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# (54) Title: SYSTEM AND METHOD FOR DETERMINING HEALTH INDICATORS FOR IMPELLERS

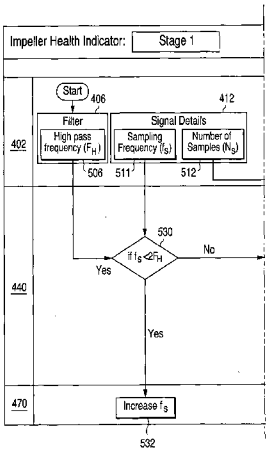


FIG. 5A

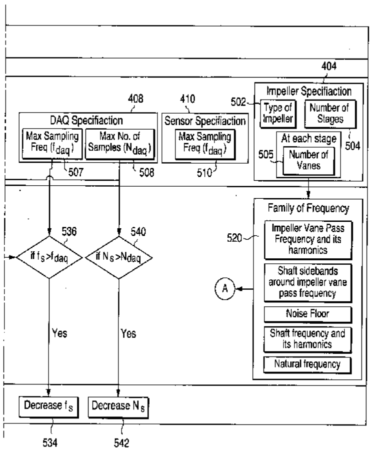
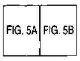


FIG. 5B



(57) **Abstract**: A system includes a plurality of sensors (422-424) configured to measure one or more characteristics of an impeller (100a-100h). The system also includes an impeller condition indicator device (400), which includes a plurality of sensor interfaces (420) configured to receive input signals associated with at least one stage of the impeller from the sensors. The impeller condition indicator device also includes a processor (440) configured to identify a fault in the impeller using the input signals and an output interface (470) configured to provide an indicator identifying the fault. The processor is configured to identify the fault by determining a family of frequencies (520) related to at least one failure mode of the impeller, decomposing the input signals using the family of frequencies, reconstructing a impeller signal using the decomposed input signals, and comparing the reconstructed impeller signal to a baseline signal (430). The family of frequencies includes a vane pass frequency and its harmonics.

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# SYSTEM AND METHOD FOR DETERMINING HEALTH INDICATORS FOR IMPELLERS

## TECHNICAL FIELD

**[0001]** This disclosure relates generally to impeller devices and, more specifically, to a system and method for determining health indicators for impellers.

## BACKGROUND

**[0002]** Impellers are routinely used in various industries. One type of impeller includes a rotor used to increase the pressure and flow of a fluid inside a cylinder, tube, or other conduit. Impellers are often used, for example, in the process control industry. However, impellers routinely suffer from various failures. Example failure modes of an impeller can include vane breakage, one or more cracks in the impeller, and wear in the impeller.

**[0003]** It is often necessary or desirable to monitor the health of an impeller in a process control system or other system in order to properly schedule maintenance for the impeller. However, it is often difficult to monitor the health of impellers because of the wide variety of impellers in use.

## SUMMARY

**[0004]** This disclosure provides a system and method for determining health indicators for impellers.

**[0005]** In a first embodiment, an apparatus includes an input interface configured to receive an input signal associated with at least one stage of an impeller. The apparatus also includes a processor configured to identify a fault in the impeller using the input signal. The apparatus further includes an output interface configured to provide an indicator identifying the fault. The processor is configured to identify the fault by determining a family of frequencies related to at least one failure mode of the impeller, decomposing the input signal using the family of frequencies, reconstructing an impeller signal using the decomposed input signal, and comparing the reconstructed impeller signal to a baseline signal. The family of frequencies includes a vane pass frequency and its harmonics.

**[0006]** In a second embodiment, a system includes a plurality of sensors configured to measure one or more characteristics of an impeller. The system also includes an impeller condition indicator device, which includes a plurality of sensor interfaces configured to receive input signals associated with at least one stage of the impeller from the sensors. The impeller condition indicator device also includes a processor configured to identify a fault in the impeller using the input signals and an output interface configured to provide an indicator identifying the fault. The processor is configured to identify the fault by determining a family of frequencies related to at least one failure mode of the impeller, decomposing the input signals using the family of frequencies, reconstructing an impeller signal using the decomposed input signals, and comparing the reconstructed impeller signal to a baseline signal. The family of frequencies includes a vane pass frequency and its harmonics.

**[0007]** In a third embodiment, a method includes receiving an input signal having vibration and/or speed information corresponding to at least one stage of an impeller. The method also includes determining a family of frequencies corresponding to at least one failure mode of the impeller, where the family of frequencies includes a vane pass frequency and its harmonics. The method further includes decomposing the input signal using the family of frequencies and reconstructing an impeller signal using the decomposed input signal. In addition, the method includes comparing the reconstructed impeller signal to a baseline signal and outputting an indicator identifying a fault when the reconstructed impeller signal differs from the baseline signal by a threshold amount.

**[0008]** Other technical features may be readily apparent to one skilled in the art from the following figures, descriptions, and claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0009]** For a more complete understanding of this disclosure, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

**[0010]** FIGURES 1A through 1G illustrates example impeller configurations;

**[0011]** FIGURES 2A and 2B illustrate example cavitation locations;

**[0012]** FIGURE 3 illustrates an example table for impeller failure mode rules according to this disclosure;

**[0013]** FIGURE 4 illustrates an example Impeller Condition Indicator (ICI) device according to this disclosure;

**[0014]** FIGURE 5 illustrates a more detailed view of an example ICI first stage operation for monitoring the health of an impeller according to this disclosure;

**[0015]** FIGURE 6 illustrates a more detailed view of an example ICI second stage operation for monitoring the health of an impeller according to this disclosure;

**[0016]** FIGURE 7 illustrates an example process for monitoring an impeller according to this disclosure; and

**[0017]** FIGURES 8 and 9 illustrate example impeller health indicators according to this disclosure.

## DETAILED DESCRIPTION

**[0018]** FIGURES 1 through 9, discussed below, and the various embodiments used to describe the principles of the present invention in this patent document are by way of illustration only and should not be construed in any way to limit the scope of the invention. Those skilled in the art will understand that the principles of the invention may be implemented in any type of suitably arranged device or system. Also, it will be understood that elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the dimensions of some elements in the figures may be exaggerated relative to other elements to help improve the understanding of various embodiments described in this patent document.

**[0019]** FIGURES 1A through 1G illustrates example impeller configurations. In FIGURES 1A through 1D, impellers 100a-100b include a rotor inside a cylinder, tube, or other conduit 105. The rotor is used to increase the pressure and flow of a fluid inside the conduit 105. The conduit 105 includes an open inlet 110 (often referred to as an "eye") that accepts incoming fluid. Vanes 115 push the fluid radially within the conduit 105. The vanes 115 can, for example, represent backward curved blades 115a, radial blades 115b, or forward inclined blades 115c. A splined, keyed, or threaded bore 120 accepts a driveshaft 125, which causes the vanes 115 to rotate. The impellers 100a-100b can be made of iron, steel, bronze, brass, aluminum, plastic, or other suitable material(s). The impeller 100a represents an axial flow impeller, and the impeller 100b represents a mixed flow impeller.

**[0020]** As shown in FIGURE 1E, an impeller 100c also can be used as the rotating component of a centrifugal pump 130. The impeller 100c transfers or converts rotating and/or kinetic energy from a motor that drives the pump 130 into potential energy of the pumped fluid by accelerating the fluid outwards from the center of rotation. The velocity achieved by the impeller 100c translates into pressure when a pump casing 135 confines the outward movement of the fluid.

**[0021]** FIGURES 1F and 1G illustrate additional types of impellers. In particular, FIGURE 1F illustrates an open impeller 100d, a semi-open impeller 100e, and a closed impeller 100f. FIGURE 1G illustrates a single suction impeller 100g and a double suction impeller 100h.

**[0022]** In addition to selecting a particular type of impeller, the design of the particular impeller can be varied to alter its performance characteristics. For example, an impeller with a large number of vanes or with vanes having large angles may have an increased "head" of the fluid. Also, an impeller with a low number of vanes or with large vane outlet angles may have poor vibration characteristics or heavy loads at the tips. Further, a larger clearance between an impeller and its casing may decrease vibration but result in an increase in size, weight, and cost.

**[0023]** One hydraulic phenomenon associated with the use of impellers is cavitation, which is illustrated in FIGURES 2A and 2B. Cavitation is a phenomenon where vapor bubbles form in a flowing liquid in or around a region where the pressure of the liquid falls below its vapor pressure. FIGURE 2A illustrates cavitation located at the discharge of an impeller, while FIGURE 2B illustrates cavitation located at the suction of an impeller.

**[0024]** Cavitation can be divided into two classes of behavior, namely inertial (or transient) cavitation and noninertial cavitation. Inertial cavitation is the process where a void or bubble in a liquid rapidly collapses, producing a shock wave. Noninertial cavitation is the process where a bubble in a fluid is forced to oscillate in size or shape due to some form of energy input, such as an acoustic field. Both types of cavitation can occur when using impellers. Moreover, the shock waves formed by cavitation may be strong enough to significantly damage moving parts, which can facilitate the erosion of an impeller and its casing or other damage to the impeller.

**[0025]** It is often difficult to monitor the health of a number of impellers due, among other things, to the various types of impellers that are in use. In accordance with this disclosure, an impeller health monitoring system is provided that can monitor the health of one or more impellers and provide an indication when a particular impeller is suffering from wear or other problems.

**[0026]** FIGURE 3 illustrates an example table 300 for impeller failure mode rules according to this disclosure. The embodiment of the table 300 shown in FIGURE 3 is for illustration only. Other embodiments of the table 300 could be used without departing from the scope of this disclosure.

**[0027]** In this example, the table 300 includes five failure conditions. The failure conditions include high flow cavitations 302, low flow cavitations 304, impeller wear 306, impeller cracking 310, and impeller vane breakage 312. The table 300 identifies the effects of these failure conditions on various frequencies associated with operation of the impeller. The impeller frequencies include the rotating shaft speed frequency ($f_r$) 322, the vane pass frequency ($f_{vane}$) 324, the shaft sideband frequencies ($f_{vane}$-

$f_r$) 326 and ($f_{vane}+f_r$) 328, and background noise 330.

