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### INTEGRATED CHATTER DETECTION

#### Abstract

A method for machine tool chatter detection which combines sensorless and sensor-based measurement methods and makes a determination based on analysis of both sensorless and sensor-based signals. The sensorless branch uses data known to the machine tool controller, such as spindle torque data or servo motor position/velocity data, where a time-series sample is recorded, the data is converted to the frequency domain and filtered, and criteria are evaluated to detect chatter. The sensor-based branch uses sound data recorded by a microphone, where data is again recorded, converted to the frequency domain, filtered, and evaluated. When both sensorless and sensor-based evaluation branches detect chatter at a common frequency, it is determined that chatter is occurring in the machine tool and appropriate steps are taken. The integrated chatter detection technique avoids false indicators of chatter which may arise due to noise present at different frequencies in the sensorless and/or sensor-based signals.

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#### Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a Continuation-In-Part of U.S. Utility patent application Ser. No. 18/494,160, titled SENSORLESS CHATTER DETECTION, filed Oct. 25, 2023.

##### BACKGROUND

###### Field

[0002] The present disclosure relates generally to the field of chatter detection in a machine tool and, more particularly, to a method for machine tool chatter detection which combines sensorless and sensor-based measurement techniques, where frequency-domain measurement data is filtered and analyzed, and then indicator criteria are evaluated to detect the presence of chatter.

###### Discussion of the Related Art

[0003] It is known in the art to use computer-controlled devices to perform machining operations, such as drilling and milling, on parts. In some applications, computer numerical controlled (CNC) machines are used which move a tool along three principal directions, with or without changes in the tool's orientation. In other applications, a multi-axis industrial robot is fitted with a machining head, and the robot can move the tool along any arbitrary spatial path while also controlling the tool orientation to any desired value.

[0004] Regardless of what type of machine tool or robot is used to perform the machining operation, the quality of the finished workpiece is always important, and conditions which may be detrimental to the workpiece quality or the longevity of the machine tool must be avoided. Chatter is a particular problem which is known to occur in some machining operations.

[0005] Chatter is a condition where unwanted vibrations of the cutting tool occur during the machining operation. For example, in a

milling operation where the milling tool (bit) is cutting in a lateral direction (perpendicular to the axis of the bit), small amounts of compliance in the machine tool and the milling bit allow a vibration of the bit against the workpiece as the cutting is occurring. The vibration causes the machined surface of the workpiece to have a “scalloped” profile rather than the desired smooth profile. In addition, in some circumstances, the cutting condition can become unstable, where the scalloped profile created in one cutting pass causes subsequent passes of the bit to cut rapidly-changing and uneven thicknesses of material. The uneven cut thickness then increases the amplitude of the chatter vibration.

[0006] When unstable chatter is experienced, the workpiece is often ruined, and damage to the milling bit or even the machine tool itself may occur. It is therefore desirable to detect chatter as soon as it happens, and take steps to eliminate it.

[0007] Techniques are known in the art for machine tool chatter detection. Many existing systems require the addition of vibration sensors or microphones to the machine tool environment, and to integrate the associated data acquisition and analysis system into the machine tool controller. Other techniques for chatter detection require measurement of the machine tool system's structural dynamics to identify natural frequencies of vibration, and use this information to predict machining stability. Still other chatter detection techniques use an artificial intelligence approach, where a machine learning system uses data from multiple sensors to learn to identify both stable and unstable cutting conditions.

[0008] The existing chatter detection techniques described above all suffer from one or more drawbacks, including the need for sensors and data acquisition equipment to be added to the machine tool system, the need for a structural dynamic model of the machine tool system to be used for prediction of problematic conditions, and the computationally-intensive and data-intensive nature of the analysis. In addition, most existing chatter detection techniques can only detect severe chatter exceeding a certain amplitude, and may therefore miss light chatter conditions.

[0009] A sensorless chatter detection technique has also been developed which is effective in many situations. However, sensorless signals such as those for a spindle motor can be quite noisy, which may reduce their effectiveness for chatter detection in some cases.

[0010] In view of the circumstances described above, there is a need for an improved machine tool chatter detection method which combines a simple data acquisition setup with the inherent capabilities of sensorless analysis, and which can detect chatter at any frequency even at low amplitude.

## SUMMARY

[0011] The present disclosure describes a method for machine tool chatter detection which combines sensorless and sensor-based measurement methods and makes an overall chatter detection determination based on analysis of both the sensorless and sensor-based signals. The sensorless branch uses data known to the machine tool controller, such as spindle torque data or servo motor position/velocity data, where a time-series sample is recorded, the data is converted to the frequency domain and filtered, and one or more criteria are evaluated to detect chatter. The sensor-based branch uses sound data recorded by a microphone, where again a time-series sample is recorded, the data is converted to the frequency domain and filtered, and criteria are evaluated to detect chatter. When both the sensorless and sensor-based evaluation branch detect chatter at a common frequency, it is determined that chatter is occurring in the machine tool and appropriate remediation steps are taken. The integrated chatter detection technique avoids false indicators of chatter which may arise due to noise present at different frequencies in the sensorless and/or sensor-based signals.

[0012] Additional features of the presently disclosed systems and methods will become apparent from the following description and appended claims, taken in conjunction with the accompanying drawings.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1 is an illustration of a workpiece machining operation and the basic concepts involved in unstable machine tool chatter;

[0014] FIG. 2 is a schematic illustration of a system including a computer-controlled machine tool performing a machining operation on a workpiece, of a type applicable to the techniques of the present disclosure;

[0015] FIG. 3 is a flowchart diagram of a method for sensorless chatter detection in a machine tool, using a two-step filtering process in the frequency domain and evaluation of two indicator criteria, according to an embodiment of the present disclosure;

[0016] FIG. 4 is a frequency response graph of motor torque command data both before and after filtering using the method of FIG. 3, according to an embodiment of the present disclosure;

[0017] FIGS. 5A and 5B are frequency response graphs of motor torque command data in a chatter condition and a non-chatter condition, respectively, illustrating the effects of the filtering steps and the resultant chatter indicator analysis of FIG. 3, according to embodiments of the present disclosure;

[0018] FIGS. 6A and 6B are frequency response graphs of motor torque ratio (cutting over air-cut) in a chatter condition and a non-chatter condition, respectively, illustrating the effects of the filtering steps and the resultant chatter indicator analysis of FIG. 3, according to embodiments of the present disclosure;

[0019] FIG. 7 is a frequency response graph of motor torque command data both before and after filtering to remove aliasing effects, according to an embodiment of the present disclosure;

[0020] FIG. 8 is a flowchart diagram of a method for sensorless chatter detection in a machine tool, using a multi-step filtering process in the frequency domain, and including both spindle and servo motor data filtering and analysis, according to an embodiment of the present disclosure;

[0021] FIG. 9 is a mock-up of a graphical user interface providing chatter detection visualization and control features for a machine tool, according to an embodiment of the present disclosure;

[0022] FIG. 10 is a graph of a measured frequency response function for a machine tool, according to an embodiment of the present disclosure;

[0023] FIG. 11 is a set of graphs plotting acceleration versus time for three of the tests contained in Table I, according to embodiments of the present disclosure;

[0024] FIG. 12 is a schematic illustration of a system comprised of a machine tool system of the type depicted in FIG. 2, with data collection equipment for sensor-based chatter detection, according to an embodiment of the present disclosure;

[0025] FIG. 13 is a flowchart diagram of a method for integrated sensorless and sensor-based chatter detection in a machine tool, including separate processing and analysis of sensorless and sensor-based data to evaluate a chatter indicator for each, according to an embodiment of the present disclosure;

[0026] FIG. 14 includes frequency response graphs of sound data from a machining system before cutting begins and during cutting operations, illustrating the effects of external noise in the sensor-based analysis portion of FIG. 13, according to embodiments of the present disclosure; and

[0027] FIG. 15 includes frequency response graphs of spindle torque command data and sound data from a machining operation, illustrating how a common frequency spike in both frequency responses is identified as real chatter, according to embodiments of the present disclosure.

#### DETAILED DESCRIPTION OF THE EMBODIMENTS

[0028] The following discussion of the embodiments of the disclosure directed to integrated sensorless and sensor-based machine tool chatter detection is merely exemplary in nature, and is in no way intended to limit the disclosed devices and techniques or their applications or uses.

[0029] Chatter is a phenomenon which sometimes occurs during machining operations by machine tools. A typical example is in a milling operation, where the tip of an end mill vibrates laterally as it cuts material from a workpiece. Because chatter can cause substandard workpiece quality, and even damage to the workpiece and/or the machine tool, it is desirable to avoid chatter as much as possible in machining operations.

[0030] FIG. 1 is an illustration of a workpiece machining operation and the basic concepts involved in machine tool chatter. An end mill **110** is fitted in a spindle of a machine tool (not shown). The end mill **110** is rotated at a high speed about its central axis by the spindle. The machine tool moves the end mill **110** according to a computer programmed tool path to perform the machining operation on a workpiece **120**. Depending on the type of machine tool or robot in which it is fitted, the end mill **110** may be moved in translation only (in three dimensions), or the end mill **110** may be rotated to different orientations in addition to the translational motion. In the example depicted in FIG. 1, the end mill **110** moves in a feed direction as indicated by the annotated arrow, and cuts material from the workpiece **120** as shown. The end mill **110** has four cutting “teeth” or flutes **112**. The end mill **110** is merely exemplary, and it is to be understood that the chatter concepts discussed here apply to cutting tools generally, and the chatter detection techniques of the present disclosure are applicable to other milling tools and other types of cutting devices where the chatter phenomenon may be encountered.

[0031] FIG. 1 depicts a chatter condition, where the end mill **110** vibrates in a lateral direction toward and away from the workpiece **120**. The vibration is made possible by small amounts of compliance and/or looseness in the machine tool—including flexibility of the end mill **110** itself, in the mounting bearings of the spindle, in the overall machine tool mounting and positioning structures, and so forth.

[0032] During machining, the machined surface of the workpiece **120** does not have a perfectly smooth profile as desired, but rather has a wavy or scalloped shape characterized by vibration marks as indicated at **122**. All of the surface waviness illustrated in FIG. 1 is exaggerated for visual effect, but the vibration marks on the workpiece surface can in fact be significant enough to negatively impact workpiece quality. Cutting conditions may be stable or unstable (i.e., chatter), as discussed further below.

[0033] In a stable cutting condition as illustrated in inset **130**, the vibration marks left by a current tooth pass **132** are in phase with the vibration marks left by a previous tooth pass **134**. That is, the vibration marks have a phase angle of zero ( $\epsilon=0$ ). When the vibration marks from one pass to the next are in phase, the amount of material being cut by the end mill **110** is essentially constant in thickness. In other words, a “chip thickness” **136** is essentially constant, as it would be in an ideal non-chattering condition.

[0034] In an unstable chatter condition as illustrated in inset **140**, the vibration marks left by a current tooth pass **142** are out of phase with the vibration marks left by a previous tooth pass **144**. That is, the vibration marks have a non-zero phase angle ( $\epsilon \neq 0$ ). In the example shown in the inset **140**, the vibration marks from the current tooth pass **142** are about 180 degrees out of phase with the vibration marks left by the previous tooth pass **144**. When the vibration marks from one pass to the next are out of phase, the amount of material being cut by the end mill **110** varies in thickness. In other words, a chip thickness **146** is not constant. The variations in the chip thickness **146** cause corresponding variations in the motor torque and speed, which can create an unstable condition where the magnitude of the vibrations increases. Unstable chatter can lead to workpiece damage and even damage to the machine tool or the end mill **110**.

[0035] FIG. 2 is a schematic illustration of a system **200** including a computer-controlled machine tool performing a machining operation on a workpiece, of a type applicable to the techniques of the present disclosure. A machine tool **210** rotates a spindle **212** in which is secured a cutting bit, in this case an end mill **220**. The machine tool **210** causes the end mill **220** to perform a machining operation on a workpiece **230**. The machine tool **210** is in communication with a controller **240**, which is a computing device that provides motion commands and spindle motor speed commands to the machine tool **210**. In a typical example, the machine tool **210** would move the rotating end mill **220** from a start point along a path which causes material to be cut from the workpiece **230**, disengage the end mill **220** from the workpiece **230** and move the end mill **220** back to a location near the start point, and then make another pass which cuts more material from the workpiece **230**.

