there is a need for a system to detect drill bit transitions from layer to layer as a hole is drilled into a multi-layer object without regard to the actual vertical position of the drill bit.

Another drill bit operational anomaly that is of interest to manufacturers of precision devices is dynamic run out (DRO). DRO is essentially wobble of the drill bit around its nominal axis of rotation.

Other machine-driven tools require or could benefit from an automatic means of determining tool status while the tool is in operation. For example, it may be desirable to know when a grinding wheel first makes contact with the target surface being ground.

**SUMMARY**

The present invention relates generally to a system and measurement method for determining the operational status of a motor-driven tool, for example, a drill. More specifically it relates to tools being driven by three-phase AC brushless motors, and more typically motors controlled by Field-Oriented Control (FOC) controllers. The FOC control process relies on the feedback of information from the motor regarding the rotor position
and/or the drive voltages and the currents being applied to the stator, and these feedback signals depend in turn on what is happening at the motor's load (the tool) - in one embodiment, the drill bit.

The motorized-tool status sensor comprises an improved and extended FOC controller wherein the feedback signals from the motor are measured and analyzed at high bandwidth and with high accuracy to determine the instantaneous status of the tool. For example, the torque that must be applied to a drill bit by the motor to maintain a constant rotation rate (assuming constant axial force) changes measurably when the tip of the drill bit makes contact with an interface between two materials. This interface may be between air and the top surface of a material or the interface may be between two material layers internal to the object being drilled. Similarly, the torque that must be applied to a drill bit to maintain a constant rotation rate (assuming constant axial force) when drilling any specific material changes measurably as the drill bit wears (becomes dull) with use. As another example, dynamic run out (DRO) of the drill bit is known to create a periodic variation in the back EMF (electro-motive force) in the driving motor.

At a very general level, three-phase AC brushless motors comprise a permanent magnet rotor having one north pole and one south pole (one pole pair) and three stator electromagnetic coils disposed nominally at 120 degree intervals around the rotor. Some motors have multiple pole pairs. The rotor is caused to rotate by the sequential energization of the three stator coils with 120 degree phase shifted periodic currents. A rotor position feedback sensor is typically used to commutate (essentially synchronize the periodic currents with the rotor position for proper operation) the motor. In some embodiments the rotor position is estimated from the stator voltages and currents.

A motor controller generates the three, 120 degree phase-shifted periodic currents required to turn the motor at a commanded speed and/or torque. The most capable class of motor controller available is the FOC controller. The key benefit of an FOC controller is that the control loop operates in'totor speed' instead of stator space. In stator space the three drive currents are phased sinusoids with a high angular frequency (viz., the rotation frequency of the motor); in rotor space the drive current is nominally at zero frequency. Essentially a high bandwidth control loop system is converted to a base-band control loop system by adding the complication of continually converting from a rotating frame-of-reference to a fixed frame-of-reference and back again.
In one aspect, the tool status sensor is a drill bit status sensor operating as an interfacial contact sensor; that is, the sensor indicates when the tip of the drill bit makes initial contact at an interface between two materials in its path. In this embodiment the sensor monitors the stator current(s), which are related to the torque on the drill bit, to identify the small variations indicative of the change in drag at the tip of the drill bit. The stator currents are monitored in rotor space where the so-called rotor quadrature-axis current is directly related to the torque applied to the drill bit. Alternatively, this embodiment of the tool status sensor operates as a drag sensor, indicating when the environment at the attached tool changes, e.g., when contact is made between the tool and a new material.

In another aspect, the tool status sensor is a drill bit status sensor wherein the sensor is an electronic processor programmed to identify the signatures of torque changes as the tip of any particular drill bit pass through the interface between two known materials.

In another aspect, the tool status sensor is a drill bit status sensor wherein the sensor’s electronic processor is also programmed to compare and correlate identified interfacial transitions with the a priori known layers in the object being drilled and to thereby track the relative location of the drill bit tip inside the object.

In another aspect, the tool status sensor is a drill bit wear sensor wherein the sensor’s electronic processor is also programmed to compare and correlate a drill’s present torque/speed/feed-rate measurements with historic torque/speed/feed-rate profiles for drilling through known materials with a sharp tool.

In another aspect, the tool status sensor is a dynamic runout sensor, wherein the sensor of its electronic processor is also programmed to estimate the motor's back EMF and identify once-per-revolution variations in the back EMF, wherein the dynamic runout is generally proportional to the back EMF.