**[0028]** If high flow cavitations 302 or low flow cavitations 304 occur, the frequencies $f_{vane}$ 324, $f_{vane}-f_r$ 326 and $f_{vane}+f_r$ 328 decrease, and the background noise 330 increases. If impeller wear 306 occurs, the frequency $f_{vane}$ 324 increases, while the frequencies $f_{vane}-f_r$ 326 and $f_{vane}+f_r$ 328 decrease. Impeller cracking 310 results in an increase in each of the frequencies $f_r$ 322, $f_{vane}-f_r$ 326, and $f_{vane}+f_r$ 328, and the frequency $f_{vane}$ 324 decreases. An impeller vane breakage 312 increases the frequencies $f_r$ 322, $f_{vane}-f_r$ 326, and $f_{vane}+f_r$ 328 while causing a decrease in the frequency $f_{vane}$ 324. With these rules in mind, an impeller health monitoring system can monitor the health of one or more impellers and can identify a specific failure mode for each impeller (if any).

**[0029]** FIGURE 4 illustrates an example Impeller Condition Indicator (ICI) device 400 according to this disclosure. The embodiment of the ICI device 400 shown in FIGURE 4 is for illustration only. Other embodiments of the ICI device 400 could be used without departing from the scope of this disclosure.

**[0030]** In this example, the ICI device 400 includes a user configuration portion 402. The user configuration portion 402 provides a user interface that facilitates operator interaction with the ICI device 400. For example, the user configuration portion 402 may enable an operator to enter impeller configuration information. As particular examples, the user configuration portion 402 may allow the operator to enter a machine configuration 404. The machine configuration 404 may include a pump rating, one or more types of pumps, one or more types of impellers, and one or more natural frequencies of the machine.

**[0031]** The operator may also enter a filter specification 406. The filter specification 406 may include a filter type, an order of the filter, a higher frequency limit, and a lower frequency limit. Data Acquisition (DAQ) specifications 408 may further be entered by the operation in the user configuration portion 402. The DAQ specification 408 may include a sampling frequency, a number of samples, and a voltage range. In addition, the operator may enter sensor specifications 410 and additional user inputs 412. The sensor specifications 410 may include types of sensors, sensor ranges and sensitivities, and sensor dynamic ranges and natural frequencies. The additional user inputs 412 may include sampling frequency, a number of samples, and a class of machine.

**[0032]** The ICI device 400 also includes a sensor signal portion 420. The sensor signal portion 420 provides an interface for receiving inputs from sensors coupled to, or otherwise associated with, an impeller and/or a centrifugal pump or other device that includes an impeller. In this example, the sensor signal portion 420 includes interfaces to an accelerometer 422 and a tachometer 424. The accelerometer 422 detects, measures, and records a vibration 426 of an impeller or device containing the impeller. The tachometer 424 can be a sensor input device such as a tachogenerator or Once Per Revolution (OPR) device. The tachometer 424 detects, measures, and records speed 428 of an impeller or device containing the impeller. The sensor signal portion 420 also can store baseline signals 430 for the impeller or device containing the impeller.

**[0033]** The ICI device 400 further includes an Artificial Intelligence (AI) portion or other processing portion 440. In this example, the AI portion 440 includes an analog-to-digital converter 441, a pre-processing filter 442, and a vibration signature processor 444. The vibration signature processor 444 can include one or more processors or other components adapted to perform FFT analysis 446, Frequency/Frequency Bandwidth Selection (FFBS) 448, signal reconstruction 450, statistical features recordation 452, and normalization 454. The AI portion 440 is also able to perform Fuzzy Rule-Based Diagnostics 456 and Rule-Based Diagnostics 458. The Fuzzy Rule-Based Diagnostics 456 include Fuzzification, Rules, Aggregation and De-fuzzification operations. These functions are described in more detail below.

**[0034]** In addition, the ICI device 400 includes an output interface 470. The output interface 470 represents an interface configured to send information to another system or device, such as a computer or a display. The output interface 470 could also represent a single display (e.g., a monitor) or multiple displays. In this example, the output interface 470 includes an impeller wear indicator 472, an impeller crack indicator 474, a cavitations indicator 476, and an impeller health indicator 478. These indicators 472-478 identify the health of the impeller being monitored.

**[0035]** The ICI device 400 can be implemented in any suitable manner. For example, the ICI device 400 can be implemented as an Analog/Digital (A/D) card, an embedded system, a display system, a central processing unit, a personal computer, or a digital signal processor.

**[0036]** The ICI device 400 detects and measures the effects resulting from various types of impeller failures. For example, the ICI device 400 measures the changes in amplitudes of the frequencies 322-330 shown in FIGURE 3. Based on those changes, the ICI device 400 classifies the impeller failure.

**[0037]** In one aspect of operation, an operator can enter a machine configuration 404 for an impeller or a device with an impeller via the user configuration portion 402. The operator can also enter a pump rating (if any), a type of pump (if any), a type of impeller, and one or more natural frequencies. The operator can further enter information relating to the filter specification 406, the DAQ specification 408, and the sensor specification 410. In addition, the operator can enter additional user inputs 412, such as a sampling frequency, a number of samples, and class of machine, that the ICI device 400 will use to monitor the impeller.

**[0038]** The ICI device 400 receives sensor input signals from sensors coupled to the ICI device 400 via a number of sensor interfaces. The ICI device 400 measures and records the sensor input signals associated with normal operation of the impeller. The ICI device 400 stores the sensor input signals corresponding to normal operation of the impeller as the set of baseline signals 430.

**[0039]** The ICI device 400 continues to monitor the performance of the impeller based on the sampling frequency included in the additional user inputs 412. The ICI device 400 filters the input signals from the sensors using the filter 442. The vibration signature processor 444 applies the FFT analysis 446 to all of the component characteristics (e.g., frequencies) in the filtered signals. The FFT analysis 446 may yield only the relevant frequencies related to the impeller being monitored.

**[0040]** The FFBS 448 isolates one or more frequencies and amplitudes that will be used in signal reconstruction 450 to reconstruct the signal. Once the signal is reconstructed using those selected frequencies and amplitudes, the vibration signature processor 444 determines statistical features 452 of the reconstructed signal. In some embodiments, the statistical feature 452 is a Root Mean Square (RMS) value. Thereafter, the vibration signature processor 444 produces a normalized signal by performing a normalization 454 of the reconstructed signal with respect to the baseline signal 430. The ICI device 400 can then apply various rules to the normalized signal. These rules may include Fuzzy Rule-Based Diagnostics 456 and/or Rule-Based Diagnostics 458.

**[0041]** The ICI device 400 presents an output of the results via the output interface 470. In some embodiments, the output interface 470 only provides an output when the ICI device 400 has determined that a fault condition exists (such as when the normalized signal differs from the baseline signals 430 by one or more threshold values). In these embodiments, the output interface 470 can provide the output by flagging, illuminating, or otherwise displaying the indicator associated with the failure (e.g., via the impeller wear indicator 472, the impeller crack indicator 474, the cavitations indicator 476, or the impeller health indicator 478).

**[0042]** FIGURE 5 illustrates a more detailed view of an example ICI first stage operation 500 for monitoring the health of an impeller according to this disclosure. The embodiment of the ICI first stage operation 500 shown in FIGURE 5 is for illustration only. Other embodiments of the ICI first stage operation 500 could be used without departing from the scope of this disclosure.

**[0043]** During a configuration stage, the operator enters data related to an impeller to be monitored, such as the filter specification 406, signal details (e.g., additional user inputs 412), the DAQ specification 408, the sensor specification 410, and the impeller specification (e.g., machine configuration 404). In this example, the operator can enter a type of impeller 502, a number of stages 504, a number of vanes 505 for each stage, a high-pass filter frequency $F_H$ 506, a maximum sampling frequency $f_{daq}$ 507 and a maximum number of samples $N_{daq}$ 508 for data acquisition, a maximum sampling frequency $f_{daq}$ 510 for each sensor, and a sampling frequency $f_S$ 511 and a number of samples $N_S$ 512.

**[0044]** The ICI device 400 also determines a Family of Frequencies (FoF) 520 for the impeller (or for each stage of the impeller if multiple stages are monitored). For example, the AI portion 440 can determine the vane pass frequency $f_{vane}$ 324 and at least three harmonics for each vane pass frequency $f_{vane}$ 324. The AI portion 440 can also determine the shaft frequency $f_r$ 322 and shaft sidebands $f_{vane}-f_r$ 326 and $f_{vane}+f_r$ 328 around the vane pass frequency $f_{vane}$ 324. It will be understood that although three harmonics for each vane pass frequency $f_{vane}$ 324 are illustrated, embodiments with other than three harmonics could be used. In addition, the AI portion 440 can determine a natural frequency for the impeller.

**[0045]** The AI portion 440 also determines if the operator has entered appropriate values for $F_H$ 506, $f_s$ 511, and $N_s$ 512. For example, the AI portion 440 compares $f_s$ 511 to $F_H$ 506 during a comparison 530. If $f_s$ 511 is less than twice $F_H$ 506 ($f_s<2F_H$), the AI portion 440 triggers an increase $f_s$ 511 indicator 532 in the output interface 470 of the ICI device 400. The increase $f_s$ indicator 532 provides a visual or audible cue to the operator that the value entered for $f_s$ 511 is too low and should be increased.

**[0046]** If the AI portion 440 determines that a sufficient $f_s$ 511 has been entered (e.g., $f_s$ 511 is not less than twice $F_H$ 506 such that $f_s \geq 2F_H$), the AI portion 440 compares $f_s$ 511 to $f_{daq}$ 507 during a comparison 536. If $f_s$

511 is greater than to $f_{daq}$ 507 ($f_s > f_{daq}$), the AI portion 440 triggers a decrease $f_s$ indicator 534 in the output interface 470. The decrease $f_s$ indicator 534 provides a visual or audible cue to the operator that the value entered for $f_s$ 511 is too high and should be decreased.

**[0047]** The AI portion 440 also compares $N_S$ 512 against $N_{daq}$ 508 during a comparison 540. If $N_S$ 512 is greater than $N_{daq}$ 508 ($N_S > N_{daq}$), the AI portion 440 triggers an decrease $N_s$ indicator 542 in the output interface 470. The decrease $N_s$ indicator 542 provides a visual or audible cue to the operator that the value entered for $N_S$ 512 is too high and should be increased. If $N_S$ 512 is less than or equal to $N_{daq}$ 508 ($N_S \leq N_{daq}$), the AI portion 440 either disables the decrease $N_s$ indicator 542 (if the decrease $N_s$ indicator 542 is enabled) or does nothing (if the decrease $N_s$ indicator 542 is not enabled).