[0036] The end mill **220** is shown in more detail in the inset, where the teeth or flutes are visible at a tip **222**. Again in this example, the end mill **220** includes four teeth or flutes. The number of flutes is significant in relation to chatter conditions, as the cutting teeth engaging the workpiece during mill rotation leave successive vibration marks.

[0037] As will be discussed in detail below, the techniques of the present disclosure are applicable to the system **200**. Specifically, the presently disclosed chatter detection method may be programmed in the controller **240** using data that is readily available in the existing controller architecture. No sensors, microphones or other data acquisition devices are needed for data collection, and no integration of separate data acquisition or sensor sub-systems with the controller **240** is required.

[0038] The elements of FIG. 2 are depicted in rather simple fashion, where the machine tool **210** is movable in three principal axes of motion—including “vertically” (parallel to the axis of the end mill **220**) and in two “horizontal” directions (orthogonal to the axis of the end mill **220**). It is to be understood that the chatter detection method of the present disclosure is applicable to any type of machine tool where chatter may be encountered—including multi-axis machines with tool positioning and orientation capability, and robotically-controlled mills and drills with an articulated robot arm providing complete tool positioning and orientation flexibility.

[0039] FIG. 3 is a flowchart diagram **300** of a method for sensorless chatter detection in a machine tool, using a two-step filtering process in the frequency domain and evaluation of two indicator criteria, according to an embodiment of the present disclosure. The method of FIG. 3 can be programmed to run in the machine tool controller **240**, and uses input data which is readily available in any controller architecture. The disclosed method includes filtering and analysis steps which enable chatter detection without the complications and limitations of previously existing methods.

[0040] Beginning at a start block **302**, the process moves to decision diamond **304** where it is determined whether the spindle of the machine tool is turning (i.e., running, or started). If the spindle is not turning, then there is no need for chatter analysis and the process waits until the spindle is started. When the spindle is turning, the process moves to decision diamond **306** where it is determined if the

cutting operation has been finished. Information about whether the spindle is turning (at the decision diamond **304**) and whether the cutting operation has finished (at the decision diamond **306**) is available in the controller from the machine control program which is running (i.e., the “numerical control” program which defines the sequence of cutting paths/operations to be performed on the workpiece). If the cutting operation has been finished, then the process ends at terminus **308**. If the cutting operation has not been finished, the process moves to decision diamond **310**.

[0041] The remaining steps in the flowchart diagram **300** are all based on analysis of motor torque data. The basic premise is that chatter, if it is occurring, will be manifested in motor torque data, as the vibrations experienced at the cutter-workpiece interface will cause corresponding oscillation of the cutter rotational speed and hence the commanded motor torque. The commanded motor torque is readily available in the software running on the machine controller, where the torque command is either directly available as a machine state, or is determinable from motor current data which is available. Throughout the remainder of the discussion, most of the analysis is based on spindle torque command data (designated as T.sub.cmd). A step which is performed in the time domain is contained in a dashed box **330**, and steps which are performed in the frequency domain are contained in a dashed box **340**.

[0042] At the decision diamond **310**, it is determined whether the cutting bit (e.g., the end mill) is in the process of cutting material from the workpiece. This determination is made by comparing the present torque command signal to a torque command signal for a known air-cut condition which is stored as a reference. Specifically, the determination is made by evaluating time-domain signals and comparing the maximum value of the present torque command to the maximum value of the air-cut torque command. The following inequality is evaluated:

$$[00001] \max T_{\text{cmd}}(t) \geq \alpha_{\text{air}} \cdot \max T_{\text{cmd}}^{\text{air}}(t) \quad (1)$$

where T.sub.cmd(t) is the present torque command signal in the time domain, T.sub.cmd.sup.air(t) is a reference air-cut torque command signal in the time domain, and  $\alpha_{\text{sub.air}}$  is a predefined constant. If  $\alpha_{\text{sub.air}}$  is defined to have a value of 1.2, for example, then when the inequality is true, the present motor torque command is at least 20% greater than the air-cut motor torque command, and it is therefore known that the cutting bit (e.g., the end mill) is in the process of cutting material from the workpiece. While Inequality (1) references the maximum value of the torque command signal, its average value may be adopted as an alternative formulation. The Inequality (1) is evaluated in the decision diamond **310**.

[0043] If the cutting bit is not presently cutting workpiece material, then at block **312** the air-cut reference torque signal is updated (such as by averaging the currently-collected air-cut torque data with previously-collected data) and the process returns to the decision diamond **306**. Updating the air-cut reference torque signal is done periodically to ensure that current data is stored, as the air-cut torque signal can change over time as conditions in the machine tool change (e.g., bearing wear, lubrication condition changes, etc.). It is important to have current and accurate air-cut reference data available, because the air-cut torque data contains characteristic features of the machine which are significant in later filtering and analysis steps.

[0044] From the decision diamond **310**, if the machine tool is presently cutting workpiece material, then at block **314** the time-domain motor torque signal is converted to the frequency domain and a two-step filtering process is performed. A Fast Fourier Transform (FFT) is a technique which may be performed in a known manner on the time-domain motor torque command signal (T.sub.cmd(t)) to produce frequency-domain torque command data (T.sub.cmd( $\omega$ )). Other techniques for converting the time-domain motor torque signal to the frequency domain, as known in the art. The frequency-domain motor torque command data (T.sub.cmd( $\omega$ )) at any moment in time (for example, at a time of 3.5 seconds into a cutting operation) may be visualized as a frequency response graph, as shown in later figures and discussed below.

[0045] Two filtering steps are then performed on the frequency-domain torque command data. The first filtering step is to remove the air-cut torque data via spectral subtraction, and is computed as follows:

$$[00002] T_{\text{cmd}}^{\text{filt}}(\omega) = T_{\text{cmd}}(\omega) - \alpha_{\text{sp}} \cdot T_{\text{cmd}}^{\text{air}}(\omega) \quad (2)$$

where T.sub.cmd.sup.filt( $\omega$ ) is the filtered frequency-domain motor torque command data, T.sub.cmd( $\omega$ ) is the original (unfiltered) frequency-domain motor torque command data from the FFT, T.sub.cmd.sup.air( $\omega$ ) is the frequency-domain reference air-cut torque command data (also from an FFT), and  $\alpha_{\text{sub.sp}}$  is a predefined constant which controls the amount of the air-cut torque data to remove. Equation (2) is applied across the frequency spectrum (from 100 Hz to 2000 Hz, for example) to produce the filtered motor torque command data with air-cut torque data removed. As will be shown in later figures and discussed below, removal of the air-cut torque data effectively eliminates many frequency response “spikes” or “hot spots” in the resulting data which clearly have nothing to do with chatter, because chatter cannot be present in air-cut conditions.

[0046] Depending on the value of  $\alpha_{\text{sub.sp}}$  and the nature of the motor torque and air-cut torque command data, it is possible for Equation (2) to result in small negative values at some frequencies. A mapping function M(.) is therefore applied to the filtered motor torque command data before proceeding further in the chatter detection method. The mapping function is defined as follows;

$$[00003] M(T_{\text{cmd}}^{\text{filt}}(\omega)) = \begin{cases} T_{\text{cmd}}^{\text{filt}}(\omega) & \text{if } T_{\text{cmd}}(\omega) - \alpha_{\text{sp}} \cdot T_{\text{cmd}}^{\text{air}}(\omega) > 0 \\ 0.01 \cdot T_{\text{cmd}}(\omega) & \text{otherwise} \end{cases} \quad (3)$$

where all of the variables appearing in Equation (3) have been defined above. The mapping function of Equation (3) dictates that, for each frequency across the frequency spectrum, if the right side of the equal sign in Equation (2) yields a positive value, then that value is used for the filtered torque command. On the other hand, if the right side of the equal sign in Equation (2) yields a negative value or zero, then the filtered torque command is computed as a small multiplier times the unfiltered torque command, in absolute value. The mapping function of Equation (3) eliminates negative values from the frequency response spectrum of the filtered motor torque data while ensuring that any significant spikes in the frequency response spectrum of the air-cut data are removed from the filtered motor torque data.

[0047] The second filtering step is to remove spindle harmonic components at specific frequencies in the frequency response spectrum of the filtered motor torque data, and is computed using the following calculation:

$$[00004] T_{\text{cmd}}^{\text{filt}}(\omega) = 0.01 \cdot T_{\text{cmd}}^{\text{filt}}(\omega) \cdot \{k = k_{\text{spindle}}\} \quad \{k = 1, 2, \dots\} \quad (4)$$

[0048] The filtering step defined in Equation (4) dictates that for each frequency  $\omega$  which is an integer multiple k of the spindle rotation speed  $\omega_{\text{sub.spindle}}$  (in revolutions per second), the filtered torque command is multiplied by a small value (e.g., 0.01) in order to dramatically reduce its magnitude. The purpose of the second filtering step is to remove spindle harmonic components which may persist and appear misleadingly significant in frequency response graphs in light chatter cases. This second filtering step has an effect similar to a comb filter, dampening out frequency response data at specific frequencies, but without the undesirable comb filtering effect of distorting

nearly contents in the frequency response spectrum.

[0049] After the second filtering step described above and in Equation (4), the filtering of the frequency-domain motor torque data at the block **314** of FIG. **3** is complete. The resultant filtered torque command data ( $T_{\text{sub.cmd.sup.filt}}(\omega)$ ) produced by Equations (2)-(4) is then used for chatter analysis and detection.

[0050] FIG. **4** is a frequency response graph **400** of motor torque command data both before and after filtering using the method of the block **314** of FIG. **3**, according to an embodiment of the present disclosure. The graph **400** plots a spindle torque command (as a percentage of a maximum value) on a vertical axis **410** against frequency on a horizontal axis **420**. Vertical dashed lines **430** coincide with spindle harmonic frequencies.

[0051] The graph **400** includes plots for both original (unfiltered) torque data and filtered torque data, as indicated by the legend. The original, unfiltered torque data includes large spikes in the response, such as those indicated at **440** and **442**. The response spikes **440** and **442** could be signal noise or from a natural frequency characteristic of the machine tool, and possibly exacerbated by the machine tool natural frequency corresponding with a spindle harmonic frequency. The spikes **440/442** and others could easily be mistaken for chatter in an analysis of the original, unfiltered torque data.

[0052] The filtered torque data includes some smaller spikes in the frequency response, such as the one indicated at **450**. A detailed analysis of the actual machine performance, during the experiment which produced this data, reveals that the spike **450** corresponds with actual chatter at 920 Hz. Two observations about this are noteworthy. First, by using the filtering techniques described above with respect to the block **314** of FIG. **3**, the frequency response content related to actual chatter becomes obvious and easy to detect. Second, in the original (unfiltered) data, the chatter at 920 Hz is not apparent, particularly in comparison to the large spikes **440** and **442** (“false positives”) which do not correspond with actual chatter of the mill against the workpiece.

[0053] Returning to the flowchart diagram **300** of FIG. **3**—after the filtering steps of the block **314**, producing data as illustrated in FIG. **4** and discussed above, at block **316** the resultant filtered torque command data ( $T_{\text{sub.cmd.sup.filt}}(\omega)$ ) is analyzed for indications of chatter. In the presently disclosed method, two different chatter indicators are evaluated at the block **316**. The data being evaluated is in the frequency domain, as explained earlier.

