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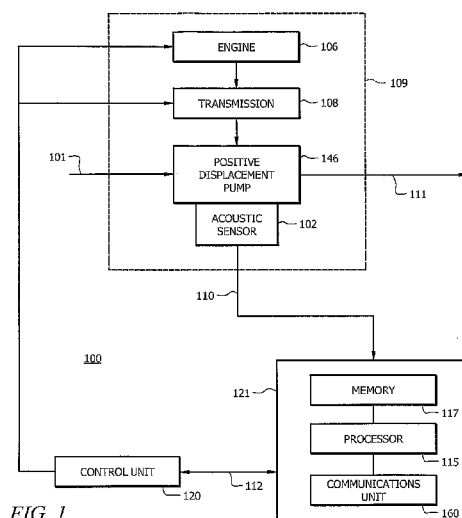


FIG. 1

(57) Abstract: A system and method for monitoring operation of a pump are disclosed herein. The methods and systems make use of acoustic sensors to collect and analyze data in order to detect cavitation. The disclosed methods and systems may also be used to detect valve damage. The pump may be a positive displacement pump that is employed in a wellbore servicing operation such as pumping a wellbore servicing fluid into a wellbore.

REAL TIME PUMP MONITORING

BACKGROUND

Field of the Invention

[0001] This invention relates generally to the field of pumps and improved systems and methods for monitoring and detecting potential problems or faults in pumps. More specifically, the invention relates to methods and systems for real time sensing of cavitation and/or valve leakage in pumps, for example positive displacement pumps used in wellbore servicing operations.

Background of the Invention

[0002] Wellbore servicing systems and equipment may include a variety of pumps, which require maintenance over time. With conventional maintenance strategies such as exception-based and periodic checking, faults developed in pumps have to be detected by human experts through physical examination and other off-line tests (*e.g.*, metal wear analysis) during a routine maintenance in order for corrective action to be taken. Faults that go undetected during a regular maintenance check-up may lead to catastrophic failure and unscheduled shutdown of the wellbore service. The probability of an unscheduled shutdown increases as the time period between successive maintenance inspections increases. The frequency of performing maintenance, however, is limited by availability of man-power and financial resources and hence is not easily increased. Some maintenance inspections, such as valve, plunger, or packing inspection may require stopping the process or even disassembling machinery. The lost production time may cost many times more than the labor cost involved. There is also a possibility that the reassembled machine may fail due to an assembly error or high start up stresses for example. Finally, periodically replacing components (via routine preventive maintenance) such as bearings, seals, or valves is costly since the service life of good components may unnecessarily be cut short.

[0003] Cavitation, leakage and valve damage are common problems/faults encountered with pumps. In particular, cavitation can cause accelerated wear and mechanical damage to pump components, couplings, gear trains, and drive motors. Cavitation is the formation of vapor bubbles in the inlet flow regime or the suction zone/stroke of the pump. This condition occurs when local pressure drops to below the vapor pressure of the liquid being pumped. These vapor bubbles collapse or implode when they enter a high pressure zone (*e.g.*, at the

discharge valve during the discharge/power stroke) of the pump causing erosion of and/or damage to pump components. If a pump runs for an extended period under cavitation conditions, permanent damage may occur to the pump structure and accelerated wear and deterioration of pump internal surfaces and seals may occur. Detection of such conditions before they become severe or prolonged can help to avoid cavitation-induced damage to the pump and facilitate extended wellbore up time. Such detection also can avoid accelerated pump wear and unexpected failures and further enable a well planned and cost-effective maintenance routine. Depending on the type of pump, other problems can occur such as inlet or outlet blockage, leakage of air into the system due to faulty pump seals or valves, leaky or damaged valves, internal parts impacting the pump casing, etc. Consequently, there is a need for improved systems and methods for monitoring and detecting potential problems or faults in pumps.

BRIEF SUMMARY

[0004] Disclosed herein is a method of servicing a wellbore, comprising establishing baseline acoustic data for a pump, pumping a wellbore servicing fluid into the wellbore with the pump, gathering service acoustic data for the pump while pumping the wellbore servicing fluid, comparing the baseline acoustic data to the service acoustic data, and determining a presence or absence of an abnormal operating condition of the pump.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] For a detailed description of the preferred embodiments of the invention, reference will now be made to the accompanying drawings in which:

[0006] Figure 1 illustrates a block diagram of an embodiment of a pump system for monitoring and/or detecting pump problems;

[0007] Figure 2A illustrates a cross-sectional view of positive displacement pump that may be used with embodiments of the pump system;

[0008] Figure 2B illustrates a top view of positive displacement pump that may be used with embodiments of the pump system;

[0009] Figure 3 illustrates a flow diagram of an embodiment of a method of detecting an abnormal operating condition in a pump;

[0010] Figures 4A-C are plots of time domain acoustic data measured by an acoustic sensor for a pump;

[0011] Figure 5 is a plot of frequency domain acoustic data measured by an acoustic sensor for a pump;

[0012] Figures 6A-C are power spectrums of acoustic data measured by an acoustic sensor for a pump;

[0013] Figures 7A-C are plots of acoustic data measured by an acoustic sensor from a pump;

[0014] Figures 8-11 are plots of g's over a test period of time for a cavitating pump operating in gears 3-6, respectively; and

[0015] Figures 12-15 are plots of g's over a test period of time for a pump having a leaky valve and operating in gears 3-6, respectively.

NOTATION AND NOMENCLATURE

[0016] Certain terms are used throughout the following description and claims to refer to particular system components. This document does not intend to distinguish between components that differ in name but not function.

[0017] In the following discussion and in the claims, the terms “including” and “comprising” are used in an open-ended fashion, and thus should be interpreted to mean “including, but not limited to...”. Also, the term “couple” or “couples” is intended to mean either an indirect or direct connection. Thus, if a first device couples to a second device, that connection may be through a direct connection, or through an indirect connection via other devices and connections.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0018] Figure 1 is a block diagram of an embodiment of a system 100 for detecting cavitation and/or valve damage in a pump 146. System 100 generally comprises a pump 146 having input 101 and output 111, an acoustic sensor 102 connected to and/or disposed proximate to pump 146, an engine 106, and a transmission 108, which may all be co-located, for example mounted on a trailer and/or housed within an enclosure 109. In an embodiment, the acoustic sensor 102 is connected/mounted to or proximate a fluid end of the pump 146. Acoustic sensor 102 may be coupled via signal 110 to a monitoring system 121 (e.g., a data

acquisition, processing, and/or control system), which may either be located locally (e.g., integral with) the pump system 100 or may be located remotely (e.g., distributed) from system 100. The monitoring system 121 may be integral with and/or further coupled to (e.g., via signal 112) a control unit 120, which may monitor the operation of the system 100 (e.g., pump 146) and provide control signals to the system 100 (e.g., pump 146 and/or component thereof such as engine 106 and/or transmission 108) during the course of an operation performed by system 100 (e.g., a pumping operation such as pumping a wellbore servicing fluid downhole).

[0019] In an embodiment, pump 146 is a positive displacement pump. Figures 2A and 2B show embodiments of a positive displacement pump, which may be used as part of the disclosed systems and methods. Figure 2A is a cross-sectional view of a portion of an embodiment of a positive displacement pump 246, which may be used as part of the disclosed systems and methods. Positive displacement pump 246 may be operated in a conventional manner. The positive displacement pump 246 includes an input 298, which receives fluid material from a fluid source (e.g., a suction line, storage or mix tank, discharge from a boost pump such as a centrifugal pump, etc.), and an output 200, which may output fluid material to a discharge source (e.g., a flowmeter, distribution header, discharge line, wellhead, etc.). A pressure transducer may be located adjacent the output 200, so that a component of system 100 (e.g., control unit 120) monitors pressure of the fluid material output from the positive displacement pump 246.

[0020] As shown in Figure 2A, the positive displacement pump 246 comprises a fluid end 105 having a suction valve 202 for controlling the receipt of fluid material through the input 298 and a discharge valve 204 for controlling the output of fluid material through the output 200. Also, the positive displacement pump 246 includes a plunger 206 for controlling a pressure in a chamber 208 of the positive displacement pump 246, so that fluid material is suitably received into the chamber 208 via the input 298 and suction valve 202 and suitably discharged from the chamber 208 via the discharge valve 204 and the output 200. In embodiments, the sensor 102 is directly/indirectly attached to the fluid end 105 of the pump 246, for example adjacent the input 298 and/or output 200 or on the outer surface or housing of the fluid end.

[0021] As shown in Figure 2A, the positive displacement pump 246 comprises a power end 103. The plunger 206 is coupled through a crosshead to a connecting rod 210. The connecting rod 210 is connected to a crankshaft 212. An engine 106 may be coupled to crankshaft 212 through a transmission 108 and a drive shaft (as shown in Figures 1 and 2). Through the

transmission 108, the engine 106 rotates the drive shaft and, in turn, rotates the crankshaft 212. At a rate of once per 360° rotation of the crankshaft 212, the connecting rod 210 moves the plunger 206 into and out of the chamber 208, completing a suction and discharge stroke of the pump.

[0022] Referring to Figure 2A, a single, representative chamber of a positive displacement pump is shown. In an embodiment as shown in Figure 2B, the positive displacement pump 246 includes two or more substantially identical chambers, for example three chambers 130 are connected to a common crankshaft 212. The crankshafts of those portions are connected to one another, yet aligned at 120° intervals relative to one another. Accordingly, each portion operates 120° and 240° out-of-phase with the other two portions, respectively, so that such portions collectively generate a more uniform rate of flow.

[0023] During operation of pump, as plunger 206 moves away from valves 202, 204 (i.e., toward the left in Figure 2A), the pressure drop or vacuum in chamber 208 causes discharge valve 204 to close and suction valve 202 to open, allowing fluid to enter chamber 208. This phase may be known as the “suction stroke.” During the “discharge stroke,” plunger 206 moves back towards the valves 202, 204 (i.e., toward the right in Figure 2A), forcing suction valve 202 to close and discharge valve 204 to open. Fluid may then be forced from chamber 208 through the open discharge valve 204.

[0024] Without being limited by theory, when insufficient fluid enters the chamber 208 from suction valve 202, bubbles may be formed inside chamber 208 (i.e., cavitation occurs). During the discharge stroke, the presence of the bubbles causes a delay in the opening of discharge valve 204 because increased pressure is required to collapse the formed bubbles. The cavitation bubbles can inflict damage to the inner surfaces of the pump through microjets and shockwaves (e.g., pressure waves) caused by bubble collapse. The collapsing bubbles may also cause acoustic vibrations (e.g., pressure waves) in the pump chamber 208 and also cause valve bounce, and the vibrations produced by cavitation and/or valve bounce may be detected by an acoustic sensor 102 such as without limitation, a knock sensor, as described herein.

[0025] Acoustic sensor 102 may be any sensor capable of monitoring or detecting acoustic signals. In one embodiment, acoustic sensor 102 is a commercially available knock sensor such as Bosch® Knock Sensor model KS-P. Other examples of acoustic sensors include without limitation, microphones, sonar, photoacoustic sensors, acoustic wave sensors, or combinations thereof. As discussed in more detail herein, the acoustic sensor 102 is effective to detect energy

signals produced by cavitation and/or valve leakage in the pump. Accordingly, one or more acoustic sensors may be mounted directly on the pump (e.g., bolted or attached to the pump housing or outer surface) or indirectly on the pump (e.g., bolted or magnetically attached to a pump mount or frame). In an embodiment, the acoustic sensor is mounted adjacent the fluid end of the pump (e.g., where fluid enters/exits the pump), in contrast to the power end of the pump (e.g., where the engine/transmission are connected to the pump). In an embodiment, one or more acoustic sensors are attached directly/indirectly, adjacent/proximate to the suction and/or discharge valves on the fluid end of the pump. In some embodiments, acoustic sensor 102 may comprise a piezoelectric element. The frequency over which the acoustic sensor is capable of detecting acoustic energy is referred to as the knock sensor's frequency response range. In various embodiments, the knock sensor may have a frequency response range of from about 1 Hz to about 20,000 Hz, alternatively from about 1 Hz to about 10,000 Hz, alternatively from about 1 Hz to about 5000 Hz, alternatively from about 100 Hz to about 5000 Hz, alternatively from about 1000Hz to about 5000Hz. In an embodiment, the knock sensor (or other component of the system 100 such as control unit 120 or monitoring system 121) may employ one or more filters to alter the frequency response range of the knock sensor. In an embodiment, the knock sensor detects acoustic energy falling within the sensor's frequency response range and provides an output as signal 110 to data acquisition, processing, and control system 121. For example, the knock sensor may output a voltage signal (e.g., a millivoltage signal). In an embodiment, the knock sensor comprises a piezoelectric element that provides the voltage signal.

[0026] Referring again to Figure 1, monitoring system 121 may comprise a computing device or system such as without limitation, computers, laptops, personal digital assistants, or combinations thereof having one or more data acquisition, processing, and control components residing therein in software, firmware, and/or hardware. Preferably, various of the data acquisition, processing, and control functions may be integrated into a single device. However, in other embodiments, data acquisition, data processing, and control functions may be divided into separate devices. The monitoring system 121 is capable of transmitting and/or receiving data to/from various components of the system 100.