**[0048]** FIGURE 6 illustrates a more detailed view of an example ICI second stage operation 600 for monitoring the health of an impeller according to this disclosure. The embodiment of the ICI second stage operation 600 shown in FIGURE 6 is for illustration only. Other embodiments of the ICI second stage operation 600 could be used without departing from the scope of this disclosure.

**[0049]** After the AI portion 440 has computed the Family of Frequencies 520 for the sensor input signals, the AI portion 440 processes the FoF 520 through the low-pass filter 442 and applies the FFT analysis 446. The low-pass filter 442 can be a Butterworth filter, a wavelet-based filter, or any other low pass filter. The FoF 520 is passed through the FFBS 448, which, in this example, includes a number of band-pass filters paths 605a-605c. A 2Hz band (e.g., from *f*+1Hz to *f*-1Hz) 605a is applied to the signals from the FFT analysis 446 whose value is less than 1000Hz ($f<1000Hz$). A 3Hz band (e.g., from *f*+1.5Hz to *f*-1.5Hz) 605b is applied to the signals from the FFT analysis 446 whose value is less than 2000Hz but greater than or equal to 1000Hz ($1000Hz\leq f<2000Hz$). A 4Hz band (e.g., from *f*+2Hz to *f*-2Hz) 605c is applied to the signals from the FFT analysis 446 whose value is greater than or equal to 2000Hz ($f\geq2000Hz$).

**[0050]** The AI portion 440 computes the minimum and maximum amplitudes for each band 605a-605c. The AI portion 440 then combines each of the maximums from the bands 605a-605c to generate a matrix of maximum amplitudes and frequencies 610. The AI portion 440 also combines each of the minimums from the bands 605a-605c to generate a matrix of minimum amplitudes and frequencies 615. The AI portion 440 creates a union 620 of all frequencies in the FoF 520 to identify the impeller component frequencies.

**[0051]** The AI portion 440 applies statistical features 452 to the union 620 and the matrix of min amplitudes and frequencies 615. The statistical features 452 can include determining the RMS or norm of each FoF 520. Thereafter, the AI portion 440 performs signal reconstruction 450 for the impeller component and noise frequencies to generate reconstructed signals for the impeller. In this example, the reconstructed signals represent an acceleration. In particular, the AI portion 440 can reconstruct a signal for the vane and harmonics, a signal for the shaft and shaft sideband frequencies, and a signal for noise frequencies.

**[0052]** Each of the reconstructed signals is passed through an RMS level detector 630, a normalized RMS level detector 635, and one of three fuzzy membership functions 640. The outputs of the fuzzy membership functions 640 are passed through fuzzy rules 645 to produce a fuzzy rule signal. The AI portion 440 compares the fuzzy rule signal to a number of indexes within an RMS or norm baseline signal 650 to produce one or more impeller or pump conditions 655. Note that the fuzzy membership functions 640 and fuzzy rules 645 could be replaced by other logic, such as when the rule-based diagnostics 458 are used.

**[0053]** The impeller or pump conditions 655 provide an indication that reflects the health of an impeller or pump based on, in this example, a sensed vibration. The ICI device 400 can output an impeller or pump condition that identifies impeller wear, impeller crack, and/or cavitations using the output interface 470.

**[0054]** In some embodiments, the ICI device 400 includes a number of threshold values stored in a memory, and the ICI device 400 can compare the identified conditions 655 to the threshold values stored in memory to determine whether to initiate an alarm or other action. The memory can be any computer readable medium, such as any electronic, magnetic, electromagnetic, optical, electro-optical, electro-mechanical, and/or other memory device that can contain, store, communicate, propagate, or transmit data. In particular embodiments, the threshold values could include a warning threshold and an alarm threshold for each condition 655 calculated by the ICI device 400. The warning threshold could trigger a warning that an impeller condition 655 is high, while an alarm threshold could trigger an alarm that a fault has been detected in an impeller.

**[0055]** FIGURE 7 illustrates an example process 700 for monitoring an impeller according to this disclosure. The embodiment of the process 700 shown in FIGURE 7 is for illustration only. Other embodiments of the process 700 could be used without departing from the scope of this disclosure. Also, for ease of explanation, the process 700 is described with respect to the ICI device 400, although the process 700 could be used with any suitable device or system.

**[0056]** In this example, the ICI device 400 uses vibration and speed signals, as processed and compared to the thresholds, to alert an operator to possible damage in an impeller. The vibration and speed signals are received by the ICI device 400 at step 705. The ICI device 400 stores the vibration and speed signals obtained during normal operation of the impeller as baseline signals at step 710. The ICI device 400 determines the relevant family of frequencies for the impeller at step 715. This may include, for example, determining the FoF 520 for each of the failure modes of the impeller. The FoF 520 can include a vane pass frequency and its harmonics, a shaft rotating frequency, sidebands of the shaft rotating frequencies around the vane pass frequency and its harmonics, and background noise. The ICI device 400 can measure the vibration signals and estimate the frequencies of the vibration signals using any available technique, such as FFT analysis.

**[0057]** The ICI device 400 continues to receive vibration and speed signals and performs signal processing at step 720. This may include, for example, decomposing the vibration and speed signals. The signal processing may also include a low-pass filter operation and an FFT analysis. In some embodiments, deconstruction (e.g., decomposition) is accomplished using a Fourier series, a Laplace transform, or a Z-transform. The ICI device 400 performs frequency/frequency bandwidth selection using the processed signals at step 725. This may include, for example, isolating frequencies and obtaining minimum and maximum frequencies and amplitudes. The ICI device 400 reconstructs the signal at step 730, such as by reconstructing an overall signal and reconstructing signals for the vane pass frequencies and its harmonics, the shaft sidebands, and the background noise. The ICI device 400 identifies one or more features from the reconstructed signal in step 735. For example, the ICI device 400 can determine features such as RMS and Kurtosis values. The ICI device 400 also identifies corresponding features in the base line signal in step 740 and the current signal in step 745. The reconstructed signals are normalized with respect to the features of the baseline signals or other indices at step 750. For example, the reconstructed signals can be normalized by dividing the features from the current signal, found in step 745, by the features from the baseline, found in step 750. The normalizing helps to generalize the model with respect to the size of a mechanical system and application type. In the event a reconstructed signal exceeds one of the thresholds, the ICI device 400 outputs the appropriate indicator (e.g., the impeller wear indicator, impeller crack indicator, and/or cavitations indicator) in step 755. The ICI device 400 applies fuzzy-rule based diagnostics to determine if the reconstructed signal exceeds one of the thresholds.

**[0058]** In some embodiments, the vibration and speed signals stored are for an impeller that currently is experiencing wear or currently includes a crack. In such embodiments, the ICI device 400 provides a warning or alarm based on a change in the signals resulting from additional wearing or further cracking of the impeller.

**[0059]** FIGURES 8 and 9 illustrate example impeller health indicators 478 according to this disclosure. The embodiments of the impeller health indicators 478 shown in FIGURES 8 and 9 are for illustration only. Other embodiments of the impeller health indicator 478 could be used without departing from the scope of this disclosure.

**[0060]** In these examples, the impeller health indicator 478 is constructed using a feature fusion of statistics on the basis of Fuzzy, Dempter-Shafer, or Bayesian theory. The health indicator 478 provides a severity index varying between a value of 0 and a value of 1. The impeller health indicator 478 includes a time 805 and two threshold values 810 and 815.

**[0061]** Although the figures above have illustrated various embodiments, any number of modifications could be made to these figures. For example, any suitable types of impellers could be monitored, and any suitable types of faults could be detected. Also, various functions shown as being performed by the ICI device 400 could be combined, further subdivided, or omitted and additional functions could be added according to particular needs. In addition, while FIGURE 7 illustrates a series of steps, various steps in FIGURE 7 could overlap, occur in parallel, occur multiple times, or occur in a different order.

**[0062]** In some embodiments, various functions described above are implemented or supported by a computer program that is formed from computer readable program code and that is embodied in a computer readable medium. The phrase "computer readable program code" includes any type of computer code, including source code, object code, and executable code. The phrase "computer readable medium" includes any type of medium capable of being accessed by a computer, such as read only memory (ROM), random access memory (RAM), a hard disk drive, a compact disc (CD), a digital video disc (DVD), or any other type of memory.

**[0063]** It may be advantageous to set forth definitions of certain words and phrases used throughout this patent document. The term "couple" and its derivatives refer to any direct or indirect communication between two or more elements, whether or not those elements are in physical contact with one another. The terms "include" and "comprise," as well as derivatives thereof, mean inclusion without limitation. The term "or" is inclusive, meaning and/or. The phrases "associated with" and "associated therewith," as well as derivatives thereof, may mean to include, be included within, interconnect with, contain, be contained within, connect to or with, couple to or with, be communicable with, cooperate with, interleave, juxtapose, be proximate to, be bound to or with, have, have a property of, or the like.

**[0064]** While this disclosure has described certain embodiments and generally associated methods, alterations and permutations of these embodiments and methods will be apparent to those skilled in the art. Accordingly, the above description of example embodiments does not define or constrain this disclosure. Other changes, substitutions, and alterations are also possible without departing from the spirit and scope of this disclosure, as defined by the following claims.

WHAT IS CLAIMED IS:

1. An apparatus (400) comprising:

an input interface (420) configured to receive an input signal associated with at least one stage of an impeller (100a-100h);

a processor (440) configured to identify a fault in the impeller using the input signal; and

an output interface (470) configured to provide an indicator identifying the fault;

wherein the processor is configured to identify the fault by:

determining a family of frequencies (520) related to at least one failure mode of the impeller, the family of frequencies including a vane pass frequency and its harmonics;

decomposing the input signal using the family of frequencies;

reconstructing an impeller signal using the decomposed input signal; and

comparing the reconstructed impeller signal to a baseline signal (430).

2. The apparatus of Claim 1, wherein the reconstructed impeller signal comprises at least one of:

a signal associated with the vane pass frequency and its harmonics;

a signal associated with a rotating shaft (125) of the impeller;

a signal associated with shaft sidebands; and

a signal associated with background noise.