The above and other features of the invention including various novel details of construction and combinations of parts, and other advantages, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular method and device embodying the invention are shown by way of illustration and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.
BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A is a diagram of a prior art torque sensing apparatus used for drill bit status sensing;
Figure 1B is a diagram of a prior art DRO sensing apparatus used for drill spindle status sensing;
Figure 2 is a diagram of a canonical Field-Orientated Control system;
Figure 3 is a schematic block diagram of the FOC system used in the motorized tool status sensor;
Figure 4 illustrates an embodiment of the motorized tool status sensor;
Figure 5A is a graph of data obtained with an embodiment of the MTSS; and
Figure 5B is a second graph of data obtained with an embodiment of the MTSS.

DETAILED DESCRIPTION

The motorized-tool status sensor comprises an improved and extended FOC motor controller system and a method of using this controller's signals to evaluate the status of certain parameters associated with a tool attached to the motor being controlled, wherein the currents and voltages applied to the motor are measured and analyzed at high bandwidth and with high accuracy to determine the instantaneous status of the tool's parameter(s).

In some embodiments, the motorized tool is a drill. It has long been recognized that drilling operations could be optimized if it were possible to continuously and accurately measure the status of various parameters of the drill bit, e.g., drill bit wear and drill bit dynamic runout (DRO). Additionally, in some embodiments it is desirable to know where the tip of the drill is, relative to structural landmarks within the workpiece.

Prior systems have attempted to estimate drill wear, DRO, and other parameter statuses by instrumenting either the drill or the workpiece mount with torque/force sensors. Figure 1A illustrates one such prior art system in which a workpiece 51 is clamped to a mounting base (not illustrated) and three axis force sensors attached to the base measure $F_x$, $F_y$, and $F_z$ (the forces along the three axes illustrated). The signals from the force sensors are collected and conditioned by electronics 50 and 53 before being analyzed by computer 54. It is suggested that the status of any number of drill parameters may be extracted from an analysis of these three force components. Similarly Figure 1B illustrates a prior art, commercially available system for measuring dynamic run-out: the Targa III Dynamic Runout System, available from Lion Precision, 563 Shoreview Park Road* St. Paul,
Minnesota 55126-7014. In this system, the drill bit is removed from the chuck and replaced with a gage pin that must be calibrated to work with sensor, which is carefully placed next to the rotating gage pin. Needless to say, such a system cannot measure DRO in real-time during actual drilling operation.

Figure 2 is a schematic block diagram of a "canonical", or generalized, Field-Oriented Control (FOC) system. The theory underlying FOC is well known and will not be discussed here. From the embodiment perspective, as shown in Figure 2, a motorized tool comprises a hardware section 100 and a software section 200 (e.g., an electronic processor executing computer program instructions). Hardware section 100 comprises a three-phase motor (shown as ACIM) 110, which is being used to drive a tool such as a drill bit; a power supply 115 that provides current to drive the motor at a constant link voltage $V_L$; a three-phase inverter 120 that distributes the current from a power supply 115 to the stator coils of motor 110 in the form of currents $I_A, I_B$; and two current sensors 130A, 130B to measure currents $I_A, I_B$ respectively. All signals crossing the boundary between hardware section 100 and software section 200 are, of course, converted appropriately between the analog and digital domains.

Software section 200 comprises several functionally distinct modules, although it will be understood the division of software into modules is only a matter of convenience in coding and clarity in exposition. Further, the digital numbers being processed and moved through the modules in software section 200 may alternately be represented by or referred to as 'Values", 'signal\hat{\text{V}}currents", etc. herein without loss of generality. Finally it will be appreciated that some or all of the transformations performed by the digital processing functions described herein could possibly be implemented in analog circuitry.

Measured currents $I_A, I_B$, being stator currents of a three-phase motor, are generally sinusoidal and are shifted in phase by approximately 120 degrees. In software section 200 these currents are processed by a Clarke Transform module 210 in which the stator currents are converted into two sinusoidal currents, $I_o$ and $I_p$, in quadrature, e.g., 90 degrees shifted in phase.