[0054] The first chatter indicator parameter is the magnitude of the filtered spindle torque command data ( $T_{\text{sub.cmd.sup.filt}}(\omega)$ ), discussed above and produced using Equations (2)-(4). In one embodiment, the criteria for evaluation of the filtered torque command data is as follows; at each frequency in the frequency response spectrum, if the magnitude of the filtered torque command is much greater than the magnitude of the air-cut torque command ( $T_{\text{sub.cmd.sup.air}}(\omega)$ ) at the same frequency, then chatter is occurring at that frequency. Conversely, if the magnitude of the filtered torque command is less than or equal to the magnitude of the air-cut torque command at the same frequency, then chatter is not occurring at that frequency. That is:

$$[00005] \text{.Math. } T_{\text{cmd}}^{\text{filt}}( ) \text{.Math. } \gg \text{.Math. } T_{\text{cmd}}^{\text{air}}( ) \text{.Math. ifchatter (5)}$$

$$\text{.Math. } T_{\text{cmd}}^{\text{filt}}( ) \text{.Math. } \leq \text{.Math. } T_{\text{cmd}}^{\text{air}}( ) \text{.Math. otherwise (6)}$$

[0055] It will be recalled that the air-cut torque command data has already been subtracted from the spindle torque command data in the filtered data, in the spectral subtraction of Equation (2). Thus, the filtered torque command data would be expected to be less than or equal to the air-cut torque data across the frequency spectrum except for any frequencies at which chatter is occurring. The spike **450** of FIG. **4** is an example which meets the criteria of Inequality (5) and is readily detectable as a chatter condition.

[0056] The second chatter indicator parameter is the magnitude ratio of the filtered spindle torque command data ( $T_{\text{sub.cmd.sup.filt}}(\omega)$ ) to the air-cut torque command data ( $T_{\text{sub.cmd.sup.air}}(\omega)$ ). In one embodiment, the criteria for evaluation of the ratio is as follows; at each frequency in the frequency response spectrum, if the magnitude of the ratio is much greater than zero, then chatter is occurring at that frequency. Conversely, if the magnitude ratio is approximately equal to zero, then chatter is not occurring at that frequency. That is:

$$[00006] \frac{\text{.Math. } T_{\text{cmd}}^{\text{filt}}( ) \text{.Math.}}{\text{.Math. } T_{\text{cmd}}^{\text{air}}( ) \text{.Math.}} \gg 0 \text{ifchatter (7)} \quad \frac{\text{.Math. } T_{\text{cmd}}^{\text{filt}}( ) \text{.Math.}}{\text{.Math. } T_{\text{cmd}}^{\text{air}}( ) \text{.Math.}} \approx 0 \text{otherwise (8)}$$

[0057] The second chatter indicator also addresses distortion from spindle dynamics. It is known that the torque command at the spindle varies from the torque at the tool tip, and that the variance (known as distortion) changes with frequency (spindle speed). However, the second chatter indicator defined above alleviates this distortion because it is a ratio, and the distortion in the numerator cancels with that of the denominator.

[0058] The meaning of “much greater than” in the Inequalities (5) and (7) may be defined in a manner found to be suitable for a particular application—such as “ten times greater”, or “fifty times greater”, etc. Preferably, the computed values of the chatter indicators are checked against pre-defined thresholds for chatter detection, where the thresholds (one for each of the chatter indicators) are defined based on experience from known chatter and non-chatter operational data. A statistical analysis such as Z-score (median and deviation analysis) may also be used to determine if particular features in the frequency response data, for both of the indicator parameters, are outliers indicative of chatter.

[0059] When either the first or second chatter indicator (or both) indicates that chatter is occurring, a chatter frequency @ chatter is identified as the particular frequency at which the Inequality (5) and/or (7) is true. When chatter is detected and the chatter frequency is identified, the two chatter indicators may be further evaluated at sideband frequencies (higher or lower than the chatter frequency by multiples of the spindle speed) for confirmative indications of chatter. This is discussed further below.

[0060] At decision diamond **318**, it is determined if chatter is detected in either of the indicators from the block **316** described above. If so, then at block **320** the machine controller takes steps to address and eliminate the chatter condition. A primary technique used to eliminate chatter is to change the spindle speed, thereby moving away from the condition (i.e., a resonance or dynamic response which creates the phase shift depicted in FIG. **1**) which is causing the chatter. One technique for identifying spindle speeds having the potential to eliminate chatter uses the following calculation:

$$[00007] \text{ spindle } = \frac{60 \text{.Math. } \text{chatter}}{2 \text{.Math. } N_{\text{flutes}} K} \{k = 1, 2, \text{.Math. } \} \text{ (9)}$$

[0061] Where  $\Omega_{\text{sub.spindle}}$  is the calculated new spindle speed in RPM,  $\omega_{\text{sub.chatter}}$  is the identified chatter frequency, and  $N_{\text{sub.flutes}}$  is the number of flutes or cutting edges on the mill. A value of the integer multiplier  $k$  can be selected to provide a spindle speed which is considered suitable for the machining operation—such as a new spindle speed which is within a certain percentage of the old spindle speed.

[0062] At the decision diamond **318**, if chatter is not detected in the analysis of the indicators at the block **316**, then the process loops back to the decision diamond **306** where, if the operation is not completed, the chatter detection methodology is repeated. This repetition of the chatter detection continues until the cutting operation is concluded.

[0063] FIGS. 5A and 5B are frequency response graphs of a motor torque command in a chatter condition and a non-chatter condition,

respectively, illustrating the effects of the filtering steps and the resultant chatter indicator analysis of FIG. 3, according to embodiments of the present disclosure. The filtered motor torque (a.k.a., spindle torque) command ( $T_{sub.cmd.sup.filt}(\omega)$ ) is the first chatter indicator parameter discussed above.

[0064] FIG. 5A is a graph 500 which plots the motor/spindle torque command (as a percentage of a maximum value) on a vertical axis 510 against frequency on a horizontal axis 520. Again, the vertical dashed lines coincide with spindle harmonic frequencies. The graph 500 includes plots for both original (unfiltered) torque data and filtered torque data, as indicated by the legend. The filtered torque data (produced as discussed above using Equations (2)-(4)) includes a large feature (spike) in the response data, indicated in ellipse 530. Based on the magnitude of this spike relative to the air-cut torque data, the spike in the ellipse 530 is easily identified as chatter. The chatter frequency  $\omega_{sub.chatter}$  is identified as 920 Hz. Two smaller spikes, also present in the filtered torque data (to the left of the ellipse 530), may be indicative of chatter occurring at frequencies which are offset from the chatter frequency by multiples of the spindle speed. That is, minor chatter sideband frequencies may occur at  $\omega = \omega_{sub.chatter} \pm k \cdot \omega_{sub.spindle}$ , where  $k = 1, 2, \dots$  and  $\omega_{sub.spindle}$  is the spindle speed in revolutions per second.

[0065] The data depicted in FIG. 5A was collected from an experimental milling operation where chatter at 920 Hz was independently verified. Conversely, FIG. 5B depicts frequency response data for a similar experimental milling operation where independent monitoring detected no chatter. FIG. 5B is a graph 550 which plots the spindle torque command (as a percentage of a maximum value) on a vertical axis 560 against frequency on a horizontal axis 570. The graph 550 again includes plots for both original (unfiltered) torque data and filtered torque data, as indicated by the legend. It can be seen that there are no significant spikes in the filtered torque response data, which agrees with the independent monitoring and analysis which was performed during the experiment. Again, the torque data filtered according to the techniques of the present disclosure make it readily apparent that no chatter is occurring in the graph 550 of FIG. 5B.

[0066] In both the graph 500 (FIG. 5A) and the graph 550 (FIG. 5B), the original, unfiltered torque data includes large spikes in the response, similar to those discussed earlier with respect to FIG. 4. Many spikes in the response—both small and large—correspond with spindle harmonic frequencies, while other spikes correspond with other machine dynamic response characteristics. The spikes in the original, unfiltered torque data are virtually all eliminated in the filtered torque data, allowing easy identification of the true chatter condition observed in FIG. 5A.

[0067] FIGS. 6A and 6B are frequency response graphs of a motor torque ratio (cutting over air-cut) in a chatter condition and a non-chatter condition, respectively, illustrating the effects of the filtering steps and the resultant chatter indicator analysis of FIG. 3, according to embodiments of the present disclosure. The motor torque ratio ( $T_{sub.cmd.sup.filt}(\omega)/T_{sub.cmd.sup.air}(\omega)$ ) is the second chatter indicator parameter discussed above.

[0068] FIG. 6A is a graph 600 which plots the motor torque ratio (cutting over air-cut) on a vertical axis 610 against frequency on a horizontal axis 620. Again, the vertical dashed lines coincide with spindle harmonic frequencies. The graph 600 includes plots for both original (unfiltered) torque data and filtered torque data, as per the previously discussed graphs. The ratio using filtered torque data includes a large feature (spike) in the response data, indicated in ellipse 630. Based on the magnitude of this spike (much greater than zero), the spike in the ellipse 630 is easily identified as chatter. The chatter frequency  $\omega_{sub.chatter}$  is identified as 920 Hz, which corresponds to the chatter frequency identified in FIG. 5A using data from the same experiment. Smaller spikes, also present in the filtered torque ratio data, may indicate chatter occurring at frequencies offset from the chatter frequency by multiples of the spindle speed.

[0069] The data depicted in FIG. 6A was collected from the experimental milling operation where chatter at 920 Hz was independently verified. Conversely, FIG. 6B depicts frequency response data for a similar experimental milling operation where independent monitoring detected no chatter. FIG. 6B is a graph 650 which plots the spindle torque ratio (cutting over air-cut) on a vertical axis 660 against frequency on a horizontal axis 670. The graph 650 again includes plots for both original (unfiltered) torque data and filtered torque data, as indicated by the legend. It can be seen that there are no significant spikes in the torque ratio data, which agrees with the independent monitoring and analysis which was performed during the experiment. Again, the torque ratio indicator according to the techniques of the present disclosure make it readily apparent that no chatter is occurring in the graph 650 of FIG. 6B.

[0070] The results depicted in FIGS. 5 and 6 have been validated in experiments using external sensors including accelerometers and audio recording equipment. In the experimental operating conditions reflected in FIGS. 5A and 6A, the external sensors confirmed the presence of chatter at the frequency of 920 Hz identified by analysis of the chatter indicator parameters discussed above. In the experimental operating conditions reflected in FIGS. 5B and 6B, the external sensors confirmed that no chatter was occurring. The torque data filtering and analysis techniques of the present disclosure have thus been demonstrated to provide the following advantages: clearly and accurately indicating the chatter condition when it exists, clearly and accurately indicating the absence of chatter when none exists, and eliminating the many false positive spikes which exist in the frequency response spectrum of the unfiltered torque data.

[0071] The preceding discussion describes frequency-domain filtering of spindle motor torque data, including two filtering steps—spectral subtraction of an air-cut reference signal, and filtering out of spindle harmonic frequencies. These filtering steps effectively prepare the spindle motor torque data for analysis to detect chatter. Other types of filtering models, and other types of motor data from the machine tool, may be added to the techniques discussed above. These additional data sources and filtering models, which have been demonstrated to be advantageous in certain chatter detection applications, are discussed below.

[0072] First, two additional filtering steps will be discussed, where these filtering steps address other sources of signal noise which are not addressed in the air-cut spectral subtraction and spindle harmonics attenuation discussed above. The two additional filtering steps discussed below include removal of aliasing artifacts and removal of encoder interpolation errors.

[0073] Aliasing is the overlapping of frequency components resulting from a data sample rate below the Nyquist frequency. The Nyquist frequency is a characteristic of a sampler, which converts a continuous function or signal into a discrete sequence. For a given sampling rate (samples per second), the Nyquist frequency (cycles per second) is the frequency whose cycle-length (or period) is twice the interval between samples, thus 0.5 cycle/sample. Insufficient sampling frequency results in distortion or artifacts when the signal is reconstructed from samples, which causes the reconstructed signal to differ from the original continuous signal.

[0074] As a simple example, consider a 10 Hz sine wave which is sampled with time-series data collected at 15 Hz and at 50 Hz. When converted to the frequency domain, the 15 Hz sample data indicates a strong frequency response at 5 Hz, which is incorrect, and is due to aliasing effects. The 50 Hz sample data indicates a strong frequency response at 10 Hz, which is correct; this is because the sampling frequency is sufficiently higher than the frequency content of the signal. In other words, a sampling rate of 50 Hz is sufficiently high to avoid aliasing effects in a 10 Hz data signal.