[0027] The monitoring system 121 may comprise various components, such as a processor 115 (a central processor unit, CPU), a memory 117, and a communications unit 160. The processor 115 may comprise one or more microcontrollers, microprocessors, etc., that are

capable of executing a variety of software components. The memory 117 may comprise various memory portions, where a number of types of data (e.g., internal data, external data instructions, software codes, status data, diagnostic data, testing profiles, operating guidelines, etc.) may be stored. The memory 117 may store various tables or other database content that could be used by the pump system 100 to control operations thereof. The memory 117 may comprise read only memory (ROM), random access memory (RAM) dynamic random access memory (DRAM), electrically erasable programmable read-only memory (EEPROM), flash memory, hard drives, removable drives, etc.

[0028] It is understood that by programming and/or loading executable instructions onto the monitoring system 121, at least one of the processor and/or memory are changed, transforming the monitoring system 121 in part into a particular machine or apparatus having the novel functionality taught by the present disclosure. It is fundamental to the electrical engineering and software engineering arts that functionality that can be implemented by loading executable software into a computer can be converted to a hardware implementation by well known design rules. Decisions between implementing a concept in software versus hardware typically hinge on considerations of stability of the design and numbers of units to be produced rather than any issues involved in translating from the software domain to the hardware domain. Generally, a design that is still subject to frequent change may be preferred to be implemented in software, because re-spinning a hardware implementation is more expensive than re-spinning a software design. Generally, a design that is stable that will be produced in large volume may be preferred to be implemented in hardware, for example in an application specific integrated circuit (ASIC), because for large production runs the hardware implementation may be less expensive than the software implementation. Often a design may be developed and tested in a software form and later transformed, by well known design rules, to an equivalent hardware implementation in an application specific integrated circuit that hardwires the instructions of the software. In the same manner as a machine controlled by a new ASIC is a particular machine or apparatus, likewise a computer that has been programmed and/or loaded with executable instructions may be viewed as a particular machine or apparatus.

[0029] The communication unit 160 is operable to facilitate communications with other components of the system 100. In particular, the communication unit 160 is capable of providing transmission and reception of electronic signals to and from acoustic sensor 102 via signal 110 and/or control unit 120 via signal 112. For example, communication unit 160 may

be a wireless device capable of transmitting and receiving signals to/from acoustic sensor 102 and/or control unit 120 without the use of wires. Alternatively, communication unit 160 may be a wired device capable of transmitting and receiving signals to/from acoustic sensor 102 and/or control unit 120 using wires. In an embodiment, monitoring system 121 is a commercially available data acquisition, processing, and control system such as a Rockwell Automation® XM-120 general monitoring device. In an embodiment, the monitoring system 121 receives an analog input (e.g., a voltage signal) from the acoustic sensor 102 and may further process the analog input signal, for example converting the signal from analog to digital and/or conversion from time domain to frequency domain, e.g., via a (Fast) Fourier transform (FFT). In an embodiment, the signal from the acoustic sensor 102 is converted from a voltage signal to a signal measured in g's via a conversion factor. In an embodiment, the conversion factor is about 26 mV/g.

[0030] Now referring to Figure 3, a flowchart of an embodiment of a method for detecting an abnormal operating condition (e.g., cavitation, valve bounce, valve leakage) in a pump is shown. The method of Figure 3 may be implemented via the system of Figure 1. In block 301, pump 146 may be operated under nominal operating conditions. Typically, pump 146 during this stage is operating without cavitation or other defect such a valve bounce or leakage. During nominal pump operation, the acoustic sensor 102 may continuously monitor acoustic data from the pump assembly as in block 303. As used herein, “nominal pump operation” may refer to pump operation without cavitation, valve damage or other abnormalities. The system 100 detects abnormalities by acquiring acoustic data during one or more pump cycles. Preferably, system 100 uses a knock sensor to acquire the acoustic data. However, as noted above, any suitable acoustic sensor may be used to collect acoustic data. The acoustic data collected during nominal pump operation in block 301 may be used to establish a baseline measurement for a normally operating pump (e.g., non-cavitating) in block 303, referred to herein as baseline data. In an embodiment, a baseline measurement of acoustic data is established for nominal operation of original equipment manufacture (OEM) equipment prior to or shortly after placing such equipment into service for the first time or alternatively for nominal operation of remanufactured, repaired, or overhauled equipment prior to or shortly after placing such equipment back into service. The baseline data may be stored in memory 117 for later comparison with acoustic data collected during real time operation of the pump while in service (e.g., while operating on a job), referred to herein as service data.

[0031] Once baseline data has been established, service data may be further collected or monitored during real-time operation of the pump in block 305 (for example, during a pumping operation at a well site such as pumping a wellbore servicing fluid down hole). Service data may be collected continuously (e.g., whenever the pump is in operation) or intermittently (upon certain intervals of pump operation, e.g., time intervals, stroke intervals, volume intervals, etc.), and may likewise be stored in memory if desired. The service data may then be compared and/or analyzed to the baseline data in block 307. Again, the comparison of block 307 may be carried out in real time during operation of the pump during the service, or the service data may be stored and compared to the baseline data subsequent to performance of the pumping service. The comparison of baseline to service acoustic data is analyzed to detect indicators of abnormal pump operation (e.g., increased acoustic magnitude at certain frequencies indicating cavitation, valve bounce, valve mis-timing, valve leakage, etc.). Several different analysis techniques (e.g., comparison of time domain data, frequency domain data, and/or power spectrum data) may be used when comparing the service data with the baseline data which will be described in more detail below. Upon analysis of the acoustic data and detection of abnormal pump operation in block 309, one or more pump, system, and or service/job parameters may be adjusted in block 313 to correct and/or compensate for the abnormal condition (e.g., reduce pump cavitation). Examples of pump parameters that may be adjusted include pump speed, boost pressure, flow rate, fluid properties, etc., and such parameters may be adjusted via the control unit 120. Additionally and/or alternatively, other remedial measures or maintenance may be performed where pump cavitation or other operating problems are detected. Following remedial measures or maintenance, further service data may be collected and monitored by returning to block 310 and/or additional baseline data may be collected by returning to block 303.

[0032] In an embodiment, the acoustic sensor 102 outputs a voltage signal to the monitoring system 121, which correlates the voltage signal to an magnitude measurement such as g's or decibels over time and establishes baseline and service data using such measurements to produce time domain data such as that shown in Figures 4A-C. In some embodiments, a given data point may represent an average of several data readings for a given period of time (e.g., 1 second), and such points may be represented as a root mean square of the several data readings for the given period. While acoustic data may be collected over a wide frequency range (e.g., the acoustic sensor's frequency response range of from about 1 Hz to about 20,000 Hz), analysis need not cover the entire measured or sampled frequency range, and in some

embodiments a frequency sub-range (e.g., 1,000 to 5,000 Hz) may be analyzed via comparison of baseline data to service data. The time domain baseline data and the time domain service data may be compared to determine if abnormal pump operating conditions exist as described in more detail herein.

[0033] In addition, acoustic data may be analyzed at specific frequencies in detecting pump abnormalities. Time domain acoustic data (e.g., voltage readings converted to energy readings over a period of time to establish baseline and service data sets) may be collected using the acoustic sensor. The time domain acoustic data may then be transformed into frequency domain acoustic data using a transform algorithm, for example a Fast Fourier Transform (FFT) algorithm. In some embodiments, the entire measured frequency range (e.g., the acoustic sensor's frequency response range of from about 1 Hz to about 20,000 Hz) need not be transformed and/or compared, provided however that in some instances a larger sub-range of the measured data (e.g., from 1 Hz to 10,000 Hz of the time domain data) may be needed in order to produce transformed data in the desired frequency range for analysis (e.g., 1 Hz to 5,000 Hz), as shown in Figure 5. The frequency domain baseline data and the frequency domain service data may be compared to determine if abnormal pump operating conditions exist as described in more detail herein.

[0034] Alternatively, the power spectrum may be derived from the transformed baseline data and the transformed service data over a given frequency range. Referring to Figures 6A-C, the power spectrum may be represented as a 2-D plot of magnitude (e.g., power) on the y-axis as a function of frequency on the x-axis. Alternatively, the power spectrum may be further represented as a 3-D plot of magnitude (e.g., power) on the y-axis as a function of frequency on the x-axis and time on the z-axis. The power spectrum of the baseline data may be compared to the power spectrum of the service data over a given frequency range to determine if abnormal pump operating conditions exist as described in more detail herein.

[0035] In an embodiment, baseline and service data (e.g., time domain, frequency domain, and/or power spectrum data) may be compared and analyzed to detect one or more indicators of pump cavitation. For example, indicators of pump cavitation include data magnitude (e.g., increases in data magnitude), valve bounce (e.g., bounce of the discharge valve upon closing), valve lag (e.g., a time lag in closure of the suction valve), or combinations thereof. In embodiments, such indicators may be detected by analyzing data in the time domain and/or the frequency domain as described herein. Without being limited by theory, one cause of valve

bounce may be the collapse of the cavitation bubbles in the chamber during cavitation. Accordingly, valve bounce may serve as another indicator of cavitation. Likewise, an increase in signal magnitude (e.g., g's) over baseline may indicate that the plunger is slamming or "hammering" closed upon collapse of bubbles, and thus may likewise indicate cavitation. Figures 4A-C show various indicators of pump cavitation for data in the time domain collected from a knock sensor located on the fluid end (FE) of a positive displacement pump. More specifically, Figure 4A is time domain baseline data for a non-cavitating pump, Figure 4B is time domain service data for a cavitating pump, and Figure 4C is an overlay of the data from Figures 4A and 4B. Baseline acoustic data (as shown in Figure 4A for a non-cavitating pump) and service acoustic data (as shown in Figure 4B for a cavitating pump) in the time domain may be collected using an acoustic sensor, and such data may be analyzed over a given time period (for example the time period corresponding to one or more pump cycles).

[0036] In an embodiment, data magnitude is an indicator of abnormal pump operation (e.g., cavitation). As can be seen by comparing the scale of the y-axis on the right sides of Figures 4A and 4B, the cavitating pump produces a higher signal magnitude as measured in g's than the non-cavitating pump. The majority of the data in the non-cavitating pump is below 2 g's, with only one peak significantly above 2 g's (i.e., the peak at about 0.225 seconds). In contrast, the cavitating pump shows numerous peaks over 5 g's, and several peaks over 10 g's. Thus, in an embodiment, acoustic data (e.g., time domain data) may be analyzed (e.g., in block 307 of Figure 3) by comparing baseline data to service data to determine whether there is an increase in measured magnitude, for example an increase in decibel level and/or g's. In an embodiment, if the service data magnitude (or an average thereof such as root mean square or other curve fit) is from about 2, 3, 4, 5, 6, 7, 8, 9, or 10 g's greater than the baseline data magnitude (or an average thereof such as root mean square or other curve fit), then the monitoring system 121 may signal a user (e.g., sound an alarm and/or send an alarm signal to control unit 120) that abnormal pump operation (e.g., cavitation) has been detected and one or more pump system parameters may be altered to implement corrective action. In another embodiment, if the service decibel level (or an average thereof such as root mean square or other curve fit) is from about 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25 or 30 dB greater than the baseline decibel level or an average thereof such as root mean square or other curve fit), then the monitoring system 121 may signal a user (e.g., sound an alarm and/or send an alarm signal to control unit 120) that abnormal pump operation (e.g., cavitation) has been detected and one or more pump system parameters may be altered to

implement corrective action. In another embodiment, if the service data magnitude (or an average thereof such as root mean square or other curve fit) is from about 50, 100, 150, 200, 250, 300, 350, 400, 450, or 500% greater than the baseline data magnitude (or an average thereof such as root mean square or other curve fit), then the monitoring system 121 may signal a user (e.g., sound an alarm and/or send an alarm signal to control unit 120) that abnormal pump operation (e.g., cavitation) has been detected and one or more pump system parameters may be altered to implement corrective action.

[0037] In an embodiment, valve bounce is an indicator of abnormal pump operation (e.g., cavitation). Such normal valve closure and/or bounce profiles may be established as baseline data as described previously and then compared to service data to detect undesired closure and/or bounce profiles that may be indicative of abnormal pump operation (e.g., cavitation). For example, the service data may be analyzed for one or more peaks of acoustic energy after a peak indicating normal valve closing time to detect bounce. More specifically, Figure 4A shows the baseline data of a non-cavitating pump for one pump cycle, whereas Figure 4B shows the service data of a cavitating pump for one pump cycle. Valve bounce as labeled in Figure 4B is indicated by a second spike or peak in acoustic energy after the initial peak of energy (the nominal valve closing peak). As shown in Figure 4A, the fluid end (FE) discharge valve may bounce upon closure as denoted on the figure, which is somewhat normal in non-cavitating operation due to the spring closure bias on the discharge valve. A similar discharge valve bounce is shown in Figure 4B as well. However, in a cavitating pump, a valve bounce is detected upon closing of the suction valve (in contrast to the normal bounce on closure of the discharge valve), as denoted on Figure 4B. No such bounce on closure of the suction valve is indicated in the non-cavitating pump of Figure 4A. Thus, these plots show that bounce on closure of the suction valve is indicative of cavitation, which without wishing to be limited by theory, may be due to the volume of fluid being less (e.g., more air present), such that the spring may slam the valve closed more violently because the spring is typically sized for the desired operational rate and density of the liquid (in contrast to air). As such, if the control unit 120 detects valve bounce (e.g., suction valve bounce) from acoustic data, it may sound an alarm and/or send a signal to change one or more pump system parameters in order to reduce cavitation.