The quadrature current signals $I_o$ and $I_p$ output from Clarke Transform module 210 are sent to two different modules. One module is a Park Transform module 220, wherein the two quadrature currents $I_o, I_p$ are converted into 'totor space': non-sinusoidal currents $I_d, I_q$. These currents are called respectively the rotor-direct and rotor-quadrature currents because
they are proportional to the magnitudes of stator (magnetic) fluxes that are parallel and perpendicular, respectively, to the axis of the rotor.

It is well understood that a stator flux component parallel to the magnet rotor axis applies no torque to the rotor and represents wasted energy. Thus, it is desirable to minimize the rotor-direct current $I_d$. In a FOC system the measured/calculated rotor-direct current is used in a feedback loop to minimize this wasted energy. In Figure 2 the feedback loop is represented by a subtraction module 223A and proportional integrator 223B, which outputs a rotor-direct command voltage $V_d$.

It is also well understood that a stator flux component perpendicular to the magnet rotor axis generates the torque which causes angular acceleration. Thus, based on a reference angular velocity, the measured/calculated rotor-quadrature current is used in a feedback loop to maintain or achieve that velocity. In Figure 2 the feedback loop is represented by a subtraction module 222A and proportional integrator 222B, which outputs a rotor-quadrature command voltage $V_q$.

The quadrature currents $I_α, I_β$ output from Clarke Transform module 210 are also sent to an estimator module 250 wherein they are combined with instantaneous stator voltage command values $V_α$ and $V_β$. Estimator 250 produces estimates of an angular position $θ_{es,t}$ and an angular velocity $ω_{es,t}$ of the rotor. Angular position estimate $θ_{es,t}$ is required to perform the Park/Inverse Park transformations in Park Transform Module 220 and an Inverse Park Transformation Module 230. The angular velocity estimate $ω_{es,t}$ provides the feedback for a motor speed feedback loop represented by a subtraction module 224A and proportional integrator 224B.

Referring again to Figure 2, the rotor-direct and rotor-quadrature feedback loops further comprise an Inverse Park Transformation Module 230, wherein the two rotor-space command voltages $V_q, V_d$ are converted into the two quadrature, sinusoidal stator voltage command signals $V_α, V_β$. These sinusoidal signals are then processed by a space-vector pulse-width modulator 240 (SVPWM). The SVPWM 240 essentially performs two transformations in series. First, it converts the two quadrature sinusoidal signals into three, 120-degree phase shifted signals, and second, it converts each continuously varying sinusoid into a two command value $(1, 0)$, pulse-width-modulated signal, where the width of each pulse is proportional to the ratio of desired voltage to power supply voltage $V_L$. These three PWM
signals are output from software section 200 and are the input to a three-phase inverter 120 in the hardware section.

The inverter 120 essentially converts the binary PWM signals (viz., 0 and 1) into bipolar currents (viz., currents having positive and negative polarity) by appropriately switching current from the fixed-voltage power supply 115 through its internal current paths to the three stator coils. Inverter 120 outputs the three stator currents, I_A, I_B, and I_c.

Figure 3 is a schematic block diagram of the Field-Oriented Control (FOC) system 100, as modified to be a motorized tool status sensor (MTSS). It may be noted that many elements in the MTSS's FOC system are identical to the canonical system of Figure 1. As shown in Figure 3, hardware section 100 comprises three-phase motor 110, power supply 115, and three-phase inverter 120. In addition, hardware section 100 comprises the two current sensors 130A, 130B and may, preferably, comprise a third current sensor 130C, which measure currents I_A, I_B, and, in some preferred embodiments, current I_c. Three voltage pickoffs 140A, 140B, and 140C are also disposed in the analog stator drive lines to measure the three stator voltages V_A, V_B, and V_c respectively. The picked off voltages are scaled to suitable levels for digitization, as is well understood by one of ordinary skill in the art, in a triple voltage divider network 150. Preferably these stator voltage sensors' output stages operate with a filtering bandwidth equal to one-half (1/2) of the PWM driver pulse frequency f_p. All signals crossing the boundary between hardware section 100 and software section 200 are, of course, converted appropriately between the analog and digital domains.

In some embodiments of the MTSS hardware section 100 further comprises an angular position sensor 160, typically a rotary encoder, to measure and report the angular position of the rotor in motor 110, said angular position being referenced to at least one of the stators.

As in the canonical FOC system of Figure 2, measured currents I_A, I_B, and, in some embodiments, current I_c, are processed by Clarke Transform module 210, wherein the 120 degree phase shifted stator currents are converted into two sinusoidal current signals in quadrature, e.g., 90 degrees shifted in phase, I_alpha and I_beta.