[0075] In the chatter detection application of the present disclosure, aliasing causes artificial peaks to be present in the frequency response spectrum resulting from the interaction between sampling frequency and cutting frequency. In a machine tool being monitored for chatter,

the torque command exists in the CNC control system with control loops operating at different frequencies. Thus, the resulting frequency response spectrum could exhibit a mixture of real contents and artificial contents due to aliasing effects from the slower component of the CNC controller. Assuming the slower component of the controller operates at a sampling frequency (f.sub.s) of 1000 Hz, the corresponding Nyquist frequency (f.sub.Nyquist) is 500 Hz, where artificial peaks due to aliasing can arise above this frequency.

[0076] The cutting frequency in a machine tool is the frequency at which the flutes or teeth of the cutting bit/tool (e.g., end mill) make contact with the workpiece. For example, for a cutting tool with six flutes turning at 1600 RPM, the cutting frequency (f.sub.cutting) is  $(1600) \cdot (1/60) \cdot (6)$ , or 160 Hz.

[0077] Nyquist zones are a series of frequency zones which are defined by the sampling frequency (f.sub.s). Artificial peaks in the frequency response spectrum may appear within Nyquist zones. The first Nyquist zone envelops the cutting frequency (f.sub.cutting) itself, which is 160 Hz. The second Nyquist zone contains an artificial peak at a frequency which is found by “folding” the cutting frequency (f.sub.cutting) in the first Nyquist zone about one-half the sampling frequency (f.sub.s/2); 160 Hz folded about/across 500 Hz is 840 Hz, which is located in the second Nyquist zone. The third Nyquist zone contains an artificial peak at a frequency which is found by folding the artificial peak in the second Nyquist zone about the sampling frequency (f.sub.s); 840 Hz folded about/across 1000 Hz is 1160 Hz, which is in the third Nyquist zone. Continuing in this manner, the artificial peak in the fourth Nyquist zone occurs at a frequency which is found by folding the artificial peak in the third Nyquist zone about 1.5 times the sampling frequency (3 f.sub.s/2); 1160 Hz folded about/across 1500 Hz is 1840 Hz, which is in the fourth Nyquist zone.

[0078] Knowing the frequencies of the artificial peaks in the Nyquist zones from the above calculations and discussion, it is possible to filter the frequency response spectrum to remove the noise (artificial peaks) which is due to aliasing artifacts. The frequencies at which aliasing noise will be found, for a sampling frequency of 1000 Hz and a cutting frequency of 160 Hz, are computed using the following calculation:

$$f_{\text{noise}} = k \cdot \text{Math. } 1000 + 160 \cdot \text{Math. } \{k = -N, \text{Math. }, N\} \quad (10)$$

[0079] The calculation of Equation (10) results in noise frequencies (f.sub.noise) of 840 Hz, 1160 Hz, 1840 Hz, 2160 Hz, etc.

[0080] A filter can then be applied to the frequency response data to remove the artificial peaks which are due to aliasing effects, as follows:

$$\text{Math. } T_{\text{cmd}}^{\text{filt}}(\text{ }) \cdot \text{Math. } = 0.01 \cdot \text{Math. } \cdot \text{Math. } T_{\text{cmd}}^{\text{orig}}(\text{noise}) \cdot \text{Math. } \{ \text{noise} = f_{\text{noise}}(k) \} \quad (11)$$

[0081] The filtering step defined in Equation (11) dictates that for each aliasing-related noise frequency  $\omega_{\text{sub.noise}} = f_{\text{sub.noise}}$  (evaluated at the values of k), the filtered torque command is computed as the original torque command multiplied by a small value (e.g., 0.01) in order to dramatically reduce its magnitude.

[0082] FIG. 7 is a frequency response graph 700 of motor torque command data both before and after filtering to remove aliasing effects, according to an embodiment of the present disclosure. The graph 700 plots a torque command (as a percentage of a maximum value) on a vertical axis 710 against frequency on a horizontal axis 720. A large spike 730 in the frequency response indicates an actual chatter occurring at about 1050 Hz.

[0083] The graph 700 includes plots for both original (before aliasing filtering) torque data and filtered torque data (after aliasing filtering), as indicated by the legend. The original, unfiltered torque data includes significant spikes in the response, indicated at 740 and 742, in addition to the spike 730 at the chatter frequency. The response spikes 740 and 742 could easily be mistaken for chatter in an analysis of the original, unfiltered torque data.

[0084] The filtered torque data includes only the spike 730 at the actual chatter frequency. The spikes 740 and 742, which are aliasing effects occurred at frequencies of 840 Hz and 1160 Hz, respectively, in the original torque data, have been eliminated using the filtering technique described above. The data on the graph 700 of FIG. 7 is from an experiment with a sampling frequency (f.sub.s) of 1000 Hz and a cutting frequency (f.sub.cutting) of 160 Hz. Thus, the resulting noise frequencies in each Nyquist zone, calculated using Equation (10) and filtered out using Equation (11), include the frequencies of 840 Hz and 1160 Hz. The elimination of the artificial peaks in the frequency response data, illustrated in FIG. 7, demonstrates how the aliasing filtering technique further improves machine tool chatter detection.

[0085] Another filtering step involves removing encoder interpolation errors from the machine tool frequency response. A common type of rotary shaft encoder interpolates rotation of a motor shaft from sine and cosine signals. Encoder interpolation errors arise from interactions between encoder line count (number of sine and cosine waves around the circumference of the shaft) and motor rotational frequency. Particularly, encoder error noise is introduced at frequencies which are multiples of the motor frequency (in Hz) multiplied by the number of lines on the encoder. The encoder interpolation errors in the time-series data, which are motor-speed-dependent, can manifest themselves in artificial spikes in the frequency response data for the machine tool.

[0086] The number of lines on the encoder is known for a particular motor. Therefore, the frequencies at which encoder error noise are expected can be computed using the following calculation:

$$f_{\text{noise}} = k \cdot \text{Math. } f_{\text{motor}} \cdot \text{Math. } N_{\text{lines}} \{k = 1, 2, \text{Math. } \} \quad (12)$$

[0087] Where f.sub.motor is the motor frequency in Hz (motor rpm divided by 60), and N.sub.lines is the number of lines on the encoder. The calculation of Equation (12) results in a set of noise frequencies (f.sub.noise) for any given motor speed.

[0088] A filter can then be applied to the frequency response data to remove the artificial peaks which are due to encoder interpolation errors, in the same manner as defined in Equation (11). That is, for each encoder error-related noise frequency  $\omega_{\text{sub.noise}} = f_{\text{sub.noise}}$  (evaluated at the values of k), the filtered torque command is computed as the original torque command multiplied by a small value (e.g., 0.01) in order to dramatically reduce its magnitude. Artificial peaks due to aliasing of the encoder interpolation errors may also exist but can be calculated and filtered as described previously.

[0089] When experimental data for a non-chatter condition is collected and the frequency response is plotted in the same manner as shown in FIG. 7, many small-to-medium size spikes appear at regular frequency intervals in the original torque command data. The frequency intervals where the spikes occur correlate to the encoder error noise frequency intervals from Equation (12). When the encoder error filtering frequencies are computed as in Equation (12) and applied to the frequency response data, the artificial spikes are eliminated from the filtered frequency response. This demonstrates the effectiveness of the filtering step for removing encoder interpolation errors, which in turn enables more accurate machine tool chatter detection.

[0090] It is worth noting that the first filtering step described earlier—spectral subtraction of the air-cut reference signal—actually removes a large portion of the encoder errors for the spindle motor (the encoder errors are contained in the air-cut reference signal, because the air-cut spindle speed is the same as the cutting spindle speed). Thus, for spindle motor torque data, the encoder error filtering

step essentially performs a clean-up of any small spikes in the frequency response spectrum which were not entirely removed by the spectral subtraction of the air-cut reference signal. In later discussion, it is explained how the encoder error filtering step is very important when using servo motor frequency response data (as opposed to spindle motor data) for chatter detection.

[0091] The discussion above has all been directed to filtering and analysis of spindle motor torque data; that is, the torque data for the motor which drives the spindle, which in turn holds the cutting bit (e.g., end mill). To summarize, four frequency-domain filtering steps have been described above; spectral subtraction of an air-cut reference signal, filtering for removal of peaks in the frequency response at spindle harmonic frequencies, filtering to remove aliasing effects, and filtering to remove encoder interpolation error effects. Referring back to the flowchart diagram of FIG. 3, all of these filtering steps are performed at the block 314. Then the filtered frequency-domain torque signal is analyzed at the block 316 to detect any chatter condition.

[0092] In addition to spindle motor data, data from the servo motors which are used for positioning the machine tool may also be analyzed to effectively detect chatter. As discussed earlier, many machine tools of the type illustrated in FIG. 2 are configured for independent positioning in three orthogonal directions—typically identified as X, Y and Z axes. A servo motor is used for positioning in each axial direction, where each of the three servo motors is controlled by the machine controller 240 in order to carry out a particular pre-programmed machining operation.

[0093] Data from the servo motors may be filtered and analyzed to detect chatter in a manner similar to that described above for spindle torque data. In fact, in some types of machines and applications, data from one or more of the servo motors may provide a more reliable indicator of chatter than the spindle motor data. For example, in a machine where the spindle is belt driven from the spindle motor, the belt-related compliance and damping which exist between the spindle motor and the cutting bit (e.g., end mill) may distort the time-domain spindle motor torque data, possibly causing the filtered frequency-domain spindle data to be less effective as a chatter indicator. In cases such as this, frequency response data from one or more of the servo motors may be the best indicator of chatter in the machine tool, and it is therefore advantageous to analyze data from all of the motors in the machine tool.

[0094] In the earlier discussion of spindle motor data collection and filtering, the data collected from the spindle motor was always described as a torque signal. This is because the time-series torque data for the spindle motor is readily available, such as by monitoring motor current. In the case of servo motors, there is another option. The frequency response analysis of servo motor data could be based on either motor torque data or pulse coder data. A pulse coder is a device integral to each servo motor which measures the angular position of the servo motor shaft. Time-domain pulse coder angular position data from each servo motor may be numerically differentiated to provide a velocity signal. Alternately, the pulse coder may provide angular velocity information directly. In either case, the time-domain velocity signal can be converted to the frequency domain, where filters can be applied and the frequency response characteristics analyzed to detect chatter in the manner described. Some considerations in using motor torque data or pulse coder position/velocity data for the servo motors are discussed further below.

[0095] The concepts described herein for servo motor data filtering and analysis are applicable to all three positioning servo motors (X, Y and Z directions). However, some the filtering and analysis of servo motor data is typically handled somewhat differently than the filtering and analysis of spindle motor data. In particular, when processing servo motor data, some of the four filtering steps described earlier are not applicable.

[0096] First, it is important to note that the positioning servo motors have time-varying motions. That is, during the course of a machining operation, each of the three positioning servo motors may turn at different speeds, and in both directions, or may be stopped altogether. This is unlike the spindle motor which generally turns in only one direction and at an essentially constant speed during both cutting and air-cut portions of a programmed machining operation.

[0097] The time-varying motions of the servo motors means that spectral subtraction of an air-cut reference signal is not possible, at least not in a practical manner. The reason is because the air-cut data needs to be collected for a specific motor speed. The only way that spectral subtraction of an air-cut reference signal can be performed accurately is if the entire machining operation is performed in air-cut mode so that the exact combinations of servo motor speeds and directions is captured in the air-cut reference signal. Keeping in mind that it is desirable to update the air-cut reference signal periodically to accurately reflect current machine conditions, spectral subtraction of an air-cut reference signal for the servo motors becomes impractical. As a result of this, spectral subtraction of an air-cut reference signal (the first of the four filtering steps) is not performed for servo motor data.

[0098] Regarding the second filtering step, for removal of spindle harmonics, this filtering step is applied to servo motor data (torque or velocity) in the same manner as applied to spindle motor data. This is to filter out the forced vibration contents which may be transmitted from the spindle rotation to the servo motors, and is done to better highlight the chatter component, especially for lighter chatter cases.