3. The apparatus of Claim 1, wherein the processor

is configured to deconstruct the input signal by decomposing the input signal through a plurality of band-pass filters (605a-605c).

4. The apparatus of Claim 3, wherein the processor is configured to reconstruct the impeller signal by:

determining maximum and minimum frequencies and amplitudes in outputs of the band-pass filters;

uniting the maximum frequencies and amplitudes to produce a first union;

uniting the minimum frequencies and amplitudes to produce a second union; and

reconstructing multiple impeller signals using the first and second unions.

5. The apparatus of Claim 1, wherein the processor further is configured to:

normalize the reconstructed signal with the baseline signal; and

apply a feature fusion technique to obtain a value for use by the indicator.

6. A system comprising:

a plurality of sensors (422-424) configured to measure one or more characteristics of an impeller (100a-100h); and

an impeller condition indicator device (400) comprising:

an input interface (420) configured to receive input signals associated with at least one stage of the impeller from the sensors;

a processor (440) configured to identify a fault in the impeller using the input signals; and

an output interface (470) configured to provide an indicator identifying the fault;

wherein the processor is configured to identify the fault by:

determining a family of frequencies (520) related to at least one failure mode of the impeller, the family of frequencies including a vane pass frequency and its harmonics;

decomposing the input signals using the family of frequencies;

reconstructing an impeller signal using the decomposed input signals; and

comparing the reconstructed impeller signal to a baseline signal (430).

7. The system of Claim 6, wherein the processor is configured to deconstruct the input signals by decomposing the input signals through a plurality of band-pass filters (605a-605c).

8. The system of Claim 7, wherein the processor is configured to reconstruct the impeller signal by:

determining maximum and minimum frequencies and amplitudes in outputs of the band-pass filters;

uniting the maximum frequencies and amplitudes to produce a first union;

uniting the minimum frequencies and amplitudes to produce a second union; and

reconstructing multiple impeller signals using the first and second union.

9. The system of Claim 6, wherein the processor is further configured to store a portion of the input signals, corresponding to normal operation of the impeller, as the

baseline signal.

10. A method comprising:

receiving (705) an input signal comprising at least one of vibration and speed information corresponding to at least one stage of an impeller (100a-100h);

determining (715) a family of frequencies (520) corresponding to at least one failure mode of the impeller, the family of frequencies including a vane pass frequency and its harmonics;

decomposing (720-725) the input signal using the family of frequencies;

reconstructing (730) an impeller signal using the decomposed input signal;

comparing (750) the reconstructed impeller signal to a baseline signal (430); and

outputting (755) an indicator identifying a fault when the reconstructed impeller signal differs from the baseline signal by a threshold amount.

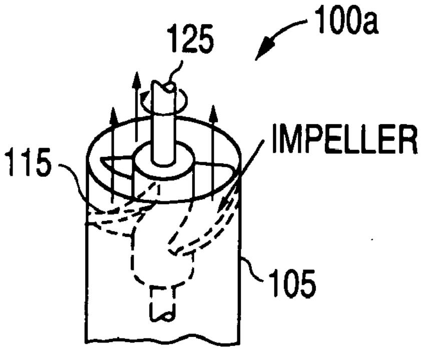


FIG. 1A

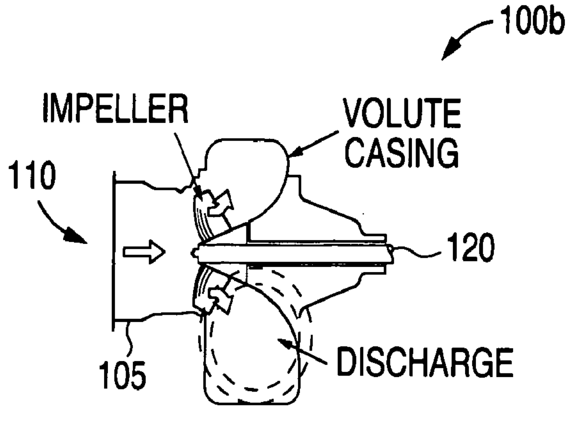


FIG. 1B

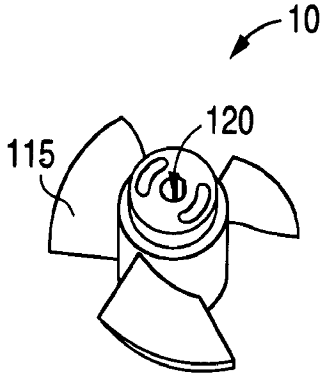


FIG. 1C

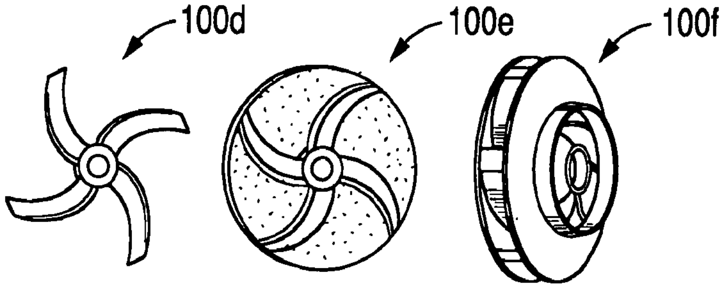
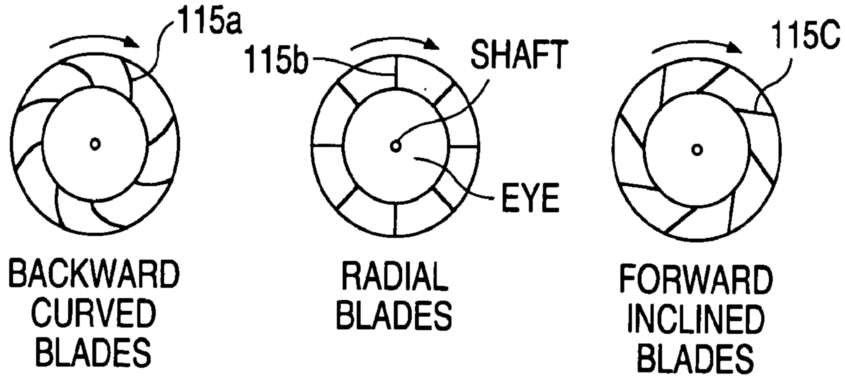


FIG. 1F



BACKWARD CURVED BLADES

RADIAL BLADES

FORWARD INCLINED BLADES

FIG. 1D

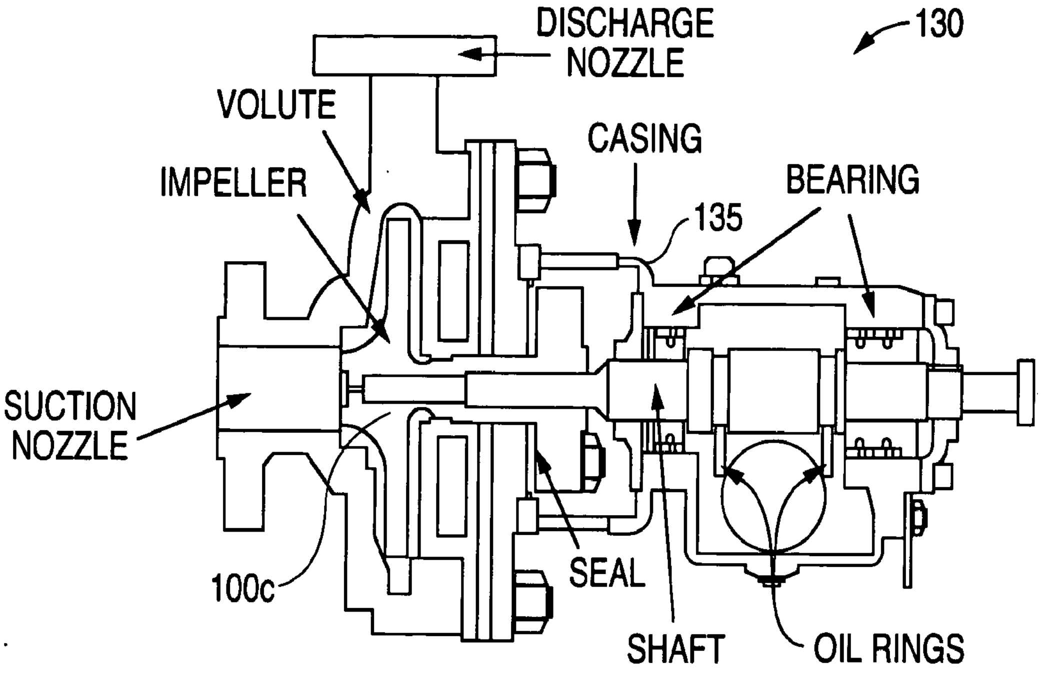

DISCHARGE NOZZLE
130
VOLUTE
CASING
IMPELLER
BEARING
135
SUCTION NOZZLE
100c
SEAL
SHAFT
OIL RINGS

FIG. 1E

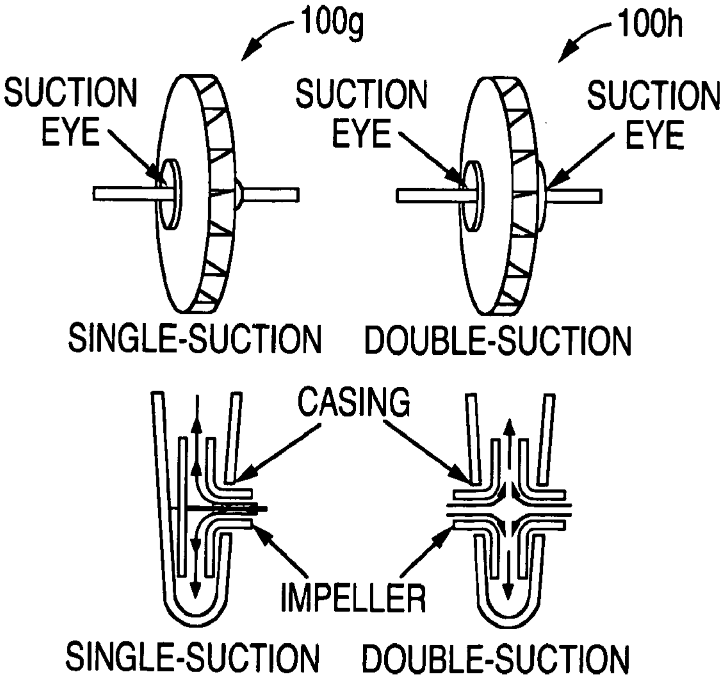

100g
100h
SUCTION EYE
SUCTION EYE
SUCTION EYE
SINGLE-SUCTION
DOUBLE-SUCTION
CASING
IMPELLER
SINGLE-SUCTION
DOUBLE-SUCTION