[0038] In an embodiment, valve lag is an indicator of abnormal pump operation (e.g., cavitation). As used herein, valve lag refers to a time delay or lag in closure of a valve.

Without being limited by theory, when cavitating the suction valve may close several milliseconds later than a suction valve during normal non-cavitating operation, which may be a function of bubble collapse. Thus, service acoustic data may be compared to baseline acoustic data to detect valve lag, as shown in Figure 4C. When service data from a cavitating pump is overlain with baseline data from a non-cavitating pump, delays in valve closure (e.g., suction valve lag, discharge valve lag, or both) are clearly identifiable as denoted on Figure 4C. Furthermore, such lag may be measured and/or detected in comparison to the expected valve closure time based upon position of the plunger, as indicated for example by a timing mark located on a mechanical component of the pump such as the cam shaft. The expected valve closure time is indicated by the start of the square notch in the plunger position line in Figure 4C, as so labeled. As is shown, the non-cavitating pump indicates closure in close correlation with the expected valve closure time as indicated by plunger position whereas the cavitating pump shows valve lag from expected valve closure time. As such, if the control unit 120 detects valve lag from acoustic data, it may sound an alarm and/or send a signal to change one or more pump system parameters in order to reduce cavitation.

[0039] In another embodiment, baseline and service time domain acoustic data can be transformed to corresponding baseline and service frequency domain acoustic data and comparisons made to detect pump abnormalities such as cavitation. The transformed frequency domain acoustic data may be analyzed (e.g., a comparison of transformed baseline data to transformed service data) at a frequency ranging from greater than about 0 Hz to about 5,000 Hz, alternatively from about 1,000 Hz to about 5,000 Hz, alternatively from about 1,000 Hz to about 4,000 Hz, alternatively from about 2,000 Hz to about 4,000 Hz, alternatively from about 2,500 Hz to about 3,500 Hz, alternatively from about 2,000 Hz to about 3,000 Hz, alternatively from about 1,750 Hz to about 2,250 Hz, alternatively about 2000 Hz, alternatively about 3,000 Hz, or combinations thereof. If spikes in the transformed service data are detected above the transformed baseline data at the above frequency ranges, then the pump is operating abnormally, for example cavitating.

[0040] When analyzing data in the frequency domain, data magnitude is an indicator of abnormal pump operation (e.g., cavitation). Figure 5 demonstrates that acoustic sensors (e.g., knock sensors) are capable of detecting cavitation in a pump. A positive displacement pump was operated under normal, non-cavitating operating conditions, as shown by the lower line plotted in Figure 5. Over a period of time, fluid flow to the suction end of a positive

displacement pump was gradually decreased in 25% increments until cavitation resulted. As shown by the upper line plotted in Figure 5, cavitation resulted in a first dramatic spike in data magnitude at from about 1500 to 2500 Hz, or 1750 to 2250 Hz, or about 2000 Hz and a second dramatic spike at from about 3500 to 5000 Hz, or 4000 to 5000 Hz, or 4500 to 5000 Hz. In an embodiment, the presence of at least two spikes in data magnitude at two different frequencies or frequency ranges may indicate abnormal pump operation (e.g., cavitation), which is explained in more detail in the Examples. Again, comparison of plots such as shown in Figure 5 may use a data average thereof such as root mean square (RMS as indicated on the y-axis) or other curve fit or data normalization technique. The results show that the acoustic sensor is capable of detecting cavitation in a positive displacement pump as indicated by an increase in data magnitude (e.g., increase in dB or g's in service data over baseline data). In some embodiments, the magnitude of increases in data magnitude in the frequency domain may fall within the indication ranges for dBs, g's, and percentage increases set forth previously for data in the time domain. Upon detection of an magnitude indication of a pump abnormality (e.g., cavitation), the monitoring system 121 may signal a user (e.g., sound an alarm and/or send an alarm signal to control unit 120) that abnormal pump operation (e.g., cavitation) has been detected and one or more pump system parameters may be altered to implement corrective action.

[0041] When analyzing data in the frequency domain, data magnitude as represented by a power spectrum analysis may serve as an indicator of abnormal pump operation (e.g., cavitation). For example, the area under the power spectrum curve for the baseline data (e.g., normal operation) can be compared to the area under the power spectrum curve for the service data, and an increase in power spectrum may indicate abnormal pump operation such as cavitation. In embodiments, the power spectrum for transformed baseline and service data are compared at a frequency ranging from greater than about 0 Hz to about 5,000 Hz, alternatively from about 1,000 Hz to about 5,000 Hz, alternatively from about 1,000 Hz to about 4,000 Hz, alternatively from about 2,000 Hz to about 4,000 Hz, alternatively from about 2,500 Hz to about 3,500 Hz, alternatively from about 2,000 Hz to about 3,000 Hz, alternatively from about 1,750 Hz to about 2,250 Hz, alternatively about 2000 Hz, alternatively about 3,000 Hz, or combinations thereof. Figures 6A-C shows the results of frequency analysis performed of acoustic energy detected from a cavitating pump using power spectrum area analysis. In Figure 6A, acoustic energy was measured over a frequency range of 0 to 12,000 Hz over the test

period. The three-dimensional waterfall plot in Figure 6A shows the large increase in acoustic energy during cavitation at a frequency range of about 2,000 Hz to about 6,000 Hz. Figure 6B shows a two-dimensional plot at a particular point in time during cavitation, as shown by cross-section line B—B of Figure 6A. Figure 6C is another two-dimensional plot at a particular frequency (e.g., about 4000 Hz) during cavitation, as shown by cross-section line C—C of Figure 6A. Figure 6C shows a large spike of acoustic energy over baseline (as measured by the ratio of area under the power spectrum curve for service data to baseline data) during the time between the suction valve closing and the discharge valve opening, which is indicative of pump cavitation and corrective action may be initiated. In another embodiment, if the ratio of service data magnitude to baseline data magnitude as represented by area under the power curve (e.g., integrated area under the power curve for a given frequency range) is equal to or greater than about 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, or 15, then the monitoring system 121 may signal a user (e.g., sound an alarm and/or send an alarm signal to control unit 120) that abnormal pump operation (e.g., cavitation) has been detected and one or more pump system parameters may be altered to implement corrective action.

[0042] In another embodiment, valve damage in pump (e.g., a positive displacement pump) may be detected by using acoustic data sensed by the acoustic sensor 102. In a pump with a damaged valve, without being bound by theory, the measured acoustic energy at high frequencies (e.g., magnitude of the service data) should be significantly larger than acoustic energy in a normal pump without a damaged valve (e.g., magnitude of the baseline data). Accordingly, the magnitude of the acoustic energy from the service and baseline data may be compared in the time domain (e.g., Figure 7A), the frequency domain (e.g., Figure 7B), or both. If the magnitude of the acoustic energy at certain time and/or frequency is higher than a predetermined range or threshold, the valve may be damaged, and an alarm may be sounded and/or a signal may be sent to change one or more pump system parameters in order to reduce cavitation. Figure 7A is a time domain plot comparing the acoustic energy in g's (top line) of a pump with a damaged suction valve (e.g., service data) and the acoustic energy in g's (bottom line) of a pump with a normal suction valve (e.g., baseline data). The magnitude of acoustic energy measured in a pump with a damaged valve (or an average thereof such as root mean square or other curve fit) is noticeably larger than the magnitude of acoustic energy in a normal pump, as represented by the delta in energy between the lines (e.g., difference in energy such as dB or g's). Without being limited by theory, this is likely due to noise or "hiss" associated with

fluid escaping through a leaky valve. Referring to Figure 7C, such “hiss” is also demonstrated in the time domain for a single pump stroke for a pump having a damaged suction valve (e.g., service data) in comparison to a pump with a normal suction valve (e.g., baseline data). Such “hiss” may be associated with pressure placed upon the damaged suction valve when closed during the discharge stroke of the pump, with fluid escaping through the damaged portion. In embodiments, “hiss” associated with valve leakage may be indicated by data magnitude (e.g., increase in service data energy over baseline energy in dB or g’s) during the discharge and/or suction stroke of the pump, as associated with suction and/or discharge valve damage, respectively. In an embodiment, if the service data magnitude (or an average thereof such as root mean square or other curve fit) is from about 2, 3, 4, 5, 6, 7, 8, 9, or 10 g’s greater than the baseline data magnitude (or an average thereof such as root mean square or other curve fit), then the monitoring system 121 may signal a user (e.g., sound an alarm and/or send an alarm signal to control unit 120) that abnormal pump operation (e.g., valve leakage) has been detected and one or more pump system parameters may be altered to implement corrective action. In another embodiment, if the service decibel level (or an average thereof such as root mean square or other curve fit) is from about 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25 or 30 dB greater than the baseline decibel level or an average thereof such as root mean square or other curve fit), then the monitoring system 121 may signal a user (e.g., sound an alarm and/or send an alarm signal to control unit 120) that abnormal pump operation (e.g., valve leakage) has been detected and one or more pump system parameters may be altered to implement corrective action. In another embodiment, if the service data magnitude (or an average thereof such as root mean square or other curve fit) is from about 50, 100, 150, 200, 250, 300, 350, 400, 450, or 500% greater than the baseline data magnitude (or an average thereof such as root mean square or other curve fit), then the monitoring system 121 may signal a user (e.g., sound an alarm and/or send an alarm signal to control unit 120) that abnormal pump operation (e.g., valve leakage) has been detected and one or more pump system parameters may be altered to implement corrective action. Additional disclosure regarding detection of cavitation and/or valve leakage is shown in the Examples.

[0043] Figure 7B is a frequency domain plot showing the frequency range of acoustic data collected from a pump with a damaged valve in comparison to a non-damaged valve. There is a significant increase (from about 6x to about 10x) in energy as measured in g’s between baseline data and service data at a frequency of from about 4,500 to 5,000 Hz. Likewise, differences

between service and baseline data at about 1,500 Hz and 3,500 Hz in Figure 7B, or in the range of from about 1,750 to about 2,250 Hz as shown in the Examples, may also indicate valve damage. These results show that using an acoustic sensor to detect acoustic energy at certain frequencies is a feasible way of detecting valve damage in a pump.

[0044] When abnormalities in pump operation (e.g., cavitation) have been detected by the various techniques described above, control system 121 may sound an alarm and/or adjust one or more pump parameters or other operating conditions to reduce or eliminate cavitations. Examples of pump parameters that may be adjusted include without limitation, pump speed, pump pressure, boot pressure, pump temperature, pump flow rate, or combinations thereof. In an embodiment, properties of the fluid being pumped may be adjusted, for example density. The pump parameters and/or operating conditions (collectively, pump system parameters) may be adjusted automatically by the control system, or they may be adjusted manually by a user. Likewise, corrective action may be taken upon detecting valve problems such as valve leakage, valve bounce, etc. by servicing the pump to replace or repair faulty valve components (seats, stems, seals, springs, etc.).

[0045] In some embodiments, the pump system and methods disclosed herein are employed in a wellbore servicing operation. The pump system may be transported to a well site, for example transported on a skid or trailer to an onshore well site or transported via barge or ship to an offshore well site. A wellbore servicing fluid may be transported to and/or prepared at the well site. In an embodiment, the wellbore service comprising preparing and placing downhole one or more wellbore servicing fluids including, but are not limited to, cement slurries, lost circulation pills, settable fluids, plugging compositions for plug-and-abandon purposes, gravel packing fluids, chemical packers, temporary plugs, spacer fluids, completion fluids, remedial fluids, fracturing fluids, or combinations thereof. In an embodiment, the wellbore service is a drilling operation and the servicing fluid is a drilling fluid. In an embodiment, the wellbore service is a cementing operation and the servicing fluid is a cementitious fluid (e.g., a cement slurry for primary and/or secondary cementing operations). In an embodiment, the wellbore service is a enhanced recovery operation (e.g., primary and/or secondary fracturing, acidizing, flooding, etc.) and the servicing fluid is a fracturing fluid (e.g., proppant slurry), acid fluid, sweeping/flooding fluid (e.g., water/steam), etc. In an embodiment, the wellbore service is a gravel packing service and the servicing fluid is a gravel pack fluid. The wellbore servicing fluid may be pumped into the wellbore during the service using a pump system as described

herein (e.g., positive displacement pump), and the operation of the pump may be monitored as described herein to detect cavitation, valve bounce, and/or valve damage therein. In various embodiments, the wellbore servicing fluid is pumped with a positive displacement pump operating at from about 100 to about 500 rpm, alternatively from about 150 to about 450 rpm, alternatively from about 150 to about 400 rpm, alternatively from about 150 to about 350 rpm, alternatively from about 150 to about 300 rpm, alternatively from about 200 to about 350 rpm, alternatively from about 250 to about 350 rpm.