[0099] The third filtering step—for removal of aliasing effects—may be performed on servo motor data, depending on the type (source) of data used for the servo motors. If torque data is used for the servo motors, then the filtering step for aliasing removal is performed in the same manner as applied to spindle more torque data. However, if pulse coder position/velocity data is used for the servo motor signals, then the aliasing effects discussed earlier are not present in the frequency response data. This is because the aliasing effects arise due to the interaction of the controller's slower feedback frequency with the cutting frequency. When servo motor torque is not used for the servo motor signal, the aliasing effect is not introduced. Therefore, if pulse coder position/velocity data is directly used for the servo motor signals, the filtering step for removal of aliasing effects is not performed.

[0100] The fourth filtering step—for removal of encoder interpolation errors—is performed and is especially important for the servo motor data. This is because the spectral subtraction of an air-cut reference signal is not performed for servo motor data (as discussed above). Therefore, the encoder interpolation errors are present in servo motor data and their removal is important for accurate and reliable chatter detection in the frequency response data. Furthermore, because the servo motors operate at variable speeds, and the encoder interpolation error frequencies are a function of motor speed, the encoder error noise frequencies (calculated in Equation (12)) must be computed and applied to frequency-domain data for the particular operating speed of each servo motor at a particular condition of the machine tool and machining program. This calculation can be performed in real time as each new brief time segment of data is converted to the frequency domain and analyzed for chatter detection.

[0101] FIG. 8 is a flowchart diagram 800 of a method for sensorless chatter detection in a machine tool, using a multi-step filtering process in the frequency domain, and including both spindle and servo motor data filtering and analysis, according to an embodiment of the present disclosure. The method of FIG. 8 can be programmed to run in the machine tool controller 240, and uses input data which is readily available in any controller architecture—including spindle motor torque data derived from spindle motor current, and either motor torque or pulse coder position/velocity data for servo motors.

[0102] The left-hand side of the flowchart diagram 800 is essentially the same as the corresponding portions of the flowchart diagram 300



of FIG. 3, discussed earlier. From a start block **802**, the process waits at a decision diamond **804** until detecting that the spindle of the machine tool has started. When the spindle is turning, at decision diamond **806** it is determined if the entire cutting or machining operation has finished, and if so, the process ends at terminus **808**. When the machining operation program is still running, at decision diamond **810** it is determined whether the cutting bit (e.g., end mill) is currently cutting material. This determination is made by comparing the time-domain spindle motor torque signal to the previously-stored air-cut reference signal, as described earlier. When material is not being cut, at block **812** the air-cut reference torque signal is updated (such as by averaging the currently-collected air-cut spindle torque data with previously-collected data) and the process returns to the decision diamond **806**.

[0103] As described earlier for corresponding portions of FIG. 3, the step contained in dashed box **830** is performed in the time domain, while the steps contained in dashed box **840** are performed in the frequency domain. The method of FIG. 3 is used for applications where only spindle motor data is to be evaluated. In the method of FIG. 8, both spindle motor and servo motor data is evaluated, and these steps are contained in the box **840**.

[0104] At block **814**, after converting the time-series spindle data to the frequency domain, the spindle data is filtered as described in detail above. This includes the four frequency-domain filtering steps designed to improve the ability to detect chatter in the frequency response data for the machine tool. At block **816**, the spindle motor frequency response data (after filtering) is analyzed to determine if chatter is occurring.

[0105] At block **818**, after converting the time-series servo motor data to the frequency domain, the servo data is filtered as described in detail above. This includes applying two or three of the frequency-domain filtering steps (depending on whether servo motor torque or pulse coder data is used as the input signal) designed to improve the ability to detect chatter in the frequency response data for the machine tool. At block **820**, the servo motor frequency response data (after filtering) is analyzed to determine if chatter is occurring.

[0106] In a preferred embodiment, one chatter indicator is used for each type of motor. For spindle motor torque data, analyzed at the block **816**, the preferred indicator is the magnitude ratio of the filtered spindle torque command data ( $T_{sub.cmd.sup.filt}(\omega)$ ) to the air-cut torque command data ( $T_{sub.cmd.sup.air}(\omega)$ ). As defined in Equations (7) and (8), when the magnitude ratio is much greater than zero at any frequency in the frequency response spectrum, this is taken as an indicator that chatter is occurring at that frequency. For servo motor data analyzed at the block **820** (from a torque signal or a pulse coder position/velocity signal), the preferred indicator is the magnitude of the filtered servo motor command data. When the magnitude of the filtered servo motor torque or velocity is much greater than zero at any frequency in the frequency response spectrum, this is taken as an indicator that chatter is occurring at that frequency.

[0107] The meaning of “much greater than zero” in the analyses at the blocks **816** and **820** may be defined in a manner found to be suitable for a particular application—such as “greater than 0.1”, or “greater than 0.25”, etc. Preferably, the computed values of the chatter indicators are checked against pre-defined thresholds for chatter detection, where the thresholds (one for each of the chatter indicators) are defined based on experience from known chatter and non-chatter operational data. A Z-score (median and deviation analysis) may also be used to determine if particular features in the frequency response data, for both the spindle motor and servo motor indicator parameters, are outliers indicative of chatter.

[0108] Returning to the flowchart of FIG. 8, after the filtered frequency response spectrum is analyzed at the blocks **816** (for spindle motor data) and **820** (for data from all three servo motors), at decision diamond **822** it is determined if chatter is detected in the analysis of data from any of the motors. When no chatter is detected, the process returns to the decision diamond **806** and the data collection and analysis continues in real time as long as the machining operation is still being performed. From the decision diamond **822**, when chatter is detected in any motor signal analysis, at block **824** the machine controller takes steps to address and eliminate the chatter condition. As discussed earlier, a primary technique used to eliminate chatter is to change the spindle speed, thereby moving away from the condition which is causing the chatter (i.e., a resonance or dynamic response which creates the phase shift depicted in FIG. 1). A technique for identifying spindle speeds having the potential to eliminate chatter was discussed earlier and defined in the calculation of Equation (9).

[0109] To summarize, the preceding discussion describes techniques for chatter detection using frequency-domain filtering and analysis of spindle motor torque data (with four different filtering operations) and also servo motor data (either torque data with three filtering operations, or pulse coder data with two filtering operations). In order to effectively apply these methods to chatter detection in a particular machine tool, it would be advantageous for the machine controller to have a user interface system which provides convenient real-time visualization of the machine's frequency response characteristics and chatter status, and allows configuration of the chatter detection parameters for the machine.

[0110] FIG. 9 is a mock-up of a graphical user interface **900** providing chatter detection visualization and control features for a machine tool, according to an embodiment of the present disclosure. The graphical user interface **900** is displayed on a display device (such as a monitor or a tablet device) which is in communication with the machine controller. The display device is understood to have user input capability, such as a touch screen feature or a mouse, and optionally also a keyboard or keypad, for selecting buttons and menu options on the graphical user interface **900**.

[0111] On the left side of the graphical user interface **900** is a frequency response graph window **910**. The frequency response graph window **910** displays a frequency response graph for a particular motor of the machine tool. The particular motor is chosen from a drop-list **912**, and in a preferred embodiment the drop-list **912** includes selectable options for; the spindle motor, the X servo motor, the Y servo motor and the Z servo motor. The frequency response graph window **910** displays the frequency response in real time, based on a rolling buffer of time-series data for the selected motor, where the time-series data for a brief time segment is converted to the frequency domain and displayed in the frequency response graph window **910**. The frequency response graph depicts the response characteristic (e.g., normalized torque) for the selected motor, across the frequency spectrum, after all of the filtering operations described above.

[0112] A Tool Geometry button **920** allows a user to define the geometry parameters of the cutting bit or cutting tool (e.g., end mill). In a preferred embodiment, when the user clicks on the Tool Geometry button **920**, a pop-up window allows the user to define a tool diameter (typically in millimeters) and a number of flutes (e.g., 4 as shown in FIG. 2). The number of flutes on the tool is used in the calculation of spindle speeds which have the potential to avoid chatter, as defined in Equation (9) and discussed earlier. The number of flutes is also used to compute the cutting frequency which is used in the calculation and filtering of aliasing effects.

[0113] A Motor Settings button **930** allows a user to define parameters for chatter detection in the operation of the machine tool. In a preferred embodiment, when the user clicks on the Motor Settings button **930**, a pop-up window appears containing a small table. In the first column of the table is a list of the motors which are included in the machine tool. In one common example, the motors include the spindle, the X servo, the Y servo and the Z servo. In a second column of the table is a priority number assigned to each of the motors. As discussed earlier, any particular machine tool is likely to exhibit different sensitivities to chatter in the different motors. For example, in one machine, the spindle motor may be the motor which most clearly depicts a chatter condition in its frequency response spectrum, while

in another machine the Z servo is most clearly depicted. Because of this, the Motor Settings button **930** allows the user to define a priority for each motor; for example, the spindle could be defined as #1 priority (top priority for chatter detection), the Z servo as the #2 priority, the X servo as #3 priority and the Y servo as #4 priority. The table also includes a threshold value which is user-definable for each motor, where the threshold could be defined as a Z-score threshold (e.g., **3.50**) above which it is determined that chatter is occurring. The Z-score was discussed earlier.

[0114] A Process Stability window **940** indicates at a glance whether the machine tool is current exhibiting a stable operating condition or if the machine tool is currently experiencing chatter (as shown in FIG. **9**). If the Process Stability window **940** indicates chatter, then a Chatter Frequency window **950** displays the frequency (in Hz) at which chatter is occurring. The chatter frequency is determined by analysis of the filtered frequency response spectrum, as described in great detail throughout the present disclosure.

[0115] If the Process Stability window **940** indicates chatter, then a window **960** displays one or more spindle speeds (in rpm) which would potentially return the machine tool to a stable operating condition. The potential stabilizing spindle speeds displayed in the window **960** are calculated using Equation (9) discussed earlier. Using a mouse or touch-screen capability, the user may select one of the spindle speeds listed in the window **960**, then click on an Accept button **970** to control the machine tool to change the spindle speed to the selected value. A Stop Program button **980** is provided to allow the user to stop the machine tool from running the machining operation program.

[0116] In some embodiments, an option may be included for the user to select the type of input signal for servo motors, where the options include servo motor torque data and pulse coder position/velocity data. These input data options, and the considerations around filtering and analyzing the frequency-domain response, were discussed earlier. The selection of the type of input data for servo motors could conveniently be included in the table which is accessed by the Motor Settings button **930**, for example. Other input data-such as the number of lines on motor shaft encoders-could be defined by the user by clicking on the Motor Settings button **930**, or elsewhere on the graphical user interface **900** as found suitable.

[0117] The graphical user interface **900** provides convenient chatter detection visualization and control features for a machine tool, while the data filtering and analysis techniques described above provide sensorless chatter detection with greater accuracy and sensitivity than previously-existing chatter detection methods.

[0118] The techniques described above-including the chatter detection methods using spindle motor and optionally servo motor data with a plurality of frequency-domain filtering steps, along with the graphical user interface for real-time monitoring and control to avoid chatter-provide powerful capabilities for detecting and eliminating chatter in machining operations. These capabilities can be further employed to minimize forced vibrations even in finishing machining operations where the depth of cut is small. By avoiding frequencies at which a particular machine tool is predisposed to exhibit excessive vibrations, the surface finish quality of the workpiece correspondingly improves.

[0119] A typical machining operation carried out by a machine tool includes a rough shaping operation followed by a finishing operation. In the rough shaping operation, where the surface finish quality is not important, a larger depth of cut can be used. The rough shaping operation machines the workpiece from its raw shape to a near-final shape. In the finishing operation, where surface finish quality is important, one or more passes are made with a smaller depth of cut.

[0120] The rough shaping operation, due to its high tool tooth forces, is much more likely to induce chatter than is the finishing operation. However, the information gained from the rough finishing operation—specifically the frequency response of the machine tool, particularly including a predominant chatter frequency—can be used to improve surface finish quality during finishing operations by avoiding the predominant chatter frequency which is near the machine tool's dominant natural frequency.