In a parallel operation, measured stator voltages V_A, V_B, and V_c are processed by a second Clarke Transform module 215 wherein the 120 degree phase shifted stator voltages are converted into two sinusoidal signals in quadrature, e.g., 90 degrees shifted in phase, V_alpha and V_beta.
The quadrature currents, $I_\alpha$ and $I_\beta$, are sent, as in the canonical system, to Park Transform module 220 where they are mapped into rotor space as $I_q$ and $I_d$ and are used to provide feedback for the stator flux control loops, comprising subtraction module 223A with proportional integrator 223B and subtraction module 222A with proportional integrator 222B to control the rotor-direct and rotor-quadrature fluxes respectively.

As it is well understood that the stator flux component perpendicular to the magnet rotor axis generates the torque, the MTSS samples $I_q$ at the output of Park Transform module 220 serve as a proxy for making a measurement of torque with a physical torque sensor. Thus the MTSS is able to estimate the status of those tool parameters that affect the magnitude of torque required to maintain a given tool rotational velocity.

The value of $I_q$ at the output of Park Transform module 220 is transmitted to a tool status evaluation module (not illustrated) wherein the variations in $I_q$ may be mapped into tool status. The tool status evaluation module is a digital processor programmed to convert the measured quantities, the rotor-quadrature current $I_q$, as described above, and the rotor angular velocity, as will be described below, into indications of some tool parameter. This conversion or status mapping depends on the tool attached to motor 110. For example, it is known in the art that if a motor is driving a drill spindle, changes in torque typically map to the transition of the drill bit tip from one medium to another— from air to the top surface of the object being drilled being a prime example. The specific algorithms to map the MTSS measurements into tool statuses are developed by the user based on his or her knowledge of the specific tool.

Referring again to Figure 3, in one embodiment the quadrature currents, $I_\alpha$ and $I_\beta$, and quadrature voltages, $V_\alpha$ and $V_\beta$, are directed to estimator 250 wherein they are combined to produce an estimate of the angular position $\theta_{s,t}$. The angular position estimate $\theta_{s,t}$ is utilized to perform the Park/Inverse Park transformations in Park Transform Module 220 and an Inverse Part Transformation Module 230 respectively. In some embodiments, in which motor 110 comprises an angular position encoder 160 and an associated encoder processor 260, estimator 250 may be eliminated from the processing flow and a measured angular position $\theta_{meas}$ output from processor 260 is used to perform the Park/Inverse Park transformations. Generally, in systems with an encoder, estimator 250 will be retained and a selection switch 255 included to allow the operator to choose between measured and estimated rotor angle.
Also in Figure 3, the rotor-direct and rotor-quadrature feedback loops further comprise Inverse Park Transformation Module 230, wherein the two rotor-space command voltages $V_{dq}$ are converted into two quadrature, sinusoidal stator voltage command signals $v_{a}, v_{b}$. These sinusoidal signals are then processed by a space-vector pulse-width modulator (SVPWM) and three-phase invertor 120. Inverter 120 outputs the three stator currents, $I_{A}, I_{B},$ and $I_{C}$.

The rotor angular position $\Theta$-estimated or measured is differentiated in a filter 262 to produce an angular velocity estimate $\omega_{est}$, which estimate provides the feedback for a motor speed feedback loop represented by a subtraction module 224A and proportional integrator 224B. In addition, angular velocity estimate $\omega_{est}$ from the output of filter 260 is transmitted to the tool status evaluation module (not illustrated) wherein the variations in angular velocity may be mapped into tool status. It may be noted that the thus produced angular velocity is considered an estimate as it was derived from the angular position $\Theta$ and not directly measured as an angular velocity.

Comparing the schematic diagrams in Figures 2 and 3, it may be noted that in the canonical system shown in Figure 2, the quadrature voltage values used in the estimator are the commanded (calculated) voltage values generated by Inverse Park module 230 whilst in the inventive MTSS shown in Figure 3 the quadrature voltage values are measured samples of the voltages actually driving currents through the stators. The measured stator voltages, as is well known, are instantaneously affected by the load, for example, by the back EMF, whereas the calculated voltages in the processor only reflect the effects of the load through residual error in the feedback loop. Thus, the MTSS angular velocity estimate $\omega_{est}$, whether produced from the measured angular position from the encoder or the estimated angular position from estimator 250, contains once-per-revolution information that is representative of the tool status, for example, dynamic run out.