[0046] In an embodiment, the system 100 is employed in a wellbore servicing operation, wherein pump 146 is a positive displacement pump pumping a wellbore servicing fluid (e.g., cement slurry, fracturing fluid, drilling fluid, etc.) down a wellbore, and wherein the wellbore servicing operation is controlled by the control unit 120, for example an ACE or ARC Control Unit available from Halliburton Energy Services. The control unit 120 may generate and deliver control signals to pump 146. For example, control unit 120 may receive automated and/or manual instructions from a user input and/or may send signals to pump 146 based on internal calculations, programming, and/or data received from monitoring system 121 and/or acoustic sensor 102. The control system 120 is capable of affecting and controlling substantially all process control variables and functions of the pump system 100.

EXAMPLES

[0047] In the following examples, a three plunger positive displacement pump of the type shown in Figure 2 was used to pump non-potable water. The acoustic sensor used to gather data was mounted on the suction header adjacent the fluid end. Sensor data was gathered and analyzed with e-Z Analyst v5.1.35 vibration and acoustic analysis software from IOtech to provide the plots set forth in Figures 8-15 discussed below. The pump was connected to an engine and transmission having a plurality of gears (e.g., 1st – 7th), allowing the pump to operate at various RPMs and flow rates (barrels per min) as set forth in the following Table 1:

<u>Gear</u>	<u>RPM Min.</u>	<u>RPM Max.</u>	<u>Flow Rate Min.</u> <u>(BPM)</u>	<u>Flow Rate Max.</u> <u>(BPM)</u>
1	57	90.8	2.24	3.57
2	79.4	126.4	3.12	4.97
3	97.1	154.8	3.82	6.09
4	121	192.8	4.76	7.58
5	135.3	215.4	5.32	8.48
6	168.5	268.5	6.63	10.56

<u>Gear</u>	<u>RPM Min.</u>	<u>RPM Max.</u>	<u>Flow Rate Min.</u> <u>(BPM)</u>	<u>Flow Rate Max.</u> <u>(BPM)</u>
7	213.9	340.6	8.41	13.40

Example 1 – Cavitation

[0048] While operating the pump in gears 3-6 as set forth in Table 1, data was collected from the knock sensor and plotted in Figures 8-11, respectively. The strip charts (i.e., the lower plots so labeled) in Figures 8-11 represent a plot of RMS g's over a test period of time for operation in gears 3-6, respectively. Within the test period for a given gear, power spectrum analysis (as represented by the upper plots so labeled in Figures 8-11) was performed via FFT at various time intervals and plotted as RMS g's as a function of frequency from 0 to 5000 Hz. During the test period, pump speed was increased for each gear and cavitation was induced in the pump by restricting fluid flow to the pump by partially closing a valve in the suction side flow line to the pump.

[0049] Referring to Figure 8, the pump was operated for a test period of about 150 seconds in gear 3. From about 0 to about 47 seconds of the test period, the pump was operating in gear 3 at lower rpms (e.g., about 100 rpm) and with no cavitation, and the strip chart of Figure 8 shows low g's of about 0.5 during this period. The upper plot of Figure 8A represents a power spectrum analysis taken at about 8 seconds (as indicated by the vertical line at 8 seconds in the lower plot of Figure 8A) into the test period and shows two groups of peaks, labeled first indicator and second indicator. The first indicator shows a maximum peak at about 0.04 g's and the second indicator shows a maximum peak at about 0.02 g's.

[0050] From about 47 to about 88 seconds of the test period, the pump was operating in gear 3 at higher rpms (e.g., about 150 rpm) and higher overall energy but no cavitation, and the strip chart of Figure 8 shows slightly higher g's of from about 0.5 to about 1 during this period. The upper plot of Figure 8B represents a power spectrum analysis taken at about 58 seconds into the test period and shows two groups of peaks, labeled first indicator and second indicator. The first indicator shows a maximum peak at about 0.08 g's and the second indicator shows a maximum peak at about 0.04 g's.

[0051] From about 88 seconds to about 113 seconds, the pump was operating in gear 3 at higher rpms (e.g., about 150 rpm) and with cavitation induced by closing a suction side valve to a $\frac{3}{4}$ setting (i.e., $\frac{3}{4}$ way open). The strip chart of Figure 8 shows much higher g's of from about 2 to about 3 during this period. The upper plot of Figure 8C represents a power spectrum analysis taken at about 100 seconds into the test period and again shows two groups of peaks,

labeled first indicator and second indicator. The first indicator shows a maximum peak at from about 0.2 to 0.25 g's and the second indicator shows a maximum peak at from about 0.1 to about 0.15 g's, and these values in Fig. 8C are much greater (e.g., at least about 1.5, 1.75, 2.0, 2.25, or 2.5 times greater than) when the pump is cavitating than the corresponding values from Figures 8A and 8B taken in the absence of cavitation. Likewise, as shown in the strip chart of Figure 8, pump cavitation is clearly identified by a sharp increase in g's during the time period of from about 90 seconds to about 113 seconds while the suction side valve is partially closed. While the pump is cavitating, the overall g readings of from about 2 to 3 may (or may not) be considered acceptable for the pump operating at these conditions (e.g., gear, rpm, flow rate, given fluid, etc.), and thus appropriate cavitation alarm thresholds may not (or may) be employed for these operating conditions.

[0052] The process described above for operation of the pump in gear 3 was repeated for gears 4, 5, and 6 as shown in Figures 9, 10, and 11, respectively. Referring to Figure 9, the pump was operated for a test period of about 72 seconds in gear 4. From about 0 to about 18 seconds of the test period, the pump was operating in gear 4 at about 192 rpm and with no cavitation, and the strip chart of Figure 9 shows low g's of about 0.5 during this period. The upper plot of Figure 9A represents a power spectrum analysis taken at about 6.5 seconds into the test period and shows two groups of peaks, labeled first indicator and second indicator. The first indicator shows a maximum peak at about 0.07 g's and the second indicator shows a maximum peak at about 0.04 g's.

[0053] From about 18 seconds to about 43 seconds, the pump was operating in gear 4 at about 192 rpm and with cavitation induced by closing a suction side valve to a $\frac{3}{4}$ setting (i.e., $\frac{3}{4}$ way open). The strip chart of Figure 9 shows much higher g's of from about 3.75 to about 4.25 during this period. The upper plot of Figure 9B represents a power spectrum analysis taken at about 25 seconds into the test period and again shows two groups of peaks, labeled first indicator and second indicator. The first indicator shows a maximum peak at from about 0.3 to 0.4 g's (e.g., greater than 0.3 g's, alternatively greater than 0.35 g's) and the second indicator shows a maximum peak at from about 0.15 to about 0.25 g's (e.g., greater than 0.15 g's, alternatively greater than 0.2 g's), and these values in Fig. 9B are much greater when the pump is cavitating than the corresponding values from Figure 9A taken in the absence of cavitation. Likewise, as shown in the strip chart of Figure 9, pump cavitation is clearly identified by a sharp increase in g's from about 18 seconds to about 43 seconds while the suction side valve is

partially closed. While the pump is cavitating, the overall g readings of about 4 are more likely to be considered problematic (e.g., in comparison to the g reading of from about 2 to 3 for gear 3 and Figure 8) for the pump operating at these conditions (e.g., gear, rpm, flow rate, given fluid, etc.), and thus appropriate cavitation alarm thresholds may be employed for these operating conditions. Alarm thresholds may be associated with the first and second indicators (as well as any other indicator described herein), and may be set in accordance with the peak magnitudes or data values associated with the indicators. For example, as shown in Figure 9B, a first alarm threshold, second alarm threshold, third alarm threshold, or combinations thereof may be employed. For example, a first alarm threshold of about 0.3 g's may be set for the first indicator, a second alarm threshold of about 0.2 g's may be set for the second indicator, a third alarm threshold of about 4 g's may be set for the time domain data represented on the strip chart, or combinations thereof.

[0054] Referring to Figure 10, the pump was operated for a test period of about 88 seconds in gear 5. From about 0 to about 39 seconds of the test period, the pump was operating in gear 5 at about 215 rpm and with no cavitation, and the strip chart of Figure 10 shows low g's of about 0.75 during this period. The upper plot of Figure 10A represents a power spectrum analysis taken at about 18 seconds into the test period and shows two groups of peaks, labeled first indicator and second indicator. The first indicator shows a maximum peak at about 0.08 – 0.09 g's and the second indicator shows a maximum peak at about 0.03 – 0.04 g's.

[0055] From about 39 seconds to about 55 seconds, the pump was operating in gear 5 at about 215 rpm and with cavitation induced by closing a suction side valve to a $\frac{3}{4}$ setting (i.e., $\frac{3}{4}$ way open). The strip chart of Figure 10 shows much higher g's of from about 4 to about 6 during this period. The upper plot of Figure 10B represents a power spectrum analysis taken at about 47 seconds into the test period and again shows two groups of peaks, labeled first indicator and second indicator. The first indicator shows a maximum peak at from about 0.35 to 0.4 g's (e.g., greater than 0.3 g's, alternatively greater than 0.35 g's) and the second indicator shows a maximum peak at from about 0.2 to about 0.3 g's (e.g., greater than 0.2 g's, alternatively greater than 0.25 g's), and these values in Fig. 10B are much greater when the pump is cavitating than the corresponding values from Figure 10A taken in the absence of cavitation. Likewise, as shown in the strip chart of Figure 10, pump cavitation is clearly identified by a sharp increase in g's from about 39 seconds to about 55 seconds while the suction side valve is partially closed. While the pump is cavitating, the overall g readings of

from about 4 to about 6 (alternatively, about 5) are more likely to be considered problematic (e.g., in comparison to the g reading of from about 2 to 3 for gear 3 and Figure 8) for the pump operating at these conditions (e.g., gear, rpm, flow rate, given fluid, etc.), and thus appropriate cavitation alarm thresholds may be employed for these operating conditions. For example, as shown in Figure 10B, a first alarm threshold, second alarm threshold, third alarm threshold, or combinations thereof may be employed. For example, a first alarm threshold of about 0.3 g's may be set for the first indicator, a second alarm threshold of about 0.2 g's may be set for the second indicator, a third alarm threshold of about 4 g's (alternatively, 5 g's) may be set for the time domain data represented on the strip chart, or combinations thereof.

[0056] Referring to Figure 11, the pump was operated for a test period of about 88 seconds in gear 6. From about 0 to about 37 seconds of the test period, the pump was operating in gear 6 at about 268 rpm and with no cavitation, and the strip chart of Figure 11 shows low g's of about 1 during this period. The upper plot of Figure 11A represents a power spectrum analysis taken at about 13.5 seconds into the test period and shows two groups of peaks, labeled first indicator and second indicator. The first indicator shows a maximum peak at about 0.1 g's and the second indicator shows a maximum peak at about 0.04 – 0.05 g's.

[0057] From about 37 seconds to about 42 seconds, the pump was operating in gear 6 at about 268 rpm and with cavitation induced by closing a suction side valve to a $\frac{3}{4}$ setting (i.e., $\frac{3}{4}$ way open). The strip chart of Figure 11 shows much higher g's of from about 7 to about 8 during this period. The upper plot of Figure 11B represents a power spectrum analysis taken at about 38 seconds into the test period and again shows two groups of peaks, labeled first indicator and second indicator. The first indicator shows a maximum peak at from about 0.4 to 0.5 g's (e.g., greater than 0.3, 0.35, 0.4, 0.45, or 5 g's) and the second indicator shows a maximum peak at from about 0.2 to about 0.3 g's (e.g., greater than 0.2, 0.225, 0.25, or 0.275 g's), and these values in Fig. 11B are much greater when the pump is cavitating than the corresponding values from Figure 11A taken in the absence of cavitation. Likewise, as shown in the strip chart of Figure 11, pump cavitation is clearly identified by a sharp increase in g's from about 37 seconds to about 42 seconds while the suction side valve is partially closed. While the pump is cavitating, the overall g readings of from about 7 to about 8 demonstrate severe cavitation and unacceptably high levels of vibrational energy (as demonstrated by the very brief cavitation testing time of about 5 seconds) for the pump operating at these conditions (e.g., gear, rpm, flow rate, given fluid, etc.), and thus appropriate cavitation alarm thresholds

may be employed for these operating conditions. For example, as shown in Figure 11B, a first alarm threshold, second alarm threshold, third alarm threshold, or combinations thereof may be employed. For example, a first alarm threshold of about 0.3, 0.4, or 0.5 g's may be set for the first indicator, a second alarm threshold of about 0.2, 0.225, 0.25, 0.275, or 0.3 g's may be set for the second indicator, a third alarm threshold of about 4, 5, 6, or 7 g's may be set for the time domain data represented on the strip chart, or combinations thereof.