FIG. 1G

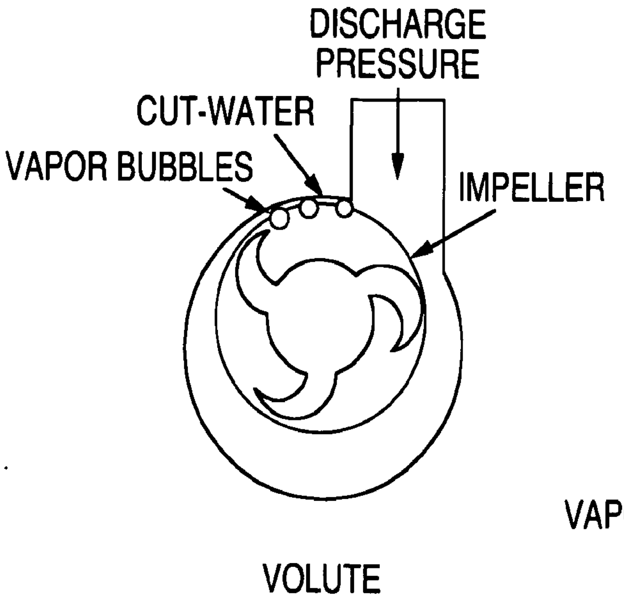


FIG. 2A

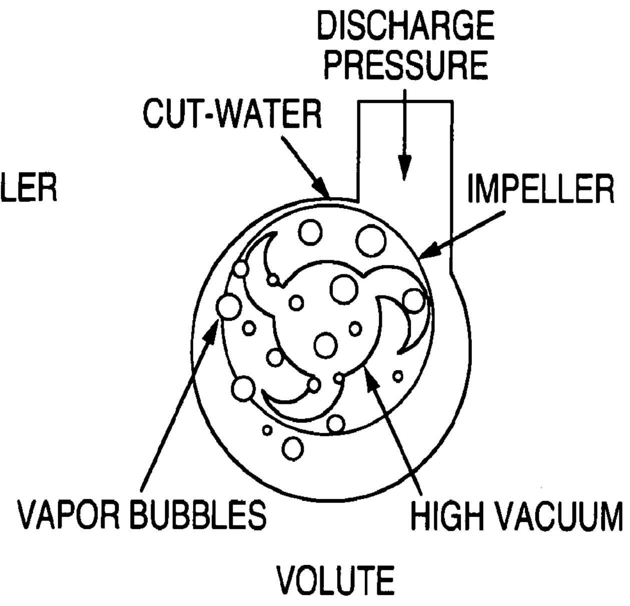


FIG. 2B

300

| | 322 | 324 | 326 | 328 | 330 |
|---|---|---|---|---|---|
| | $f_r$ | $f_{vans}$ | $f_{vans}-f_r$ | $f_{vans}+f_r$ | Back-ground Noise |
| 302 High Flow Cavitations | | ⇩ | ⇩ | ⇩ | ⇧ |
| 304 Low Flow Cavitations | | ⇩ | ⇩ | ⇩ | ⇧ |
| 306 Impeller Wear | | ⇧ | ⇩ | ⇩ | |
| 310 Impeller Crack | ⇧ | ⇩ | ⇧ | ⇧ | |
| 312 Impeller Vane Breakage | ⇧ | ⇩ | ⇧ | ⇧ | |

FIG. 3

FIG. 4A

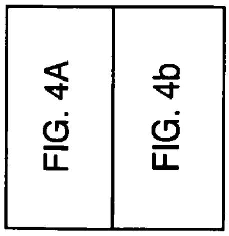
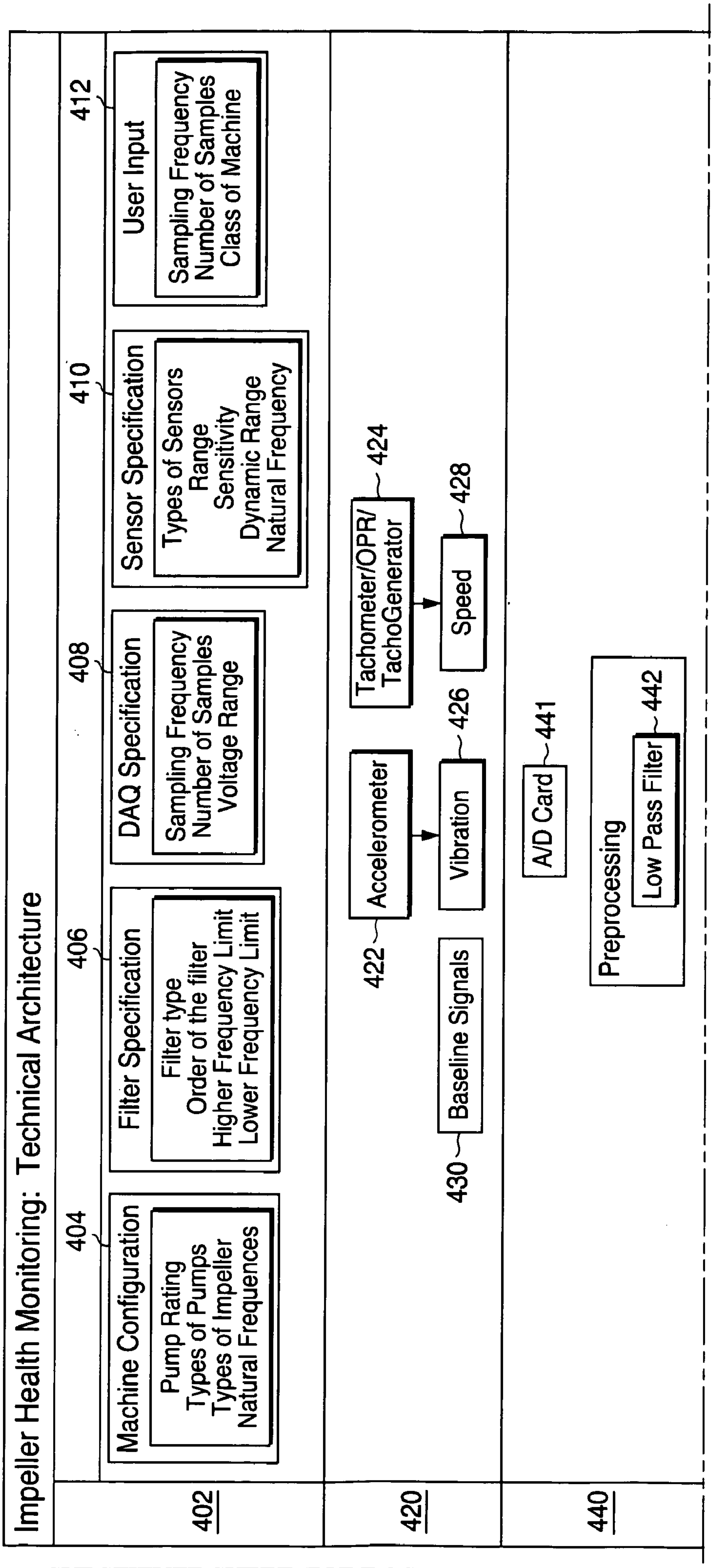


FIG. 4A
FIG. 4b



Impeller Health Monitoring: Technical Architecture
402
404
Machine Configuration
Pump Rating
Types of Pumps
Types of Impeller
Natural Frequences
406
Filter Specification
Filter type
Order of the filter
Higher Frequency Limit
Lower Frequency Limit
408
DAQ Specification
Sampling Frequency
Number of Samples
Voltage Range
410
Sensor Specification
Types of Sensors
Range
Sensitivity
Dynamic Range
Natural Frequency
412
User Input
Sampling Frequency
Number of Samples
Class of Machine
420
422
Accelerometer
424
Tachometer/OPR/
TachoGenerator
426
Vibration
428
Speed
430
Baseline Signals
440
441
A/D Card
442
Preprocessing
Low Pass Filter