As mentioned previously, and as is obvious to one of skill in the art, all of the measured values in the analog hardware portion of the system are digitized before transmission to the digital software processor. It should be noted that the analog-to-digital converters performing these conversions are preferably at least 14-bit converters.

Figure 4 is a block diagram of an embodiment of the MTSS. Figure 4 is divided into an analog hardware portion and a digital hardware portion. As will be understood by one of ordinary skill in the electrical engineering art, virtually the entirety of the MTSS digital
processing may be embodied in a single Field Programmable Gate Array 1200. In one embodiment FPGA 1200 is an Altera part# EP4CE75F23C8N, CYCLONE IV FPGA 75K 484FBGA, available from Altera Corporation, 101 Innovation Drive, San Jose, CA 95134. The basic specifications for this FPGA are listed in Table 1.

Table 1 FPGA Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>EP4CE75F23C8N</th>
<th>CYCLONE IV FPGA 75K 484FBGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Integrated Circuits (ICs)</td>
<td>Embedded - FPGAs (Field Programmable Gate Array)</td>
</tr>
<tr>
<td>Family</td>
<td>Embedded - FPGAs (Field Programmable Gate Array)</td>
<td>CYCLONE IV</td>
</tr>
<tr>
<td>Series</td>
<td>CYCLONE IV</td>
<td></td>
</tr>
<tr>
<td>Number of LABs/CLBs</td>
<td>4713</td>
<td>75408</td>
</tr>
<tr>
<td>Number of Logic Elements/Cells</td>
<td>2810880</td>
<td>111</td>
</tr>
<tr>
<td>Total RAM Bits</td>
<td>2810880</td>
<td>111</td>
</tr>
<tr>
<td>Voltage - Supply</td>
<td>1.15 V ~ 1.25 V</td>
<td>DC ~ 85°C</td>
</tr>
<tr>
<td>Mounting Type</td>
<td>Surface Mount</td>
<td></td>
</tr>
<tr>
<td>Package / Case</td>
<td>484-BGA</td>
<td>484-FBGA (23x23)</td>
</tr>
<tr>
<td>Supplier Device Package</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Free Status</td>
<td>Lead free</td>
<td></td>
</tr>
<tr>
<td>RoHS Slams</td>
<td>RoHS Compliant</td>
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</tr>
</tbody>
</table>

In addition to the main functional component- the FPGA 1200- it will be obvious to one of skill in the art that a processor requires various support electronics, indicated for completeness in Figure 4 as a synchronous dynamic random access memory (SDRAM) 1210, flash memory 1220, and an Ethernet interface 1230. Software 200 is, of course, loaded into FPGA 1200.

The MTSS software processor receives digital signals from the analog hardware and transmits digital commands to the analog hardware. In Figure 4 the digital commands of significance are shown as a signal S100, which contains safety and interlock commands to prevent a three-phase power bridge 1120 (or inverter) from outputting high current and/or
high voltage at inappropriate times, and as a set of six signals S200, which are the switching commands that allow power bridge 1120 to send the proper drive currents to motor 1110.

Returning to Figure 4 to examine the analog portion of the MTSS, the major element is power bridge 1120, which receives current at a constant voltage $V_L$ from a DC power supply 1115 as signal $V_{100A}$ and redirects it to the three stator windings of motor 1110 in accordance with the switching commands received from FPGA 1200. The three stator currents $I_A$, $\frac{3}{4}$, and $I_c$ each pass through a current sensor 1130A, 1130B, 1130C respectively. In one embodiment the current sensors are LEM part# CKSR 15-NP current transducer. Table 2 lists the basic specifications for this transducer.