[0058] As shown in Figures 8-11, the second indicator as measured in g's is typically smaller than the first indicator. In some embodiments, the second indicator as measured in g's is from about $\frac{1}{2}$ to about $\frac{2}{3}$ the first indicator, alternatively about $\frac{1}{2}$ the first indicator, alternatively about $\frac{2}{3}$ the first indicator. The position (e.g., frequency ranges) of the first and second indicators as measured in Hz may shift slightly in frequency with changes in gearing, but the indicators remain clearly present. In some embodiments, the frequency range of the first indicator may be from about 2,000 to about 3,000 Hz, alternatively from about 2,250 to about 3,000 Hz, alternatively from about 2,500 to about 3,000 Hz, alternatively from about 2,250 to about 2,750 Hz, alternatively from about 2,500 to about 2,750 Hz, alternatively about 2,750 Hz. In some embodiments, the frequency range of the second indicator may be from about 3,500 to about 4,500 Hz, alternatively from about 3,500 to about 4,250 Hz, alternatively from about 3,500 to about 4,000 Hz, alternatively from about 3,750 to about 4,250 Hz, alternatively from about 3,750 to about 4,000 Hz, alternatively about 4,000 Hz. Where multiple peaks are present within a given frequency range for a given indicator, reference is typically made to the highest peak within the given frequency range. The frequency ranges of the first and/or second indicators may be further correlated with the various values for the first and/or second alarm thresholds (e.g., a first indicator having a designated frequency range and a corresponding first alarm threshold having a designated value). Furthermore, the first and/or second indicators; the first, second, and/or third alarm thresholds; or combinations thereof may be further correlated to a given operating gear and/or rpm range for the pump (e.g., a first indicator having a designated frequency range and a corresponding first alarm threshold having a designated value and further corresponding to a pump operating in a designated gear, rpm range, or flow rate such as those shown in Table 1). As demonstrated, the indicators of cavitation may show a multi-fold increase (e.g., equal to or greater than about 1x, 1.25x, 1.5x, 1.75x, 2x, 2.25x, 2.5x, 2.75x, 3x, 3.25x, 3.5x, 3.75, or 4x) increase as compared to a corresponding indicator of non-cavitation. Example 1 clearly demonstrates that pump cavitation can be identified from a number of

acoustical energy indicators or data provided by an acoustical sensor, and that one or more alarms may be associated with one or more threshold values for such indicators and/or data.

Example 2 – Leaky Suction Valve

[0059] Valve leakage was reproduced by placing a known leaky suction valve in one of the chambers of the three chamber pump. While operating the pump in gears 3-6 as set forth in Table 1, data was collected from the knock sensor and plotted in Figures 12-15, respectively. The strip charts in Figures 12-15 represent a plot of RMS g's over a test period of time for operation in gears 3-6, respectively. Within the test period for a given gear, power spectrum analysis (as represented by the upper plots so labeled in Figures 12-15) was performed via FFT at various time intervals and plotted as RMS g's as a function of frequency from 0 to 5000 Hz.

[0060] Referring to Figure 12, the pump was operated for a test period of about 60 seconds in gear 3 at about 150 rpm. The strip chart of Figure 12 shows g's ranging from about 3 to about 5 (alternatively, from about 3.5 to about 4.5 g's, alternatively equal to or greater than about 4 g's) during this period, which may be associated with the "hiss" of fluid passing through the leaky suction valve. The upper plot of Figure 12 shows a power spectrum analysis taken at about 7 seconds into the test period and shows two groups of peaks, labeled fourth indicator and fifth indicator. The fourth indicator shows a maximum peak at about 0.03 to about 0.35 g's (alternatively, equal to or greater than 0.25, 0.275, or 0.3 g's) and the fifth indicator shows a maximum peak at about 0.03 to about 0.35 g's (alternatively, equal to or greater than 0.25, 0.275, or 0.3 g's). Figure 12 also shows a sixth indicator having a maximum peak at about 0.225 to about 0.275 g's (alternatively, equal to or greater than 0.20, 0.225, or 0.25 g's). Alarm thresholds may be associated with the fourth, fifth, and/or sixth indicators, and may be set in accordance with the peak magnitudes associated with the indicators. In this instance, the fourth and fifth indicators are about equal to each other in magnitude, and thus the fourth and fifth alarm thresholds may likewise be about equal to each other (e.g., equal to or greater than 0.25, 0.275, or 0.3 g's). Also in this instance, the sixth indicator/alarm threshold may be less than the fourth and fifth. Alternatively, the fourth, fifth, and sixth alarm thresholds may be about equal (e.g., equal to or greater than about 0.25 g's).

[0061] Referring to Figure 13, the pump was operated for a test period of about 62 seconds in gear 4 at about 190 rpm. The strip chart of Figure 13 shows g's ranging from about 3.5 to about 4.5 (alternatively, from about 3.5 to about 4 g's, alternatively equal to or greater than about 4 g's) during this period, which may be associated with the "hiss" of fluid passing

through the leaky suction valve. The upper plot of Figure 13 shows a power spectrum analysis taken at about 31 seconds into the test period and shows two groups of peaks, labeled fourth indicator and fifth indicator. The fourth indicator shows a maximum peak at about 0.03 to about 0.35 g's (alternatively, equal to or greater than 0.25, 0.275, or 0.3 g's) and the fifth indicator shows a maximum peak at about 0.03 to about 0.35 g's (alternatively, equal to or greater than 0.25, 0.275, 0.3, or 0.325 g's). Figure 13 also shows a sixth indicator having a maximum peak at about 0.3 to about 0.4 g's (alternatively, from about 0.3 to about 0.4, alternatively equal to or greater than 0.25, 0.275, 0.3, 0.325, 0.35, or 0.375 g's). Alarm thresholds may be associated with the fourth, fifth, and/or sixth indicators, and may be set in accordance with the peak magnitudes associated with the indicators. In this instance, the fourth, fifth and/or sixth indicators are about equal to each other in magnitude, and thus the fourth, fifth, and/or sixth alarm thresholds may likewise be about equal to each other (e.g., equal to or greater than 0.25, 0.275, or 0.3 g's).

[0062] Referring to Figure 14, the pump was operated for a test period of about 64 seconds in gear 5 at about 215 rpm. The strip chart of Figure 14 shows g's ranging from about 3.5 to about 4.5 (alternatively, from about 3.5 to about 4 g's, alternatively, from about 4 to about 4.5 g's, alternatively equal to or greater than about 4 g's) during this period, which may be associated with the "hiss" of fluid passing through the leaky suction valve. The upper plot of Figure 14 shows a power spectrum analysis taken at about 7 seconds into the test period and shows two groups of peaks, labeled fourth indicator and fifth indicator. The fourth indicator shows a maximum peak at about 0.04 to about 0.55 g's (alternatively, equal to or greater than 0.4, 0.45, 0.5, or 0.55 g's) and the fifth indicator shows a maximum peak at about 0.03 to about 0.4 g's (alternatively, equal to or greater than 0.25, 0.3, 0.35, or 0.4 g's). Figure 14 also shows a sixth indicator having a maximum peak at about 0.2 to about 0.25 g's (alternatively equal to or greater than 0.2, 0.225, or 0.25 g's). Alarm thresholds may be associated with the fourth, fifth, and/or sixth indicators, and may be set in accordance with the peak magnitudes associated with the indicators. In this instance, the fourth and fifth alarm thresholds may be about equal to each other (e.g., equal to or greater than 0.3 or 0.35 g's). Also in this instance, the sixth indicator/alarm threshold is less than the fourth and fifth. Alternatively, the fourth threshold (e.g., 0.4, 0.45, or 0.5 g's) is greater than the fifth threshold (e.g., 0.3 or 0.35 g's), which is greater than the sixth threshold (e.g., 0.2 g's). Alternatively, the fourth, fifth, and sixth alarm thresholds may be about equal (e.g., equal to or greater than about 0.2 g's).

[0063] Referring to Figure 15, the pump was operated for a test period of about 62 seconds in gear 6 at about 268 rpm. The strip chart of Figure 15 shows g's ranging from about 3.5 to about 4.5 (alternatively, from about 3.5 to about 4 g's, alternatively, from about 4 to about 4.5 g's, alternatively equal to or greater than about 4 g's) during this period, which may be associated with the "hiss" of fluid passing through the leaky suction valve. The upper plot of Figure 15 shows a power spectrum analysis taken at about 41 seconds into the test period and shows two groups of peaks, labeled fourth indicator and fifth indicator. The fourth indicator shows a maximum peak at about 0.25 to about 0.35 g's (alternatively, equal to or greater than 0.2, 0.25, 0.3, or 0.35 g's) and the fifth indicator shows a maximum peak at about 0.45 to about 0.55 g's (alternatively, equal to or greater than 0.3, 0.35, 0.4, 0.45, or 0.5 g's). Figure 15 also shows a sixth indicator having a maximum peak at about 0.25 to about 0.3 g's (alternatively equal to or greater than 0.2, 0.25, 0.275, or 0.3 g's). Alarm thresholds may be associated with the fourth, fifth, and/or sixth indicators, and may be set in accordance with the peak magnitudes associated with the indicators. In this instance, the fourth and sixth alarm thresholds may be about equal to each other (e.g., equal to or greater than 0.25 or 0.3 g's). Also in this instance, the fifth indicator/alarm threshold is greater than the fourth and sixth. Alternatively, the fourth, fifth, and sixth alarm thresholds may be about equal (e.g., equal to or greater than about 0.3 g's).

[0064] The strip chart in each of Figures 12-15 shows g's ranging from about 3.5 to about 4.5, and thus a seventh alarm threshold may be set for this data stream, for example equal to or greater than about 3.5, 4, or 4.5 g's. The seventh alarm threshold may be used alone or in combination with any of the other indicators/alarm thresholds set forth herein to provide an indication of valve leakage.

[0065] The position (e.g., frequency ranges) of the fourth, fifth, and/or sixth indicators as measured in Hz may shift slightly in frequency with changes in gearing, but the indicators remain clearly present. In some embodiments, the frequency range of the fourth indicator may be from about 2,500 to about 3,000 Hz, alternatively from about 2,500 to about 2,750 Hz, alternatively from about 2,600 to about 2,700 Hz. In some embodiments, the frequency range of the fifth indicator may be from about 3,500 to about 4,500 Hz, alternatively from about 3,750 to about 4,250 Hz, alternatively from about 3,750 to about 4,000 Hz. In some embodiments, the frequency range of the sixth indicator may be from about 1,750 to about 2,250 Hz, alternatively from about 1,750 to about 2,000 Hz, alternatively from about 1,500 to about 2,000 Hz. Where multiple peaks are present within a given frequency range for a given indicator, reference is

typically made to the highest peak within the given frequency range. The frequency ranges of the fourth, fifth and/or sixth indicators may be further correlated with the various values for the fourth, fifth and/or sixth alarm thresholds (e.g., a fourth indicator having a designated frequency range and a corresponding fourth alarm threshold having a designated value). Furthermore, the fourth, fifth and/or sixth indicators; the fourth, fifth, and/or sixth alarm thresholds; or combinations thereof may be further correlated to a given operating gear and/or rpm range for the pump (e.g., a fourth indicator having a designated frequency range and a corresponding fourth alarm threshold having a designated value and further corresponding to a pump operating in a designated gear, rpm range, or flow rate such as those shown in Table 1).

[0066] Comparisons can be made between the data collected and plotted in Figures 8-11 for pump cavitation and data collected and plotted in Figures 12-15 for leaky valves, and such comparisons provide the ability to detect pump cavitation, valve leakage, or both; distinguish pump cavitation from valve leakage; or combinations thereof. That is, the various indicators and alarm thresholds for cavitation as shown in Figures 8-11 may be used in a variety of combinations with the various indicators and alarm thresholds for valve leakage as shown in Figures 12-15. For example, differences in the intensity of the indicators (e.g., maximum peak g's of the first and second indicators of Figures 8-11 in comparison to fourth and fifth indicators of Figures 12-15) may be used to distinguish pump cavitation from valve leakage or vice-versa. Likewise, differences in the frequency band of the indicators (e.g., Hz band of the first and second indicators of Figures 8-11 in comparison to fourth and fifth indicators of Figures 12-15) may be used to distinguish pump cavitation from valve leakage or vice-versa. Differences in the relative intensity (e.g., maximum g's) and/or frequency band (e.g., Hz band) in the indicators (e.g., comparing the first indicator to the second indicator of Figs. 8-11 in view of comparing the fourth indicator to the fifth indicator of Figs. 12-15) may also be used to distinguish cavitation from valve leakage or vice-versa.