[0121] FIG. **10** is a graph **1000** of a measured frequency response function for a machine tool, according to an embodiment of the present disclosure. The graph **1000** plots a normalized ratio of the output amplitude to the input amplitude on a vertical axis **1010** against frequency on a horizontal axis **1020**. The graph **1000** includes a frequency response plot for one of the principal direction axes (i.e., Y axis) of the machine tool, measured at the cutting bit (e.g., end mill). A large spike **1030** in the frequency response function plot indicates a natural frequency of vibration at about 900 Hz.

[0122] The frequency response function plotted on the graph **1000** provides important information about the machine tool on which it was measured. Unfortunately, obtaining the natural frequency of vibration information as depicted on the graph **1000** requires an experimental setup which can be laborious, expensive and time-consuming; this includes fitting the machine tool with one or more motion sensors such as accelerometers, and running tests with a specialized impact device, a data acquisition system and computer. Fortunately, the natural frequency of the machine tool as depicted on the graph **1000** can also be estimated, without performing frequency response function testing, by using the sensorless chatter detection techniques disclosed above.

[0123] The methods of FIG. **3** (spindle data only) and FIG. **8** (both spindle and servo motor data) describe techniques for detecting chatter in a machine tool by filtering and analyzing frequency-domain torque or pulse coder data from the motors. FIGS. **6A**, **7** and **9** all show a distinct spike in a frequency response graph which indicates chatter at a particular frequency. The chatter frequency detected in these filtered frequency response results can be used, in lieu of frequency response function testing, to determine a natural frequency of vibration to be avoided for the particular machine tool. When the disclosed sensorless chatter detection techniques were employed in a rough shaping machining operation on the same machine tool as embodied in the FIG. **10** results, the disclosed sensorless chatter detection techniques identified chatter at a frequency of around 900 Hz—the same result as the frequency response function testing.

[0124] As mentioned earlier, for finishing operations, the small depth of cut does not tend to excite significant chatter in the machine tool. However, finishing operations can still benefit from chatter detection technology, particularly because any excessive vibration in a finishing operation can ruin a workpiece. Therefore, it is desirable to know the predominant natural frequency of vibration for a particular machine tool, and ensure that the cutting frequency during finishing operations does not come near the machine's natural frequency.

[0125] The manufacturers of cutting bits (e.g., end mills) know that workpiece surface finish quality will suffer if the cutting bit is damaged. The manufacturers therefore tend to recommend a combination of spindle speed and feed speed which keeps the cutting tool in a healthy state. However, these recommendations do not take into account the actual natural frequencies of a particular machine tool. Thus, the recommended cutting speeds may not realize the optimal surface quality or productivity, and most operations would require further fine-tuning.

[0126] Table I contains setup parameters for five machining operation tests performed to determine the correlation between cutting frequency and vibration amplitude for finishing operations using the same machine tool as embodied in the FIG. **10** results.

TABLE-US-00001	TABLE I	Cutting Freq. + $\Omega$ F	Harmonics Test #	[rev/min.]	[mm/flute/rev]	[Hz]
1	9231	0.082	615, 1231, 1846, . . .	2	10000	0.082
3	11000	0.082	733, 1467, 2200, . . .	4	12000	0.082
5	13500	0.082	900, 1800, 2700, . . .			

[0127] All of the tests shown in Table I were run at the same feed per flute ( $F=0.082$  mm/flute/rev) and the same depth of cut and width of cut, where the depth of cut was 15.0 mm and the width of cut was 1.0 mm in all tests. The spindle speed  $\Omega$  was varied from a manufacturer-recommended speed of 9231 rpm to a speed of 13500 rpm over the five tests. Regarding the feed speed  $F$ , it can be deduced that for a constant feed speed  $F$  expressed in mm/flute/rev, a higher spindle speed  $\Omega$  results in a higher linear velocity of the tool in mm/sec. In other words, a higher spindle speed  $\Omega$  allows a machining operation to be performed faster while maintaining a constant feed speed  $F$ .

[0128] The right-hand column of Table I shows the cutting frequency in Hertz, which is the number of flute impacts on the workpiece per second (discussed earlier in connection with the Nyquist zone computations), along with harmonics of the cutting frequency. For the machine tool on which the Table I tests were run, the disclosed sensorless chatter detection techniques identified chatter at a frequency of around 900 Hz—the same result as the frequency response function testing shown in FIG. 10. Because the machine tool is a structure with little inherent damping, the natural frequency spike in the frequency response function is fairly sharp, and the frequency band to be avoided can be defined to be fairly narrow. One example dictates that for the 900 Hz natural frequency of the machine tool, cutting frequencies in a range from 800 Hz to 1000 Hz should be avoided.

[0129] Returning to Table I, the spindle speed (9231 rpm) and feed speed recommended by the cutting tool manufacturer, used for Test #1, result in a cutting frequency of 615 Hz, which is well below the range to be avoided (800-1000 Hz). The remaining tests increased the spindle speed in increments up to 13500 rpm, which equates to a cutting frequency of 900 Hz.

[0130] FIG. 11 is a set of graphs plotting acceleration versus time for three of the tests contained in Table I, according to embodiments of the present disclosure. A graph 1110 plots acceleration vs time for Test #1 of Table I, a graph 1130 plots acceleration vs time for Test #3 of Table I, and a graph 1150 plots acceleration vs time for Test #5 of Table I. All three of the graphs 1110, 1130 and 1150 plot the acceleration on a common vertical axis scale versus time on a common horizontal axis scale.

[0131] The graph 1110 depicts results from Test #1 with  $\Omega=9231$  rpm and a cutting frequency of 615 Hz, which is well below the natural frequency of vibration (900 Hz) of the machine tool. The graph 1130 depicts results from Test #3 with  $\Omega=11000$  rpm and a cutting frequency of 733 Hz, which is still below the natural frequency of vibration (900 Hz) and below the frequency band to be avoided (800-1000 Hz) of the machine tool. However, the graph 1150 depicts results from Test #5 with  $\Omega=13500$  rpm and a cutting frequency of 900 Hz, which is equal to the natural frequency of vibration (900 Hz) of the machine tool. It can be seen that the vibration amplitude for the graph 1150 (Test #5) is significantly greater than for the other two graphs 1110 and 1130. The vibration amplitude (shown on the graphs of FIG. 11) correlates to surface finish quality, where greater vibration amplitude leads to lower surface finish quality. Thus, even though Test #5 does not exhibit chatter vibrations, it will produce poorer workpiece surface finish quality as a result of having the cutting frequency nearing the natural frequency of the machine tool.

[0132] It can also be seen on FIG. 11 that the elapsed time of each machining operation is different—where Test #1 runs for about 3.0 seconds, Test #3 runs for about 2.6 seconds, and Test #5 runs for about 2.2 seconds. This is because a higher spindle speed equates to a higher rate of linear travel of the cutting bit, as discussed above. Because machine throughput is always a concern for part manufacturers, it is desirable to run machining operations at a spindle speed and feed speed which are as high as possible (to maximize throughput) while keeping the cutting frequency out of the machine's natural frequency avoidance band. Therefore, it is preferable to run machining operations in the conditions of Test #3, which has a vibration amplitude no higher than Test #1, but a significantly shorter machining operation time duration.

[0133] The preceding discussion highlights the importance of avoiding a machine tool's natural frequency of vibration, even for light machining operations such as finishing where chatter is unlikely. Thus, after identifying a chatter frequency using the sensorless chatter detection techniques of the present disclosure, subsequent machining operations can be performed using machine speeds which avoid a frequency band defined as the chatter frequency plus or minus a certain amount (such as  $\pm 100$  Hz). This enables finishing operations to be carried out with the greatest spindle speed and feed speed (thus maximizing throughput) while staying away from the machine's natural frequency (thus maximizing surface finish quality).

[0134] The graphical user interface 900 of FIG. 9 could readily be enhanced to include features which guide the user to avoid cutting frequencies in the natural frequency band of the machine tool. For example, a machine settings button could be added which enable the user to define a spindle speed and a feed speed. Then, after a machining operation is performed where chatter is detected (as in FIG. 9 at the chatter frequency of 975 Hz), the graphical user interface 900 could recommend a spindle speed which is as high as possible while maintaining the cutting frequency outside the band (e.g.,  $\pm 100$  Hz) surrounding the now-known chatter frequency of the machine tool. Other implementations may be envisioned by those skilled in the art—including a behind-the-scenes feature which pops up a warning if a spindle speed and feed speed are input which cause the cutting frequency to fall in the machine's natural frequency band.

[0135] The sensorless chatter detection techniques discussed above have been proven to be highly effective in many machining environments. Their advantages include ease of implementation and the need for no sensors or other hardware to be added to a machining operation setup. However, there are some situations where sensorless chatter detection techniques may be less effective. This could be a result of a noisy spindle motor torque signal, or other reasons. For this reason, an integrated sensorless and sensor-based chatter detection technique has been developed which provides the advantages of each different chatter detection methodology. This integrated chatter detection technique is discussed below.

[0136] FIG. 12 is a schematic illustration of a system 1200 comprised of a machine tool system of the type depicted in FIG. 2, with data collection equipment for sensor-based chatter detection, according to an embodiment of the present disclosure. A machine tool 1210, a cutting tool 1220, a workpiece 1230 and a controller 1240 of FIG. 2 all correspond with similarly-numbered elements shown in FIG. 2. As discussed earlier, a spindle torque signal can be evaluated by the controller 1240 to perform sensorless chatter detection in the machine tool 1210. In addition, the system 1200 includes a microphone 1250, and an optional computing device 1260 separate from the controller 1240. An accelerometer 1270 may also be provided.

[0137] The basic premise of the presently disclosed integrated chatter detection technique is that the frequencies present in audio data collected during a machining operation can be used as an indicator of the likely presence of a chatter condition, and the audio (sensor-based) chatter indicator can be combined with a sensorless chatter indicator determined as discussed earlier. An overall determination of a chatter condition can be made based on both the sensorless and sensor-based chatter detection indicators. The details of the technique are discussed below.

[0138] The microphone 1250 is any suitable audio data collection device capable of collecting and providing audio signal data to a processor such as the computing device 1260. In fact, both the microphone 1250 and the computing device 1260 may be embodied in a mobile device such as a smartphone running an application for collecting and processing the audio signal data as discussed below. In other

embodiments, the audio signal data is provided to the computing device **1260**, which may be a desktop or laptop computer or any other type of computer, and the computing device **1260** processes the audio signal data as discussed below. In still other embodiments, the audio signal data is provided directly to the controller **1240**, and all processing steps are programmed into an algorithm which runs on the controller **1240**. The accelerometer **1270**, if used, is mounted to the machine tool and provides vibration data (accelerations in one or more directions) to the controller **1240** or the computing device **1260**. The data may be provided by a wired or wireless connection between the accelerometer **1270** and the controller **1240** or the computing device **1260**; the connection means are not depicted in order to minimize drawing clutter.

[0139] FIG. **13** is a flowchart diagram **1300** of a method for integrated sensorless and sensor-based chatter detection in a machine tool, including separate processing and analysis of sensorless and sensor-based data to evaluate a chatter indicator for each, according to an embodiment of the present disclosure. The steps of the flowchart diagram **1300** which related to time-domain data are contained in a box **1302**, and the steps which related to frequency-domain data are contained in a box **1304**. The sensorless chatter detection steps are arranged on an upper path/branch of the flowchart diagram **1300**, while the sensor-based chatter detection steps are arranged on a lower path.

[0140] At box **1310**, a time-series data sample is collected for the machine tool spindle motor and/or a machine tool positioning servo motor, in the manner discussed earlier. This data is generically labeled motor signal data. The data collected at the box **1310** is parameter data known to the machine tool controller and thus is “sensorless”—i.e., does not require any sensors for measurement. The data collected at the box **1310** could include one or more of spindle torque command data (directly, or via motor current), servo motor torque data or servo motor pulse coder data (that is, servo motor shaft position sensor data, which could be provided as velocity directly, or position differentiable to velocity). All of these types of sensorless data collection were discussed earlier.