<table>
<thead>
<tr>
<th>Table 2 CKSR 15-NP Specifications</th>
</tr>
</thead>
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<tr>
<td>Output Type : Instantaneous</td>
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<tr>
<td>Technology : Fluxgate</td>
</tr>
<tr>
<td>Measurement : Current</td>
</tr>
<tr>
<td>Primary Nominal Value : 15 A</td>
</tr>
<tr>
<td>Accuracy : 0.8 %</td>
</tr>
<tr>
<td>Mounting : -</td>
</tr>
<tr>
<td>Measuring Range : 51 A</td>
</tr>
<tr>
<td>Supply Voltage : 5 - 5</td>
</tr>
<tr>
<td>Supply Voltage type : Unipolar</td>
</tr>
<tr>
<td>Secondary Signal : 625 mV</td>
</tr>
</tbody>
</table>

In addition, each stator drive signal has a voltage pick off 1140A, 1140B, 1140C respectively which feeds a voltage divider network 1150A, 1150B, 1150C to provide voltage feedback signals to FPGA 1200 in accordance with MTSS software 200. The output voltages from the voltage dividers and the current sensors are digitized in parallel by six A/D converters 1190A through 1190F, whose digitized values are transmitted to FPGA 1200. In this embodiment each physical converter is a Texas Instruments part# ADS8363 dual 16-bit,
1MSPS analog-to-digital converter (ADC) with eight pseudo- or four fully-differential input channels grouped into two pairs for simultaneous signal acquisition.

Returning to Figure 4, the output of power supply 1115 is also directed to a brake resistor 1185. Brake resistor 1115 absorbs the energy from power supply 1115 when motor deceleration is desired. Brake resistor 1115 is required because power supply 1115 cannot shut down instantaneously when the FPGA 1200 commands power bridge 1120 to stop sending power to motor 1110. Instead, the FPGA 1200 must ramp motor 1110 from its operating speed down to zero speed, causing the unneeded current to flow through resistor 1185. At the same time, the FPGA 1200 must not allow so much current to flow through resistor 1185 that it overheats. A current sensor 1180 monitors the current flowing through the resistor and provides the needed feedback to the FPGA 1200 through A/D converter 1190G.

Finally, Figure 4 illustrates an optional encoder 1160 that is included in some embodiments of the MTSS. The analog quadrature outputs, typical of many encoders, are digitized by A/D converters 1190H, 11901 before being converted to motor angular position in software arctangent module 260, illustrated in Figure 3.

Representative data from an embodiment of the MTSS is illustrated in Figures 5A and 5B. Figure 5A data was collected with a 6.35 mm drill bit mounted in a spindle rotating at 333 revolutions/sec under the control of the MTSS. The bit was driven in a multi-layer printed circuit board at a nominally constant 16 in/min feed rate. In Figure 5B the data was collected with a 1.0 mm drill bit mounted in a spindle rotating at 800 revolutions/sec under the control of the MTSS. The bit was driven in a multi-layer printed circuit board at a nominally constant 57 in/min feed rate.

In each figure the upper trace is the estimated (instantaneous) angular velocity, \( \omega_{est} \), while the lower trace is the rotor-quadrature current, \( I_q \), which is generally proportional to the torque being felt by the rotating drill. Both data sets are raw data; they have not been filtered or otherwise processed.

The graphs of Figures 5A and 5B show that system signal-to-noise ratio diminishes with decreasing drill bit diameter and increasing drill rotation rate. Nonetheless, it is quite clear from each \( I_q \) trace the time at which the drill bit touches the top (metallized) surface of the PCB (at approximately the 1 second mark in Figure 5A), the time at which it passes out of that thin layer (at approximately the 1.15 second mark in Figure 5A), and the time at which the bit crosses the internal interface between layers in the PCB (at approximately the 1.35...
second mark in Figure 5A). These transitions are confirmed by matching changes in the angular speed.

While various embodiments of the invention have been particularly shown and described, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.
CLAIMS

What is claimed is:

1. A system for evaluating the status of a parameter of a tool being driven by a three-phase brushless motor, said motor including three stator coils and a rotor, comprising:
   a rotor angle position estimation subsystem, said subsystem comprising one or more sensing elements and an electronic angle processor;
   a control subsystem for controlling the speed and/or the torque of the motor, said control subsystem comprising one or more sensing elements and an electronic control processor; and
   an electronic status processor configured to receive measurements from the rotor angle position estimation subsystem and the control subsystem and further configured to generate estimates of a tool parameter status.

2. The system of claim 1 wherein the control subsystem comprises a Field-Orientated Control (FOC) subsystem operating upon rotor-space signals created by a state-space transformation of stator-space signals representing outputs of the sensing elements.

3. The system of claim 2 wherein the FOC subsystem comprises at least two stator current sensors.

4. The FOC subsystem of claim 3 wherein the stator current sensors' signals are digitized with resolution of at least 14 bits.