[0067] While embodiments of the invention have been shown and described, modifications thereof can be made by one skilled in the art without departing from the spirit and teachings of the invention. The embodiments described herein are exemplary only, and are not intended to be limiting. Many variations and modifications of the invention disclosed herein are possible and are within the scope of the invention. Where numerical ranges or limitations are expressly stated, such express ranges or limitations should be understood to include iterative ranges or limitations of like magnitude falling within the expressly stated ranges or limitations (e.g.,

from about 1 to about 10 includes, 2, 3, 4, etc.; greater than 0.10 includes 0.11, 0.12, 0.13, etc.). For example, whenever a numerical range with a lower limit, R_L , and an upper limit, R_U , is disclosed, any number falling within the range is specifically disclosed. In particular, the following numbers within the range are specifically disclosed: $R = R_L + k * (R_U - R_L)$, wherein k is a variable ranging from 1 percent to 100 percent with a 1 percent increment, i.e., k is 1 percent, 2 percent, 3 percent, 4 percent, 5 percent, 50 percent, 51 percent, 52 percent,, 95 percent, 96 percent, 97 percent, 98 percent, 99 percent, or 100 percent. Moreover, any numerical range defined by two R numbers as defined in the above is also specifically disclosed. Use of the term "optionally" with respect to any element of a claim is intended to mean that the subject element is required, or alternatively, is not required. Both alternatives are intended to be within the scope of the claim. Use of broader terms such as comprises, includes, having, etc. should be understood to provide support for narrower terms such as consisting of, consisting essentially of, comprised substantially of, etc.

[0068] Accordingly, the scope of protection is not limited by the description set out above but is only limited by the claims which follow, that scope including all equivalents of the subject matter of the claims. Each and every claim is incorporated into the specification as an embodiment of the present invention. Thus, the claims are a further description and are an addition to the embodiments of the present invention. The discussion of a reference in the Description of Related Art is not an admission that it is prior art to the present invention, especially any reference that may have a publication date after the priority date of this application. The disclosures of all patents, patent applications, and publications cited herein are hereby incorporated by reference, to the extent that they provide exemplary, procedural or other details supplementary to those set forth herein.

CLAIMS:

1. A method of servicing a wellbore, comprising:
establishing baseline acoustic data for a pump;
pumping a wellbore servicing fluid into the wellbore with the pump;
gathering service acoustic data for the pump while pumping the wellbore servicing fluid;
comparing the baseline acoustic data to the service acoustic data; and
determining a presence or absence of an abnormal operating condition of the pump.
2. A method according to claim 1, wherein the baseline acoustic data and the service acoustic data are provided by a knock sensor coupled to the pump.
3. A method according to claim 1 or 2, wherein the baseline acoustic data, the service acoustic data, or both are time domain data.
4. A method according to claim 1, 2 or 3, further comprising converting the time domain data to frequency domain data.
5. A method according to claim 4, wherein the baseline acoustic data and the service acoustic data are compared at a frequency range of from greater than about 0 to about 5000 Hz.
6. A method according to claim 5, wherein the comparing further comprises comparing the magnitude of the service acoustic data to the baseline acoustic data and determining the presence of an abnormal operating condition of the pump when the service acoustic data is at least 50% greater than the service data.
7. A method according to claim 6, wherein the service acoustic data and the baseline acoustic data are measures in g's, are compared at a first sub-frequency range of from about 2,000 to about 3,000 Hz, and the abnormal operating condition is identified as cavitation.

8. A method according to claim 7, wherein the service acoustic data and the baseline acoustic compared at a second sub-frequency range of from about 3,500 to about 4,500 Hz, and the abnormal operating condition is identified as cavitation.
9. A method according to claim 6, wherein the service acoustic data and the baseline acoustic data are measures in g's, are compared at a first sub-frequency range of from about 4,500 to about 5,000 Hz, and the abnormal operating condition is identified as valve leakage.
10. A method according to claim 9, wherein the service acoustic data and the baseline acoustic compared at a second sub-frequency range of from about 1,750 to about 2,250 Hz, and the abnormal operating condition is identified as valve leakage.
11. A method according to any one of claims 1 to 5, wherein the comparing further comprises comparing the service acoustic data to the baseline acoustic data and determining the presence of an abnormal operating condition of the pump when valve bounce is detected upon closing of a suction valve of the pump.
12. A method according to claim 11, wherein the abnormal operating condition is cavitation.
13. A method according to any one of claims 1 to 5, wherein the comparing further comprises comparing the service acoustic data to the baseline acoustic data and determining as present an abnormal operating condition of the pump when lag is detected in closure of a valve of the pump.
14. A method according to claim 13, wherein the lag is detected in comparison to an expected valve closure time based upon position of a plunger in the pump.
15. A method according to claim 13, wherein the abnormal operating condition is cavitation.

16. A method according to any preceding claim, wherein the pump is a positive displacement pump.
17. A method according to claim 2, or according to any one of claims 3 to 16 when dependent on claim 2, wherein the pump is a positive displacement pump fluid end and the knock sensor is mounted adjacent the fluid end.
18. A method according to claim 17, wherein the pump is operated at from about 100 to about 500 rpm.
19. A method according to any preceding claim, further comprising sounding an alarm upon determining the presence of an abnormal operating condition.
20. A method according to any preceding claim, further comprising adjusting one or more pump system parameters upon determining the presence of an abnormal operating condition.

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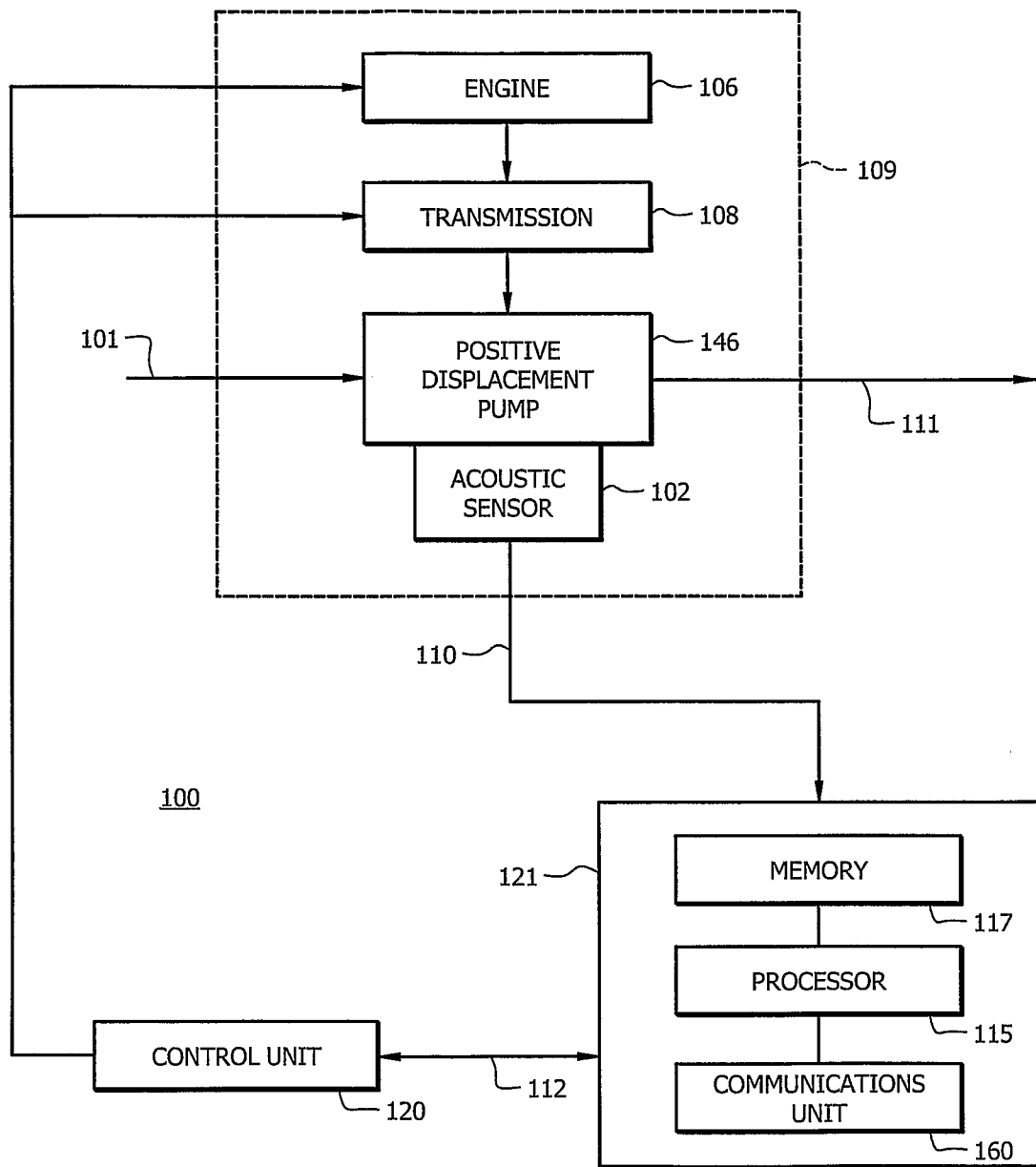


FIG. 1

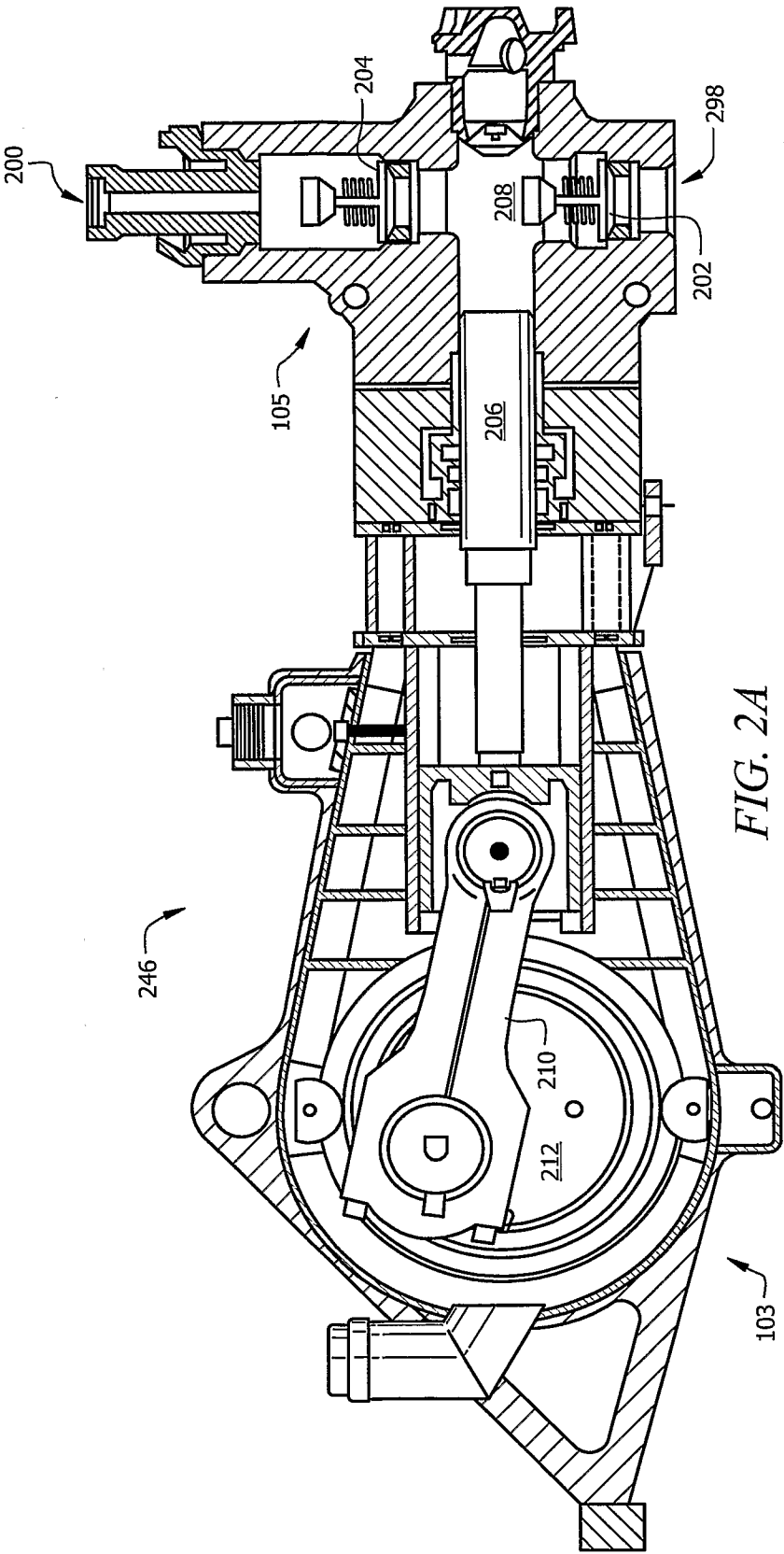
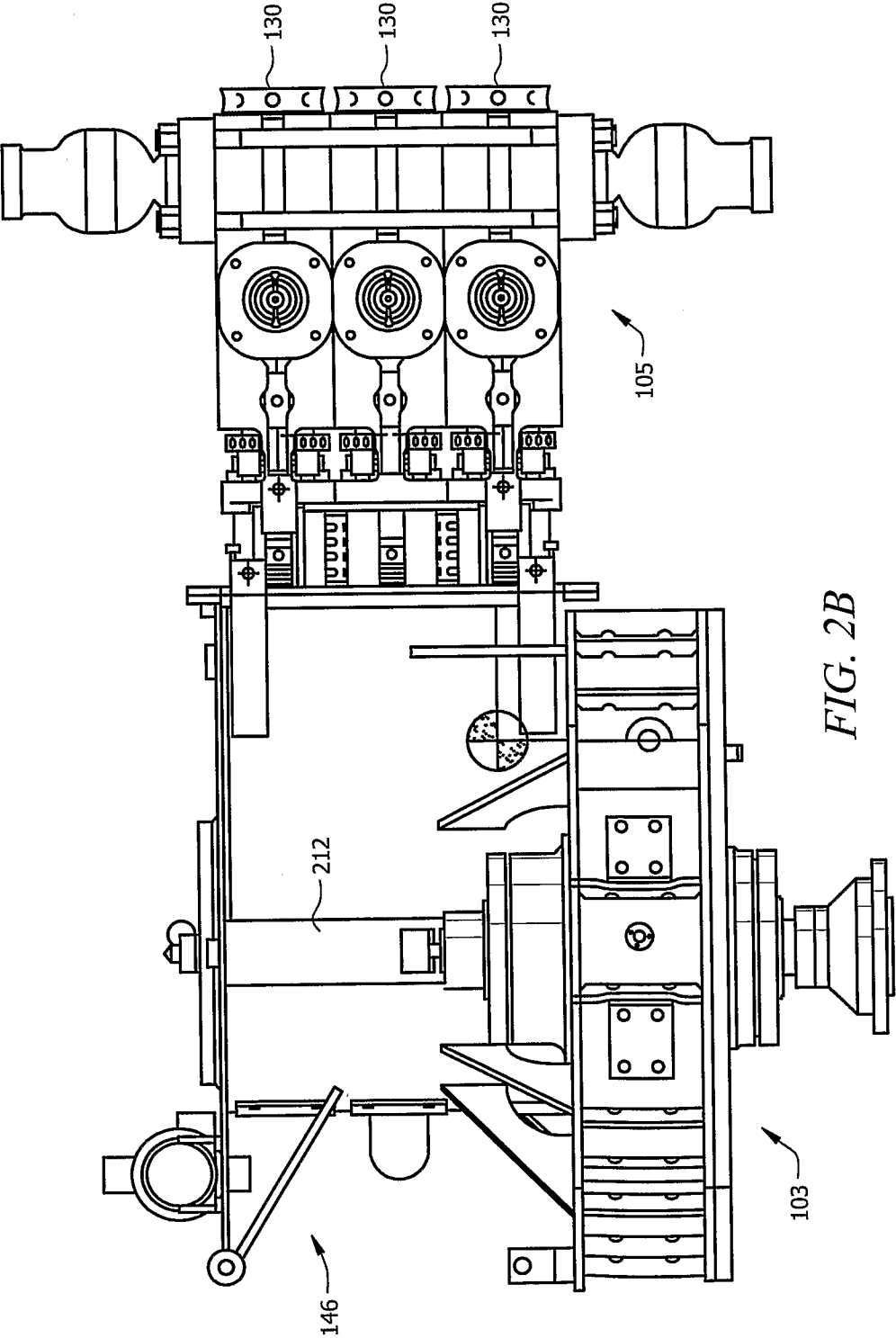