[0141] The time-series data sample from the box **1310** is converted to the frequency domain, such as by performing an FFT. At box **1320**, the motor signal frequency response data is analyzed in the manner also described earlier. That is, depending on the type of data (spindle vs. servo), one or more filtering steps may be performed to remove noise and other false peaks and improve the condition of the frequency response data. For example, spindle torque frequency response data may have an air cut frequency response subtracted, and may have spindle harmonics filtered out, as discussed above with respect to FIG. **3**. Spindle torque data may be further filtered to include removal of aliasing artifacts and removal of encoder interpolation errors, as also discussed above. One or more filtering steps may be performed on servo motor frequency response data, including filtering out spindle harmonics, removal of aliasing artifacts and removal of encoder interpolation errors.

[0142] Still at the box **1320**—following the filtering steps discussed above—one or more criteria are evaluated to detect chatter in the motor signal frequency response data. For spindle motor torque data, the criteria include the magnitude of the filtered spindle torque command frequency response data and/or the magnitude ratio of the filtered spindle torque command data to the air-cut torque command data. For servo motor torque or velocity, the criteria include the magnitude of the filtered servo motor torque or velocity frequency response data.

[0143] At decision diamond **1330**, it is determined whether chatter is detected in the sensorless motor signal data. This determination is based on the criteria discussed above with respect to the box **1320**. For example, if the magnitude of the filtered frequency response data for the parameter being evaluated (e.g., spindle motor torque, or servo velocity) is above a threshold value at a particular frequency, then it is determined that chatter is occurring at that frequency. It is to be understood that any of the types of motor signal data (spindle and/or servo(s)) and any of the criteria may be used in various embodiments of the sensorless chatter detection steps discussed above.

[0144] From the decision diamond **1330**, if no chatter is detected in the sensorless data, then the process loops back to the box **1310** to collect another time-series data sample. Different types of motor signal data could be collected from one loop to the next—such as spindle motor torque data in one pass, and X-axis servo motor velocity data in the next pass, etc. Time delays may or may not be added between loops, and the loop through the sensorless steps **1310-1330** may be synchronized with a loop through sensor-based steps **1340-1360** discussed below. If chatter is detected in the sensorless data at the decision diamond **1330**, the process moves to decision diamond **1370** for further evaluation.

[0145] In the lower branch of the flowchart diagram **1300**, at box **1340**, a time-series data sample of sound data is collected from the machining operation. In preferred embodiments, the data collected at the box **1340** is sound data from the microphone **1250**, and the sensor-based data will be described as sound data throughout the following discussion. However, the sensor-based data could be vibration data from one or more accelerometers, as discussed earlier.

[0146] The time-series data sample from the box **1340** is converted to the frequency domain, such as by performing an FFT. At box **1350**, the sensor-based (e.g., sound) frequency response data is analyzed to detect chatter. First, one or more filtering steps may be performed to remove noise and other false peaks and improve the condition of the frequency response data. For example, sound-based frequency response data may have an ambient noise frequency response subtracted, where the ambient noise is recorded in a time-series sample just before recording the sound data for the machining operation at the box **1340**. The ambient noise frequency response data might include a peak at a cutting frequency from a machining operation at a nearby machine tool for example, and it may be beneficial to filter out such significant peaks in ambient noise from the sensor-based sound frequency response data. This optional filtering out of ambient noise frequency response peaks would be performed in the same manner as the spectral subtraction used for filtering out air cut peaks from the spindle torque frequency response data, as discussed earlier. Other filtering steps may be performed on the sound-based frequency response data as deemed suitable.

[0147] Still at the box **1350**—following the filtering steps discussed above—one or more criteria are evaluated to detect chatter in the sensor-based (e.g., sound) frequency response data. For example, the sensor-based chatter detection criteria could include the magnitude of the filtered frequency response data at any frequency being above a prescribed threshold. A second, higher threshold may also be defined and used in chatter detection criteria, as discussed further below.

[0148] At decision diamond **1360**, the process branches one way or another depending on whether chatter is detected in the sensor-based (sound) data. This determination is based on the criteria discussed above with respect to the box **1350**. For example, if the magnitude of the filtered frequency response data for the sound is above a threshold value at a particular frequency, then it is determined at the decision diamond **1360** that chatter is occurring at that frequency.

[0149] From the decision diamond **1360**, if no chatter is detected in the sensor-based data, then the process loops back to the box **1340** to collect another time-series data sample. Time delays may or may not be added between loops, and the loop through the sensor-based steps **1340-1360** may be synchronized with a loop through the sensorless steps **1310-1330** discussed above. If chatter is detected in the sensor-based data at the decision diamond **1360**, as determined by the magnitude of the filtered frequency response data at any frequency being above the prescribed threshold, then the process moves on to the right for further evaluation.

[0150] At a decision diamond **1362**, it is determined whether a strong indication of chatter is detected in the sensor-based frequency response. This is done by comparing the magnitude of the filtered frequency response data at all frequencies to a different threshold value. The threshold used at the decision diamond **1362** is greater (higher magnitude) than the threshold used at the decision diamond **1360**. If the magnitude of the filtered frequency response data for the sensor-based (sound) data is above the high threshold value at any frequency, then it is determined that chatter is occurring at that frequency, and from the decision diamond **1362** the process moves to a box **1380** where action is taken to address the chatter situation. The idea behind the high-threshold detection step at the decision diamond **1362** is that the sensor-based chatter detection may be more sensitive to chatter conditions in some applications (such as light machining) and, therefore, if a strong chatter indication is detected in the sensor-based data, this can be used to directly trigger a chatter notification to the machine operator. If it is not desired to use the second, high-threshold test for chatter in the sensor-based data, the threshold at the decision diamond **1362** can simply be set to a value higher than any expected frequency response magnitude; this has the effect of skipping the decision diamond **1362** and moving directly to the decision diamond **1370**.

[0151] If the magnitude of the filtered frequency response data for the sensor-based (sound) data is below the high threshold value at all frequencies, then from the decision diamond **1362** the process proceeds upward to the decision diamond **1370**. Thus, the decision diamond **1370** may be reached by either chatter being detected in the sensorless data (yes at the decision diamond **1330**) or chatter being detected in the sensor-based data (yes at the decision diamond **1360** and no at the decision diamond **1362**), or from both the sensorless and the sensor-based branches of the flowchart.

[0152] At the decision diamond **1370**, it is determined whether both the sensorless signal analysis at the box **1320** and the sensor-based signal analysis at the box **1350** have detected chatter at a common frequency (within a prescribed tolerance band, such as the frequencies matching within 2%). If so, then it is determined that chatter is occurring at the common detected frequency, and at the box **1380** an action is taken and/or a notification is issued to draw attention to the chatter situation. The notification could be any combination of a display on an operator console, an audible or visual alarm at the machine tool station, a notification to a mobile device of an operator and/or a plant manager, etc., as would be understood by those skilled in the art. When a notification of chatter is issued at the box **1380**, the machine tool operator takes steps to address and alleviate the chatter condition; the steps could include changing the spindle speed and/or the feed speed, or some other steps, including simply stopping the machining operation in order to prevent damage to the machine tool or the workpiece. The aforementioned steps may also be taken by the controller itself, without any required action by an operator.

[0153] At the decision diamond **1370**, if there is not an indication of chatter at a common frequency from both the sensorless and sensor-based branches, then the process returns to the boxes **1310** and **1340** to record a next set of time-series data samples. One scenario is where only one branch (either sensorless or sensor-based) detects chatter, and the other branch does not; this would result in no common chatter detection at the decision diamond **1370**. Another scenario is where both sensorless and sensor-based branches detect chatter, but not at a common frequency; this would also result in no common chatter detection at the decision diamond **1370**.

[0154] As described above, a strong chatter indication at the decision diamond **1362** can be used to trigger an action or a notification to address the chatter condition at the box **1380**, even if no chatter is detected in the sensorless data.

[0155] FIG. **14** includes frequency response graphs of sound data from a machining system before cutting begins and during cutting operations, illustrating the effects of external noise in the sensor-based analysis portion of FIG. **13**, according to embodiments of the present disclosure.

[0156] A graph **1410** plots the frequency response from a sound sample collected at a machine tool before the cutting operation begins. The sound sample time-series data is converted to the frequency domain via FFT in order to produce the data plotted on the graph **1410**. The graph **1410** contains a peak **1420** in the frequency response. The peak **1420** is the only significant spike in the frequency response data from before cutting begins, and occurs at a frequency of about 1660 Hz. The peak **1420** is the frequency signature of external or ambient noise in the machine tool environment, such as a cutting frequency from a nearby machine tool. The frequency response data from the graph **1410**, from sound data collected before cutting begins, may be used in a filtering step as discussed above.

[0157] A graph **1450** plots the frequency response from a sound sample collected at the machine tool during the cutting operation. The sound sample time-series data is converted to the frequency domain via FFT in order to produce the data plotted on the graph **1450**. The graph **1450** contains a peak **1460** and a peak **1470** in the frequency response, along with other smaller responses. The peak **1470** occurs at the frequency of 1660 Hz which was observed in the ambient noise frequency response data on the graph **1410**. Thus, the peak **1470** corresponds with the peak **1420**, and does not indicate chatter occurring on the machine tool. The peak **1470** has a different magnitude than the peak **1420** because of the effects of overall sound amplitude (in the presence of a louder chatter sound) and the resultant FFT conversion to frequency response. The peak **1460** is the dominant frequency response signature on the graph **1450** and is known to indicate a chatter condition, as it was observed that chatter was occurring on the machine tool in the experiment which produced this data. The graph **1450** is a visual depiction of the analysis which is performed at the box **1350** of FIG. **3**. If the frequency response threshold for sound amplitude data is set at 0.02, for example, then the logic at the decision diamond **1360** would result in a yes; that is, the sensor-based data analysis reveals that chatter is occurring at 945 Hz.

[0158] Filtering out the ambient noise frequency response data (i.e., spectral subtraction of the peak **1420**) may or may not be necessary, for two reasons. First, the peak in the ambient noise frequency response data (from other machine tools) may be dwarfed by any chatter-related sound from the machine tool being evaluated, and the peak in the ambient noise data may therefore fall below the selected threshold; this effect is visible in the graph **1450** on FIG. **14**. Second, the peak in the ambient noise (sensor-based) frequency response data is not likely to coincide with any non-chatter (e.g., false) peaks in the motor signal (sensorless) frequency response data; thus, absent a matching frequency condition, the integrated chatter detection method would not result in a chatter avoidance action or notification at the box **1380** anyway.

[0159] FIG. **15** includes frequency response graphs of spindle torque command data and sound data from a machining operation, illustrating how a common frequency spike in both frequency responses is identified as real chatter, according to embodiments of the present disclosure.

[0160] A graph **1510** plots the frequency response from a spindle torque command data sample collected sensorlessly from a machine tool during cutting operations. The motor data is converted from time-series data to the frequency domain via FFT and then filtered in order to produce the data plotted on the graph **1510**, as discussed earlier. For example, in the case of spindle motor torque command data, two to four filtering steps are preferably performed. The graph **1510** contains a prominent peak **1520** in the frequency response, another smaller peak **1530** at a different frequency, and several other still smaller peaks at other frequencies. The peak **1520** occurs at a frequency of 945 Hz; based on this frequency's correspondence to a peak in the sensor-based data, the peak **1520** is determined to be caused by a chatter condition. The peak **1530** occurs at a frequency of about 2000 Hz; based on this frequency's lack of correspondence to a peak in the

sensor-based data, the peak **1530** is determined to be caused by noise. Noise in the sensorless frequency response data could come from any of the sources discussed earlier (harmonics, aliasing, etc.), or could simply be random noise, as witnessed by the numerous other small peaks in the frequency response data on the graph **1510**. If the frequency response threshold for motor data is set at 0.001 for example ( $1 \times 10^{-3}$  as shown on the graph Y-axis), then the logic at the decision diamond **1330** would result in a determination from the sensorless data analysis that chatter is occurring at 945 Hz and also at about 2000 Hz. If the frequency response threshold for motor data is set at 0.0015 or 0.002, then the logic at the decision diamond **1330** would result in a determination from the sensorless data analysis that chatter is occurring only at 945 Hz.