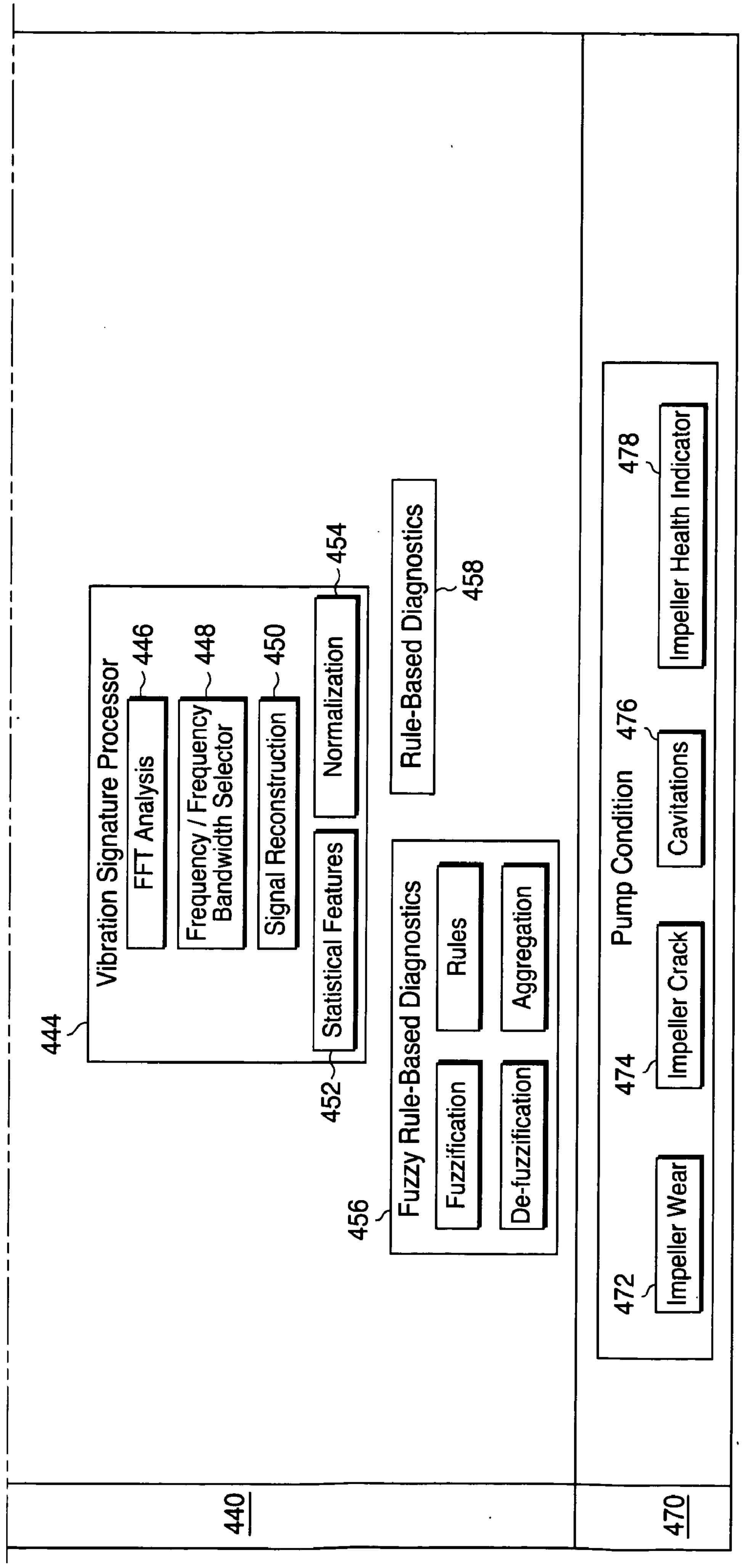

440
444
Vibration Signature Processor
FFT Analysis
446
Frequency / Frequency Bandwidth Selector
448
Signal Reconstruction
450
Statistical Features
452
Normalization
454
Fuzzy Rule-Based Diagnostics
456
Fuzzification
Rules
De-fuzzification
Aggregation
Rule-Based Diagnostics
458
470
Pump Condition
Impeller Wear
472
Impeller Crack
474
Cavitations
476
Impeller Health Indicator
478

FIG. 4B

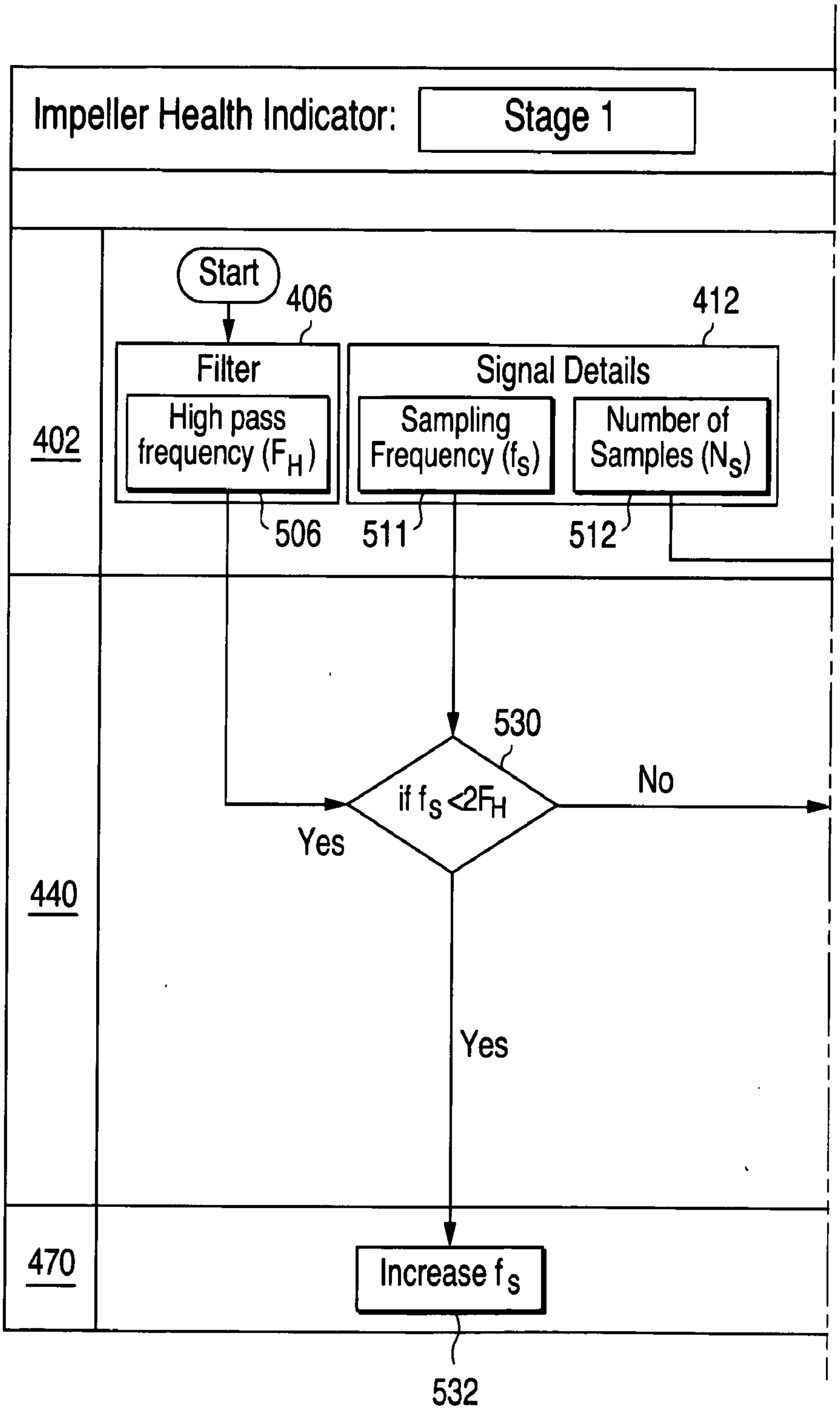

Impeller Health Indicator:
Stage 1
402
440
470
Start
406
Filter
High pass frequency ($F_H$)
506
412
Signal Details
Sampling Frequency ($f_S$)
511
Number of Samples ($N_S$)
512
530
if $f_S < 2F_H$
Yes
No
Yes
Increase $f_S$
532