5. The FOC subsystem of claim 3 wherein the stator voltage sensors' signals are digitized with resolution of at least 14 bits.

6. The system of claim 2 wherein the FOC subsystem comprises one or more stator drive voltage sensors.

7. The system of claim 1 wherein the control subsystem comprises a pulse-width-modulated (PWM) stator current driver, said driver having a pulse frequency $f_p$. 

- 15 -
8. The system of claim 7 wherein the stator voltage sensors’ output operate with a filtering bandwidth equal to one-half (1/2) of the PWM driver pulse frequency $f_p$.

9. The system of claim 1 wherein rotor angle position estimation subsystem comprises one or more stator drive voltage sensors, one or more stator current sensors, and a predictive estimation processing module.

10. The system of claim 1 wherein rotor angle position estimation subsystem comprises a rotary position sensing head and an angle processing module.

11. The system of claim 1 wherein the tool is a drill bit and the tool parameter is drill bit tip location relative to an interfacial layer in the object being drilled.

12. The system of claim 1 wherein the tool is a drill bit and the tool parameter is drill bit wear.

13. The system of claim 1 wherein the tool parameter status for which estimates are generated includes an increase in torque and a decrease in angular speed indicative of transitions between layers of a material.

14. The system of claim 1 wherein the tool parameter status for which estimates are generated includes a once-per-revolution variation of speed or torque indicative of runout.

15. A method of evaluating a status of a parameter of a three-phase brushless motor-driven tool controlled by a Field-Orientated Control approach, comprising the steps of:
   measuring at least two stator currents driving the motor;
   measuring or estimating the angular position of a rotor in the motor;
   combining said stator currents and said angular position to estimate rotor direct-axis current and rotor quadrature axis current;
   optionally filtering the rotor quadrature axis current to remove rotor rotation rate components;
   analyzing the rotor quadrature axis current using pre-determined criteria to determine a status of a tool parameter.
16. The method of claim 15 wherein the tool is a drill bit and the tool parameter is drill bit tip location relative to an interfacial layer in the object being drilled.

17. The method of claim 16 wherein the step of analyzing further comprises the steps of:
   scaling rotor quadrature-axis current values to estimated torque values, wherein the scaling factor includes known drill bit specifications;
   comparing drill bit torque variations with to a library of reference signatures, wherein the library of reference signatures contains drill torque requirements for material penetration;
   reporting drill bit tip location relative to the known layer structure of the object being drilled.

18. A method of evaluating a status of a parameter of a three-phase brushless motor-driven tool controlled by a Field-Orientated Control (FOC), comprising the steps of:
   measuring or estimating angular position of a rotor in the motor;
   estimating an instantaneous angular velocity of the rotor;
   optionally filtering the rotor instantaneous angular velocity for the rotor rotation rate;
   analyzing the instantaneous angular velocity to determine a tool parameter.

19. The method of claim 18, further comprising:
   measuring at least two stator currents driving the motor;
   combining said stator currents and said angular position to estimate rotor direct-axis current and rotor quadrature axis current;
   optionally filtering the rotor quadrature axis current to remove rotor rotation rate components;
   analyzing the rotor quadrature axis current along with the instantaneous angular velocity using pre-determined criteria to determine a status of the tool parameter.
6.35 mm Drill k_p=0.4165 k_p/k_i=64k 16 in/min feedrate 20 krpm 09-12-12

FIG. 5A
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(B) - E21B 44/04 (2014.01)
USPC - 175/39

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

B. DOCUMENTS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(B) - E21B 7/00, 44/04, 47/00 (2014.01)
USPC - 7/152,48, 175/99, 46

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>WO 2012/016045 A1 (EDBURY et al) 02 February 2012 (02.02.2012) entire document</td>
<td>17</td>
</tr>
</tbody>
</table>

* Special categories of cited documents:
  "A" document defining the general state of the art which is not considered to be of particular relevance
  "E" earlier application or patent but published on or after the international filing date
  "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
  "O" document referring to an oral disclosure, use, exhibition or other means
  "P" document published prior to the international filing date but later than the priority date

Further documents are listed in the continuation of Box C.

Date of the actual completion of the international search: 08 February 2014
Date of mailing of the international search report: 21 February 2014

Name and mailing address of the ISA/US
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450
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