[0161] A graph **1550** plots the frequency response from a sound sample collected at the machine tool during the same cutting operation as the data from the graph **1510**. The graph **1550** is the same as the graph **1450** of FIG. **14**. That is, a significant peak **1560** occurs at a frequency of 945 Hz, and a much smaller peak **1570** occurs at a frequency of about 1660 Hz. As discussed above with respect to FIG. **14**, the peak **1560** in the sound data is caused by chatter on the machine tool, while the peak **1570** in the sound data is caused by ambient noise from a nearby machine tool. If the frequency response threshold for sound amplitude data is set at 0.02, for example, then the logic at the decision diamond **1360** would result in a determination from the sensor-based data analysis that chatter is occurring at 945 Hz.

[0162] A visual comparison of the graphs **1510** and **1550** reveals what would be determined at the decision diamond **1370** of FIG. **3**. That is—both the decision diamond **1330** (i.e., the graph **1510**) and the decision diamond **1360** (i.e., the graph **1550**) indicate chatter is occurring on the machine tool, and the most prominent peak in the frequency response data from both sensorless and sensor-based methods is at the same frequency of 945 Hz. Thus, according to the logic described earlier (common frequency identified in sensorless and sensor-based data analysis), the overall determination at the decision diamond **1370** is that chatter is occurring.

[0163] The graphs **1510** and **1550** also reveal an advantageous characteristic of the integrated chatter detection techniques of the present disclosure. That is, it is not necessary to filter out all noise spikes in the sensorless and sensor-based frequency response data, and it is not necessary to select exactly the right thresholds for identifying peaks in the frequency response data. Even if noise-driven peaks in the frequency response data are identified as “chatter” in the sensorless and sensor-based branches of the FIG. **13** flowchart, only a true chatter condition and frequency will be identified when the sensorless and sensor-based frequency response results are compared to each other at the decision diamond **1370**. This is the strength of the integrated chatter detection method.

[0164] The labels “chatter” and “noise” on the graphs of FIG. **15** are provided merely for the sake of explanation. It is emphasized that the determination of what is chatter and what is noise is made automatically using the separate sensorless and sensor-based data analysis and criteria followed by the comparison of the sensorless and sensor-based results, according to the integrated chatter detection technique of the present disclosure.

[0165] In another embodiment of integrated chatter detection method, instead of making a separate chatter detection determination for the sensorless and sensor-based data and then identifying chatter only when both techniques indicate chatter at a common frequency, the sensorless and sensor-based data could be combined and used in a single chatter detection determination. One way the sensorless and sensor-based data could be combined would be to normalize the frequency response data for sensorless and sensor-based data, combine the normalized frequency responses, and evaluate the combined frequency response data. This approach would naturally amplify the response at any frequency where there is a peak in both the sensorless and sensor-based frequency response data.

[0166] Other embodiments of integrated sensorless and sensor-based chatter detection are also envisioned. In one alternative embodiment, an accelerometer is used instead of a microphone in the system of FIG. **12**. An accelerometer typically requires a more complicated installation procedure than a microphone, but the accelerometer offers the advantage of only detecting vibrations happening on the particular machine tool on which it is installed—whereas a microphone can pick up audio data from the surrounding environment, such as a neighboring machine tool. Thus, in some applications, it may be advantageous to use vibration data from an accelerometer for the sensor-based chatter detection, integrated with the sensorless chatter detection in the manner described.

[0167] Throughout the preceding discussion, various computers and controllers are described and implied. It is to be understood that the software applications and modules of these computers and controllers are executed on one or more electronic computing devices having a processor and a memory module. In particular, this includes the machine controller **240** of FIG. **2** and the machine controller **1240** of FIG. **12** which were discussed earlier, along with the computing device **1260** which may optionally be used for processing sound data from the microphone. Specifically, the processor in the controller **1240** and the optional computing device **1260** are configured to perform the integrated sensorless and sensor-based machine tool chatter detection described above, including the method steps of FIG. **13**, and the calculations using the disclosed equations, the control of the machine tool itself and the user interaction via the graphical user interface discussed earlier.

[0168] While a number of exemplary aspects and embodiments of the method for integrated sensorless and sensor-based machine tool chatter detection have been discussed above, those of skill in the art will recognize modifications, permutations, additions and sub-combinations thereof. It is therefore intended that the following appended claims and claims hereafter introduced are interpreted to include all such modifications, permutations, additions and sub-combinations as are within their true spirit and scope.

## Claims

1. A method for machine tool chatter detection, said method comprising: storing, in a controller of a machine tool, a sensorless data sample and a sensor-based data sample collected while the machine tool is performing a cutting operation on a workpiece, where the sensorless data sample is motor parameter data known to the controller for controlling the cutting operation, and the sensor-based data sample is provided by a sensor attached to or proximal the machine tool; converting the sensorless data sample and the sensor-based data sample from time-series data to a frequency domain to create a sensorless frequency response and a sensor-based frequency response, respectively; identifying any frequency in the sensorless frequency response which has a response magnitude greater than a first threshold; identifying any frequency in the sensor-based frequency response which has a response magnitude greater than a second threshold; determining, by the controller, that a chatter condition exists when any frequency identified in the sensorless frequency response matches any frequency identified in the sensor-based frequency response within a predefined frequency tolerance; and taking an action to address the chatter condition when it is determined that the chatter condition exists.
2. The method according to claim 1 wherein the sensorless data sample includes spindle motor torque command data, or torque command data, position data or velocity data from a positioning servo motor of the machine tool.
3. The method according to claim 2 further comprising filtering the sensorless frequency response after it is created.
4. The method according to claim 3 wherein, when the sensorless data sample includes spindle motor torque command data, filtering the

- sensorless frequency response includes spectrally subtracting a multiple of an air-cut frequency response from the sensorless frequency response, and downscaling the sensorless frequency response at frequencies equal to integer multiples of spindle speed.
5. The method according to claim 4 wherein the air-cut frequency response is obtained by recording an air-cut data sample including the spindle motor torque command data when a spindle is turning but before the cutting operation begins, and converting the air-cut data sample to the frequency domain.
6. The method according to claim 4 wherein filtering the sensorless frequency response further includes applying a filter to remove aliasing effects in the spindle motor torque command data, and applying a filter to remove encoder interpolation error effects in the spindle motor torque command data.
7. The method according to claim 3 wherein, when the sensorless data sample includes torque command data, position data or velocity data from a positioning servo motor, filtering the sensorless frequency response includes applying a filter to remove spindle harmonics, applying a filter to remove aliasing effects, and applying a filter to remove encoder interpolation error effects.
8. The method according to claim 1 wherein the sensor-based data sample includes sound data collected by a microphone proximal the machine tool, or vibration data collected by an accelerometer mounted on the machine tool.
9. The method according to claim 8 further comprising, when the sensor-based data sample includes sound data, filtering the sensor-based frequency response after it is created, including spectrally subtracting an ambient noise frequency response.
10. The method according to claim 1 further comprising determining, by the controller, that a chatter condition exists when any frequency in the sensor-based frequency response has a response magnitude greater than a third threshold, where the third threshold is greater than the second threshold.
11. The method according to claim 1 wherein converting the sensorless data sample and the sensor-based data sample from time-series data to a frequency domain includes using a Fast Fourier Transform (FFT).
12. The method according to claim 1 wherein the sensorless data sample and the sensor-based data sample are collected during a same or overlapping time period.
13. The method according to claim 1 wherein taking an action to address the chatter condition includes one or more of; sending a notification to an operator, raising an audible or visual alarm, and changing operating conditions of the cutting operation, where the operating conditions include a spindle speed and/or a feed speed.
14. A method for machine tool chatter detection, said method comprising: storing, in a controller of a machine tool, a sensorless data sample and a sensor-based data sample collected while the machine tool is performing a cutting operation on a workpiece, where the sensorless data sample is spindle motor torque data known to the controller for controlling the cutting operation, and the sensor-based data sample is sound data provided by a microphone placed proximal the machine tool, and where the sensorless data sample and the sensor-based data sample are collected during a same or overlapping time period; converting the sensorless data sample and the sensor-based data sample from time-series data to a frequency domain to create a sensorless frequency response and a sensor-based frequency response, respectively; filtering the sensorless frequency response, including spectrally subtracting a multiple of an air-cut frequency response from the sensorless frequency response, and downscaling the sensorless frequency response at frequencies equal to integer multiples of spindle speed; filtering the sensor-based frequency response, including spectrally subtracting an ambient noise frequency response from the sensor-based frequency response; identifying any frequency in the sensorless frequency response which has a response magnitude greater than a first threshold; identifying any frequency in the sensor-based frequency response which has a response magnitude greater than a second threshold; determining, by the controller, that a chatter condition exists when any frequency in the sensor-based frequency response has a response magnitude greater than a third threshold, where the third threshold is greater than the second threshold; determining, by the controller, that a chatter condition exists when any frequency identified in the sensorless frequency response matches any frequency identified in the sensor-based frequency response within a predefined frequency tolerance; and taking an action to address the chatter condition when it is determined that the chatter condition exists, where the action includes changing operating conditions of the cutting operation, and where the operating conditions include a spindle speed and/or a feed speed.
15. A machine tool chatter detection system, said system comprising: a machine tool configured for performing a cutting operation on a workpiece; a sensor attached to or proximal the machine tool; and a controller in communication with the machine tool and the sensor, said controller being configured to detect chatter by performing steps including; storing a sensorless data sample and a sensor-based data sample collected while the machine tool is performing the cutting operation, where the sensorless data sample is motor parameter data known to the controller for controlling the cutting operation, and the sensor-based data sample is provided by the sensor; converting the sensorless data sample and the sensor-based data sample from time-series data to a frequency domain to create a sensorless frequency response and a sensor-based frequency response, respectively; filtering the sensorless frequency response; identifying any frequency in the sensorless frequency response which has a response magnitude greater than a first threshold; identifying any frequency in the sensor-based frequency response which has a response magnitude greater than a second threshold; determining that a chatter condition exists when any frequency identified in the sensorless frequency response matches any frequency identified in the sensor-based frequency response within a predefined frequency tolerance; and taking an action to address the chatter condition when it is determined that the chatter condition exists.
16. The system according to claim 15 wherein the sensorless data sample includes spindle motor torque command data, or torque command data, position data or velocity data from a positioning servo motor of the machine tool.
17. The system according to claim 16 wherein, when the sensorless data sample includes spindle motor torque command data, filtering the sensorless frequency response includes spectrally subtracting a multiple of an air-cut frequency response from the sensorless frequency response, and downscaling the sensorless frequency response at frequencies equal to integer multiples of spindle speed, where the air-cut frequency response is obtained by recording an air-cut data sample including the spindle motor torque command data when a spindle is turning but before the cutting operation begins, and converting the air-cut data sample to the frequency domain.
18. The system according to claim 17 wherein filtering the sensorless frequency response further includes applying a filter to remove aliasing effects in the spindle motor torque command data, and applying a filter to remove encoder interpolation error effects in the spindle motor torque command data.
19. The system according to claim 16 wherein, when the sensorless data sample includes torque command data, position data or velocity data from a positioning servo motor, filtering the sensorless frequency response includes applying a filter to remove spindle harmonics, applying a filter to remove aliasing effects, and applying a filter to remove encoder interpolation error effects.
20. The system according to claim 15 wherein the sensor is a microphone placed proximal the machine tool and the sensor-based data sample includes sound data collected by the microphone, or the sensor is an accelerometer attached to the machine tool and the sensor-

based data sample includes vibration data collected by the accelerometer.

**21.** The system according to claim 20 wherein, when the sensor-based data sample includes sound data, the controller is further configured to filter the sensor-based frequency response after it is created, including spectrally subtracting an ambient noise frequency response.

**22.** The system according to claim 15 wherein the controller is further configured to determine that a chatter condition exists when any frequency in the sensor-based frequency response has a response magnitude greater than a third threshold, where the third threshold is greater than the second threshold.

**23.** The system according to claim 15 wherein the sensorless data sample and the sensor-based data sample are collected during a same or overlapping time period.

**24.** The system according to claim 15 wherein taking an action to address the chatter condition includes one or more of; sending a notification to an operator, raising an audible or visual alarm, and changing operating conditions of the cutting operation, where the operating conditions include a spindle speed and/or a feed speed.

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