FIG. 5A

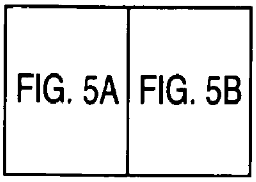


FIG. 5A
FIG. 5B

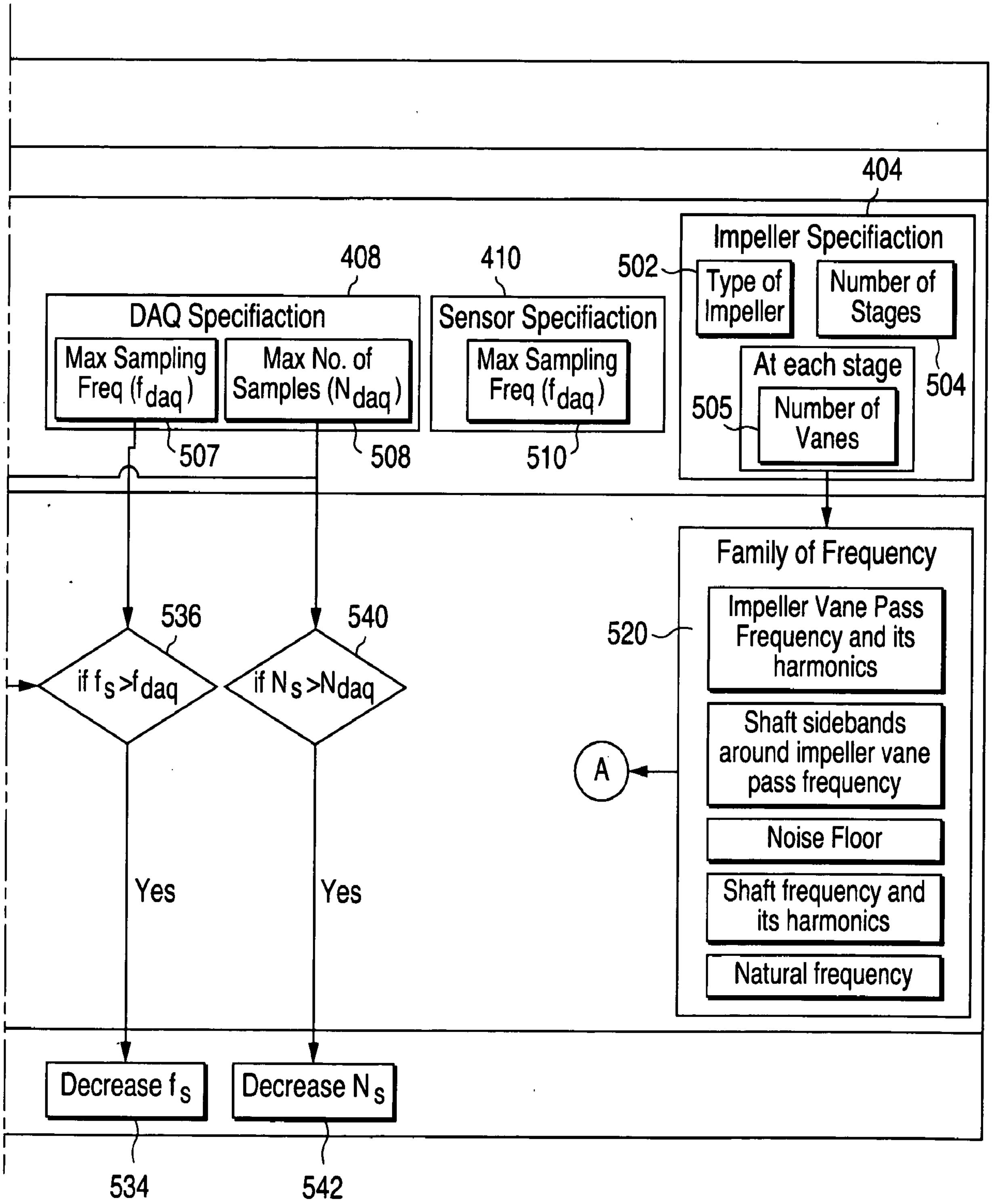
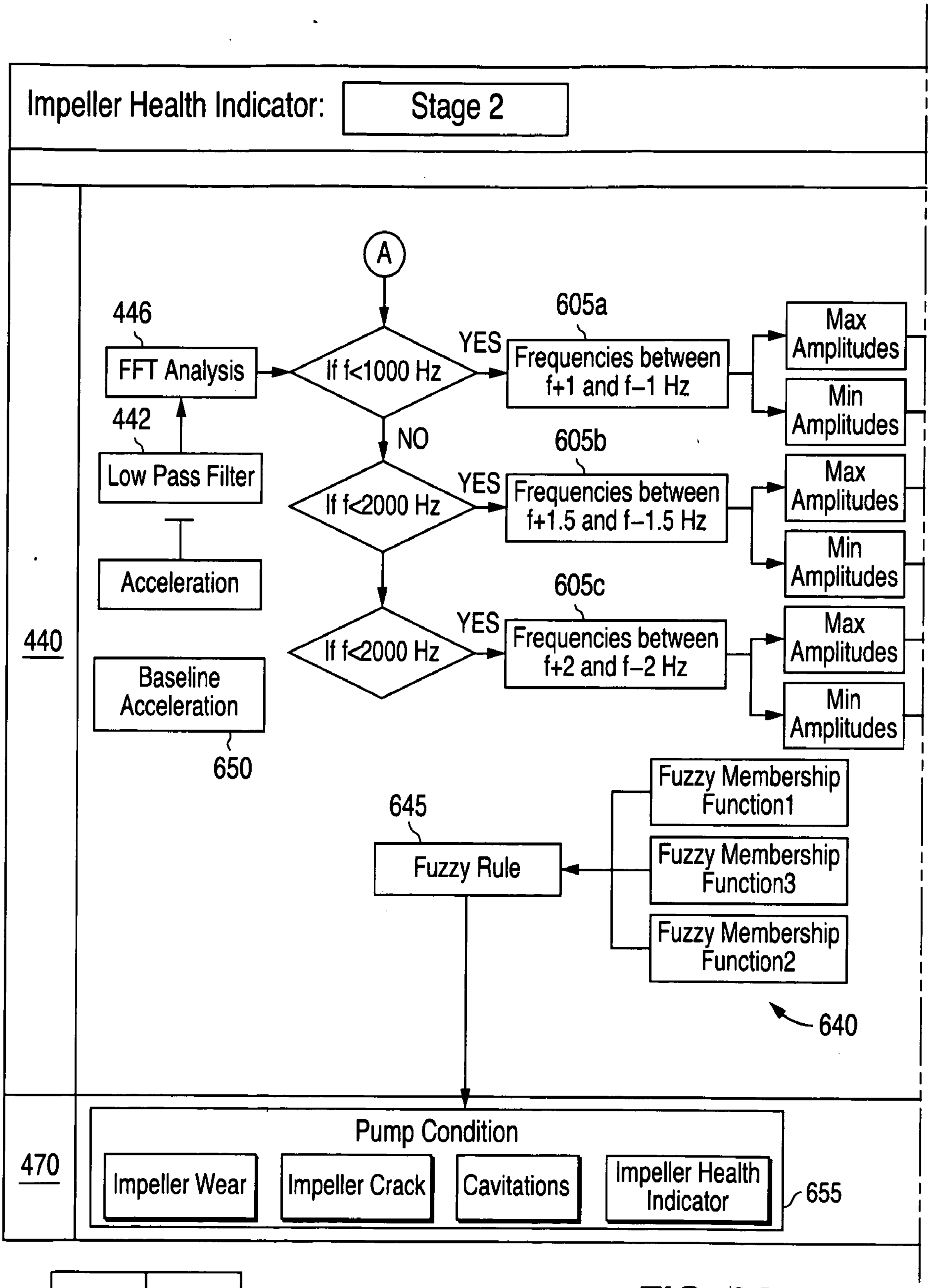

404
Impeller Specifiaction
502
Type of Impeller
Number of Stages
504
At each stage
505
Number of Vanes
408
DAQ Specifiaction
Max Sampling Freq ($f_{daq}$)
Max No. of Samples ($N_{daq}$)
507
508
410
Sensor Specifiaction
Max Sampling Freq ($f_{daq}$)
510
Family of Frequency
520
Impeller Vane Pass Frequency and its harmonics
Shaft sidebands around impeller vane pass frequency
Noise Floor
Shaft frequency and its harmonics
Natural frequency
A
536
if $f_s > f_{daq}$
540
if $N_s > N_{daq}$
Yes
Yes
Decrease $f_s$
Decrease $N_s$
534
542

FIG. 5B


Impeller Health Indicator:
Stage 2
440
A
446
FFT Analysis
442
Low Pass Filter
Acceleration
Baseline Acceleration
650
If f<1000 Hz
YES
NO
605a
Frequencies between f+1 and f−1 Hz
Max Amplitudes
Min Amplitudes
If f<2000 Hz
YES
605b
Frequencies between f+1.5 and f−1.5 Hz
Max Amplitudes
Min Amplitudes
If f<2000 Hz
YES
605c
Frequencies between f+2 and f−2 Hz
Max Amplitudes
Min Amplitudes
645
Fuzzy Rule
Fuzzy Membership Function1
Fuzzy Membership Function3
Fuzzy Membership Function2
640
470
Pump Condition
Impeller Wear
Impeller Crack
Cavitations
Impeller Health Indicator
655

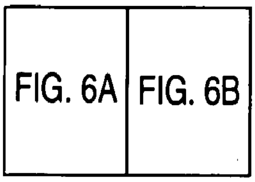


FIG. 6A
FIG. 6B

FIG. 6A

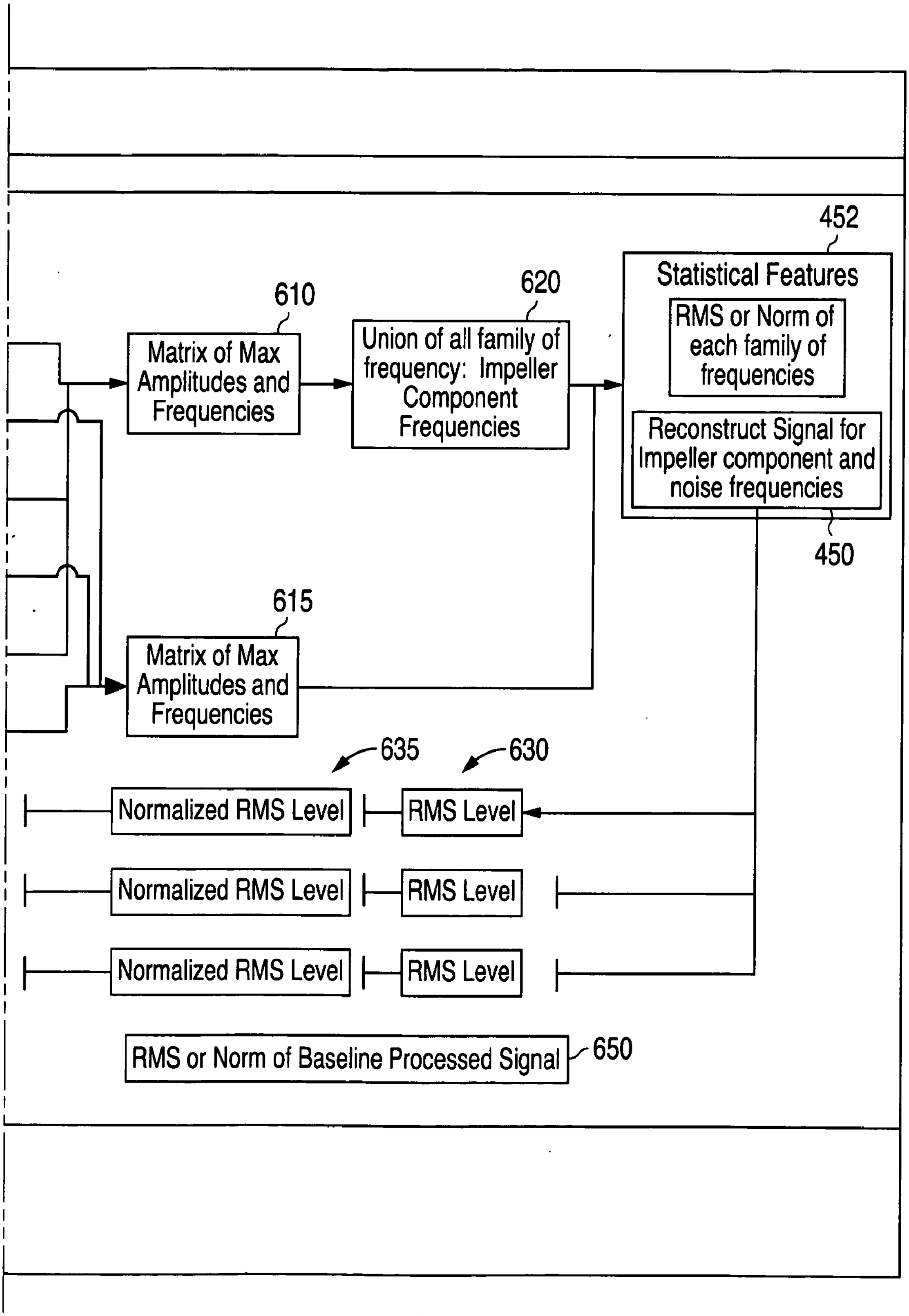

452
Statistical Features
RMS or Norm of each family of frequencies
Reconstruct Signal for Impeller component and noise frequencies
450
610
Matrix of Max Amplitudes and Frequencies
620
Union of all family of frequency: Impeller Component Frequencies
615
Matrix of Max Amplitudes and Frequencies
635
630
Normalized RMS Level
RMS Level
Normalized RMS Level
RMS Level
Normalized RMS Level
RMS Level
RMS or Norm of Baseline Processed Signal
650