FIG. 2A



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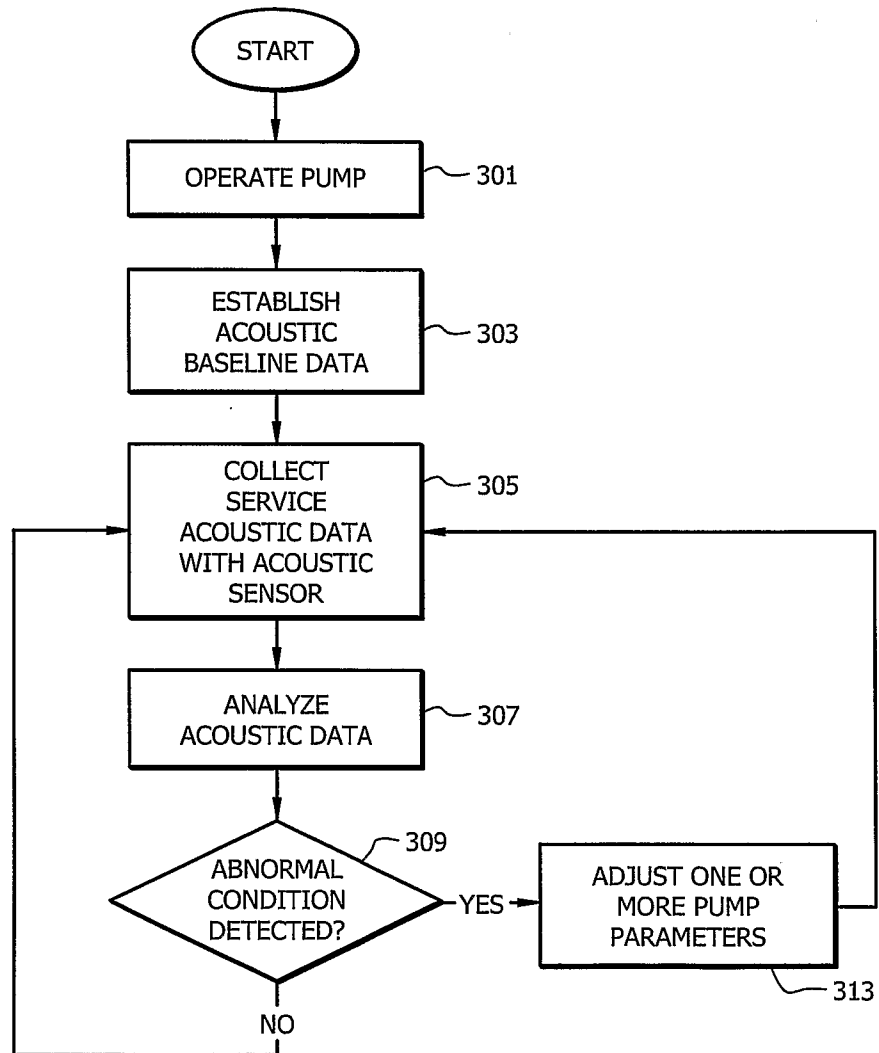


FIG. 3

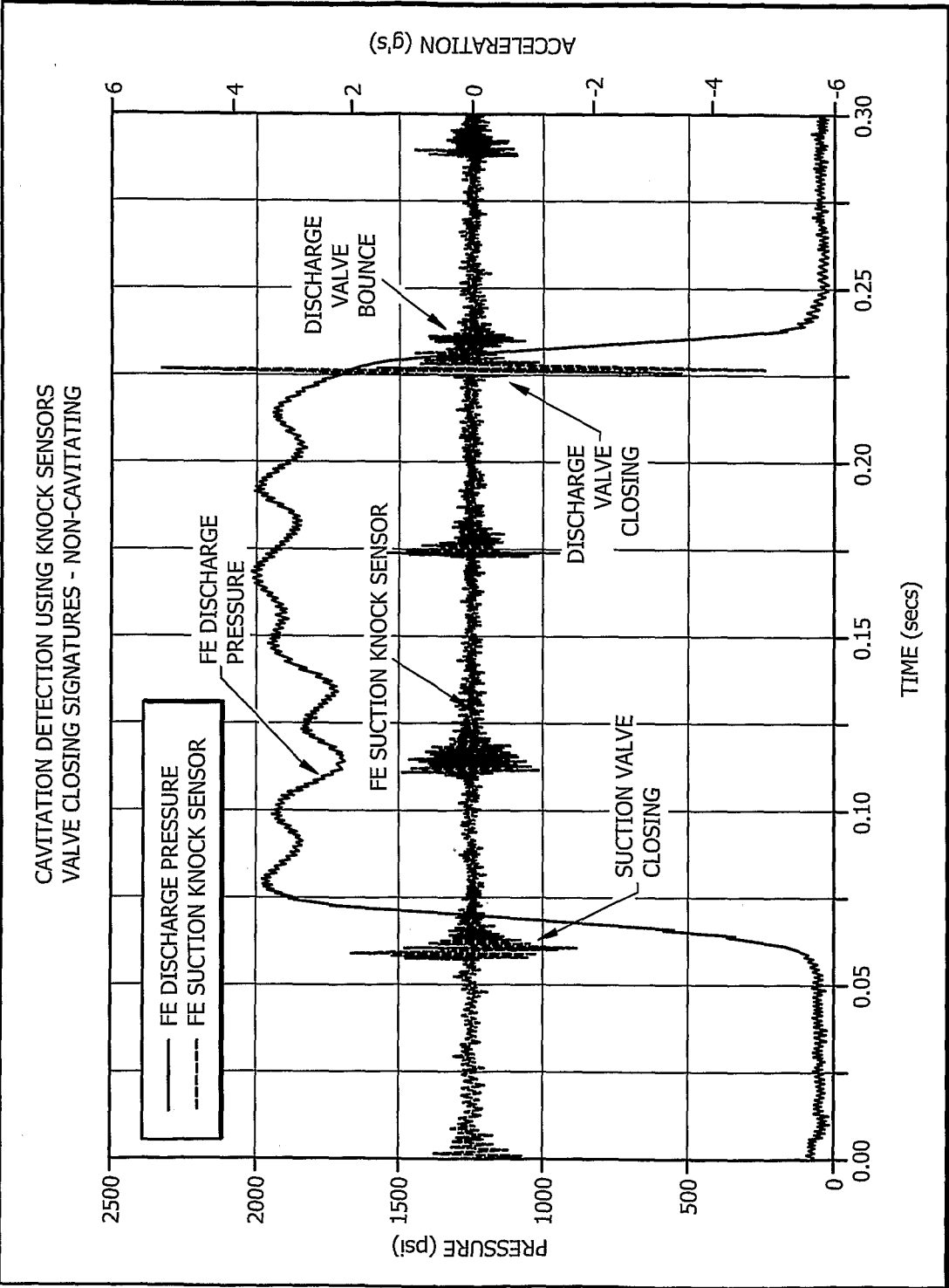


FIG. 4A

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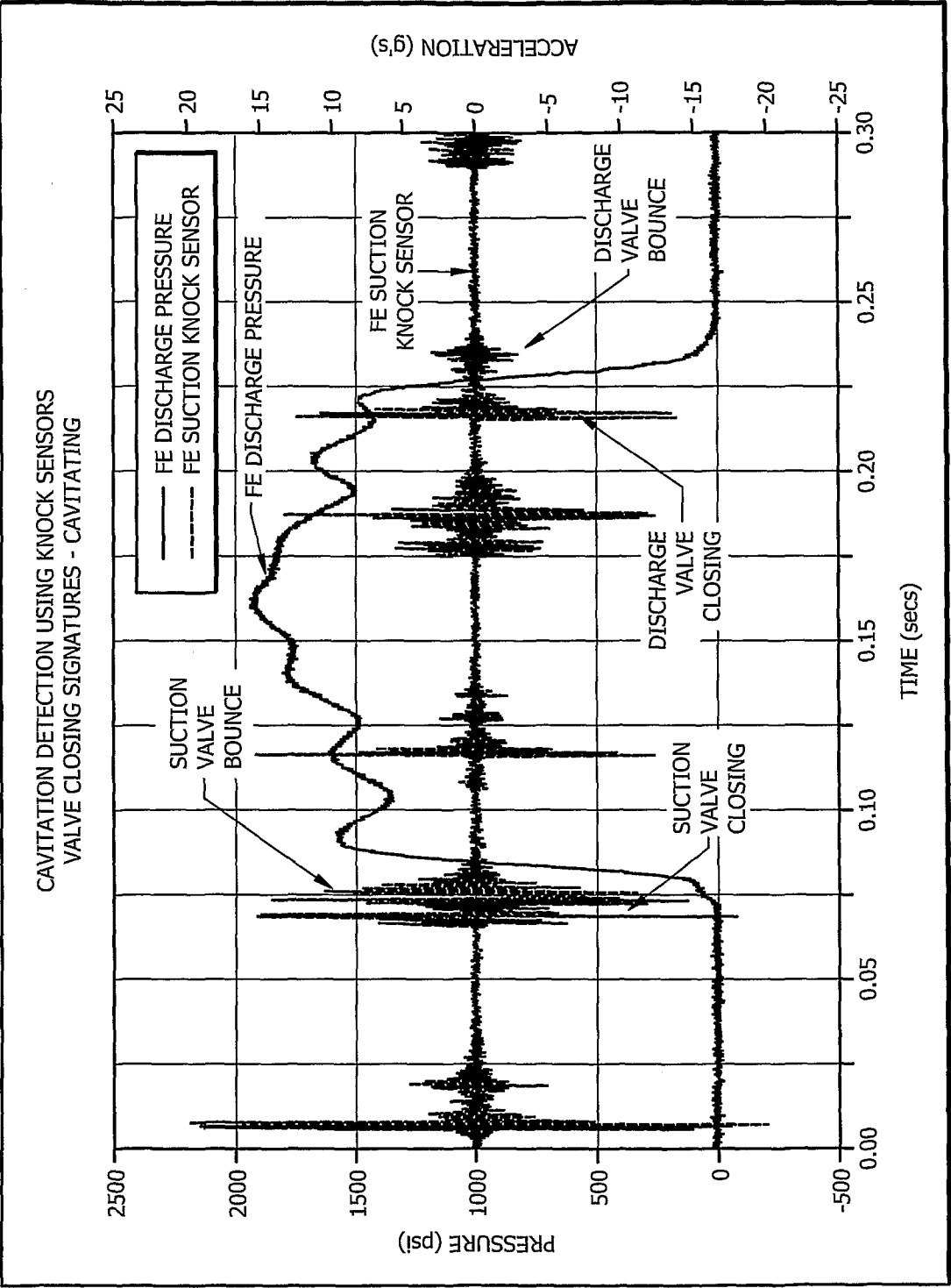