FIG. 6B

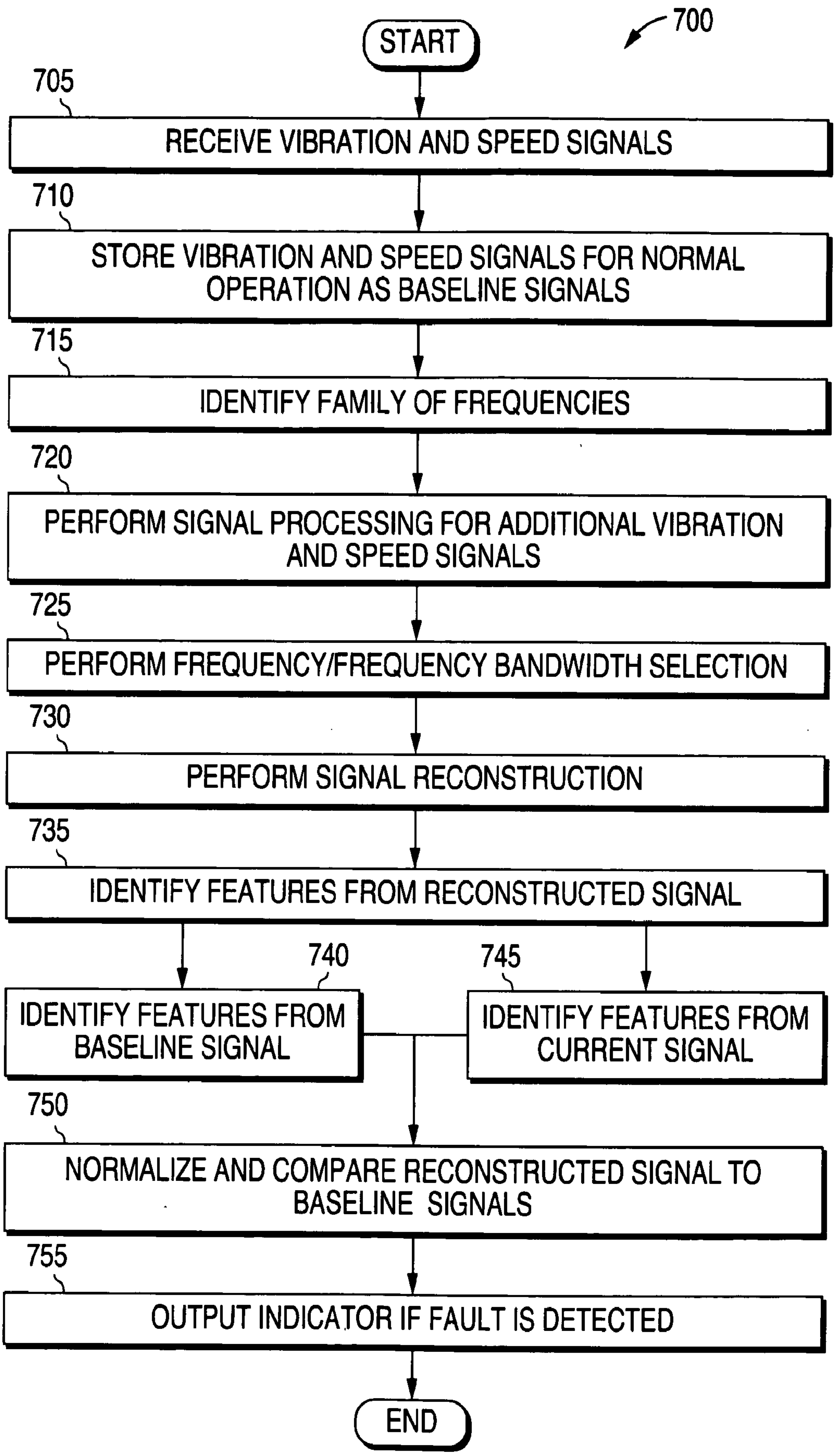

700
START
705
RECEIVE VIBRATION AND SPEED SIGNALS
710
STORE VIBRATION AND SPEED SIGNALS FOR NORMAL OPERATION AS BASELINE SIGNALS
715
IDENTIFY FAMILY OF FREQUENCIES
720
PERFORM SIGNAL PROCESSING FOR ADDITIONAL VIBRATION AND SPEED SIGNALS
725
PERFORM FREQUENCY/FREQUENCY BANDWIDTH SELECTION
730
PERFORM SIGNAL RECONSTRUCTION
735
IDENTIFY FEATURES FROM RECONSTRUCTED SIGNAL
740
IDENTIFY FEATURES FROM BASELINE SIGNAL
745
IDENTIFY FEATURES FROM CURRENT SIGNAL
750
NORMALIZE AND COMPARE RECONSTRUCTED SIGNAL TO BASELINE SIGNALS
755
OUTPUT INDICATOR IF FAULT IS DETECTED
END

FIG. 7

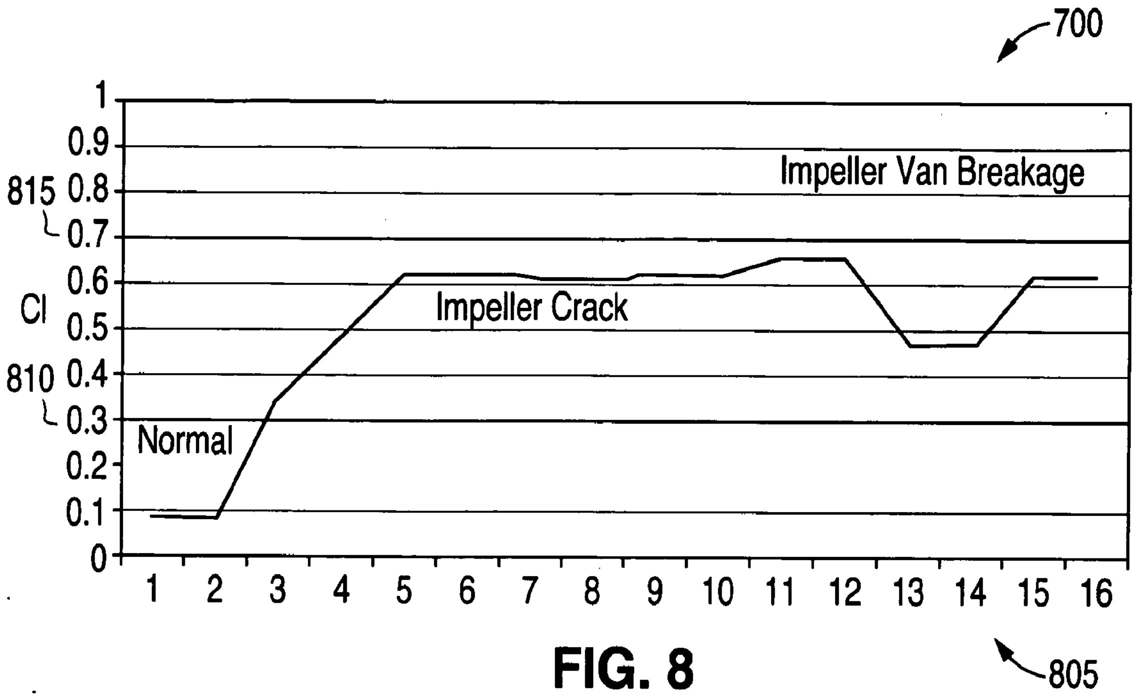

700
1
0.9
815 0.8
0.7
0.6
CI 0.5
810 0.4
0.3
0.2
0.1
0
Impeller Van Breakage
Impeller Crack
Normal
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
805

**FIG. 8**

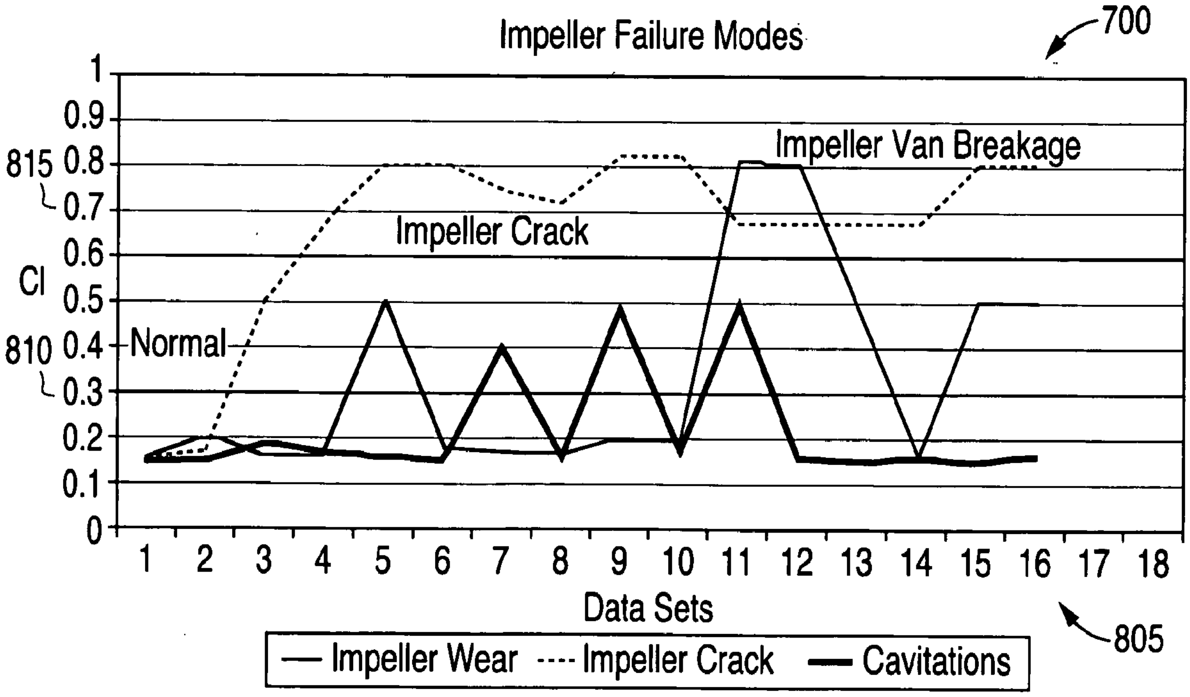

Impeller Failure Modes
700
1
0.9
815 0.8
0.7
0.6
CI 0.5
810 0.4
0.3
0.2
0.1
0
Impeller Van Breakage
Impeller Crack
Normal
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Data Sets
— Impeller Wear ---- Impeller Crack ━ Cavitations
805

**FIG. 9**