FIG. 4B

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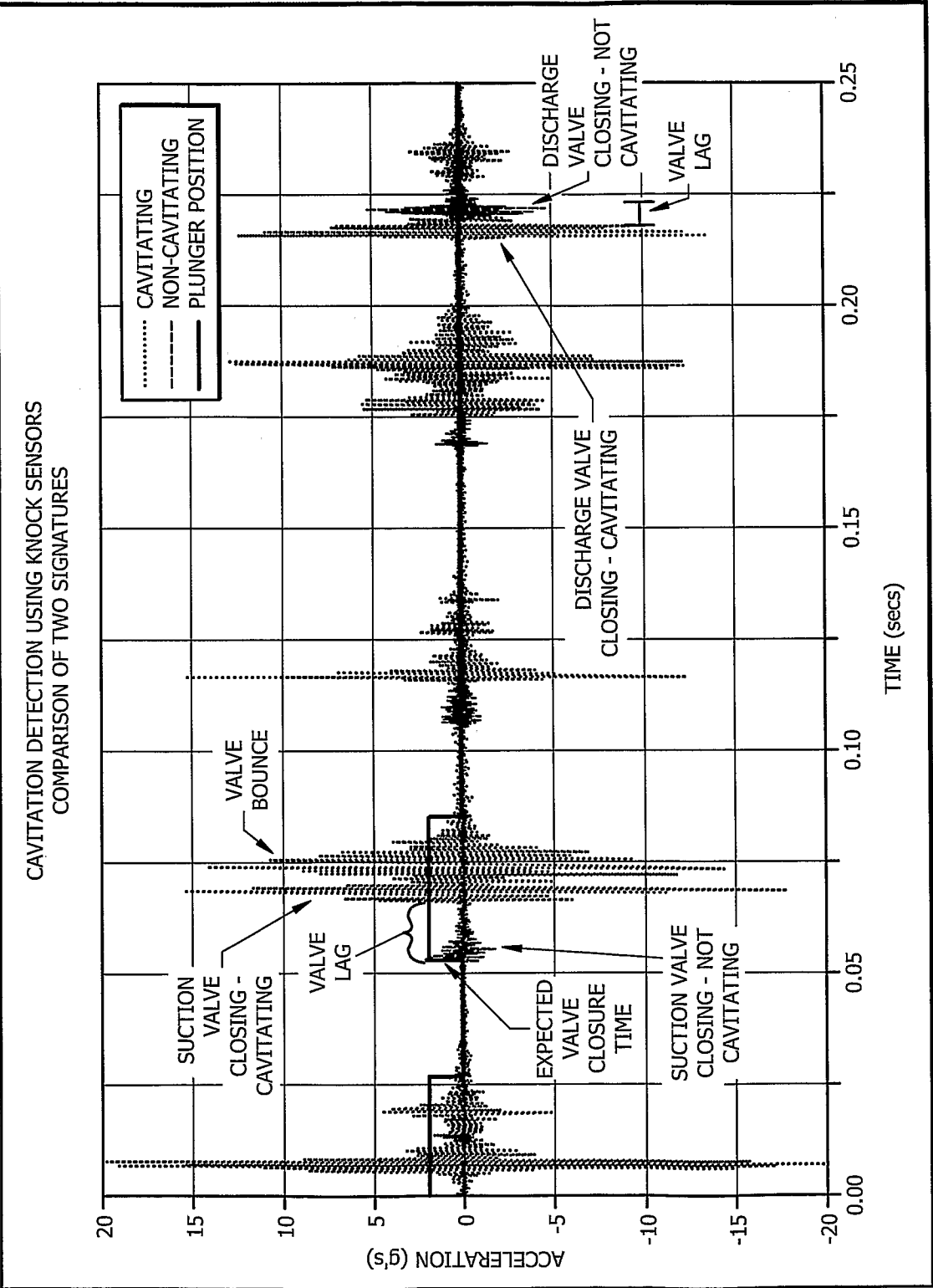


FIG. 4C

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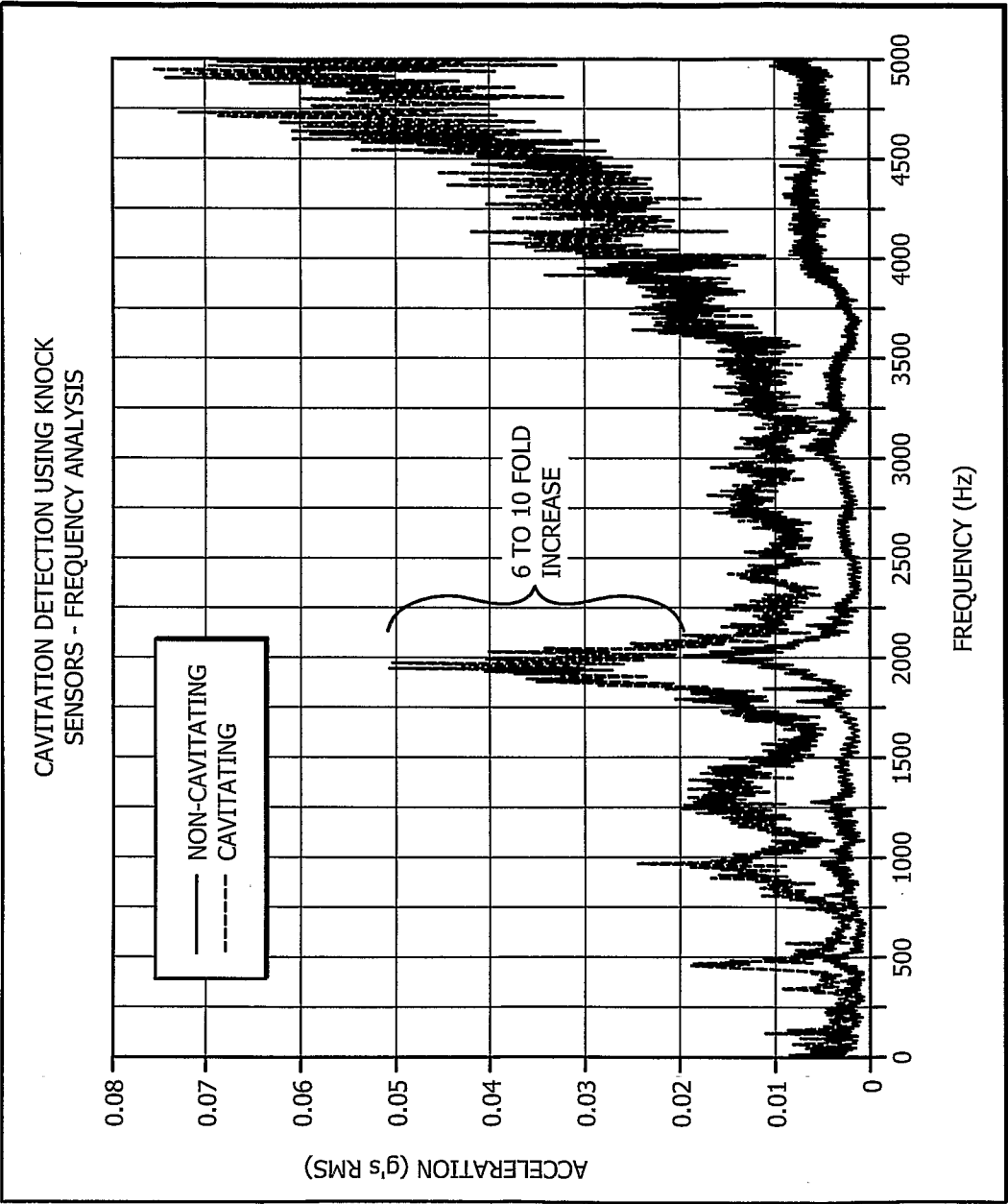


FIG. 5

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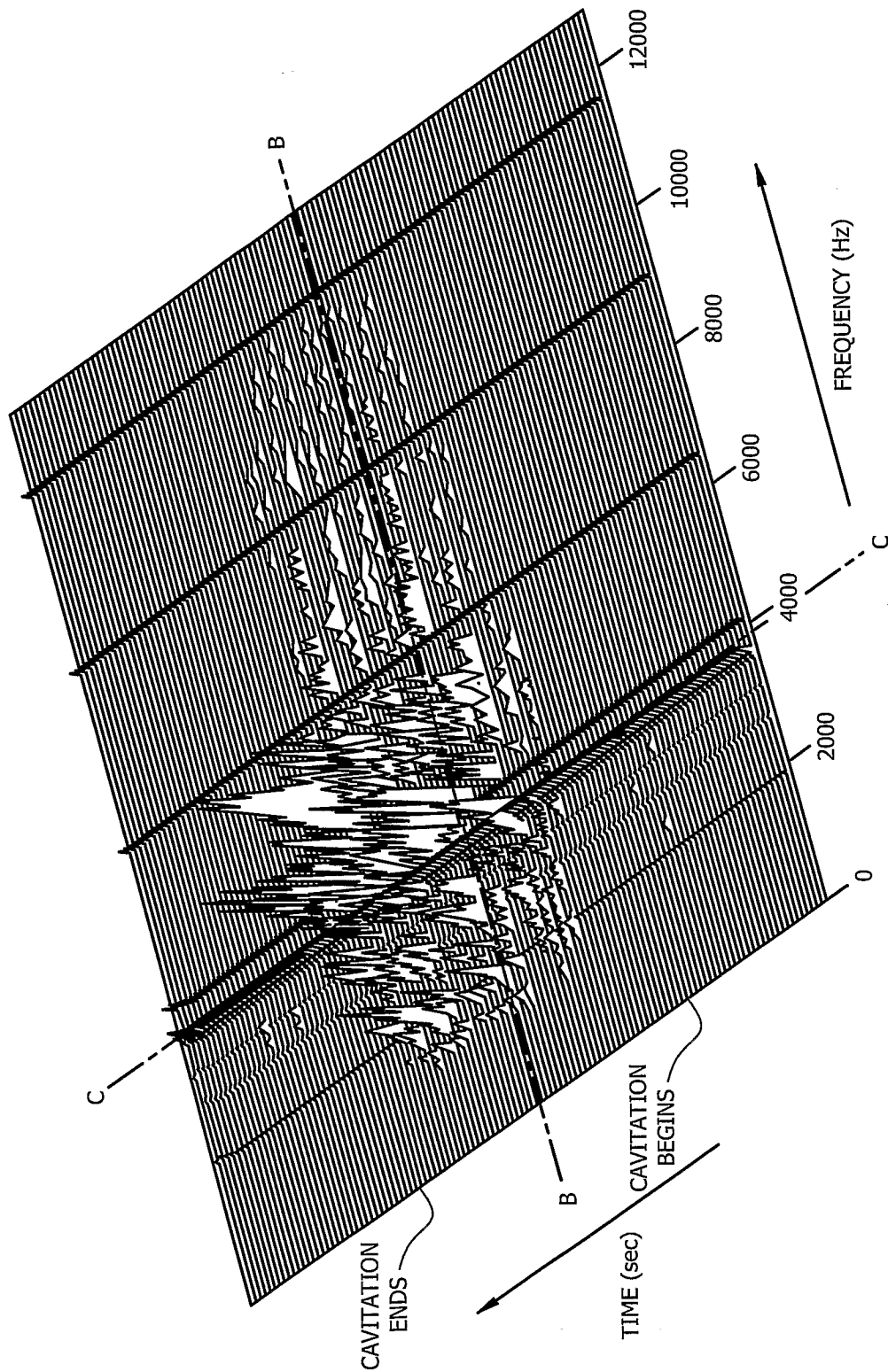


FIG. 6A

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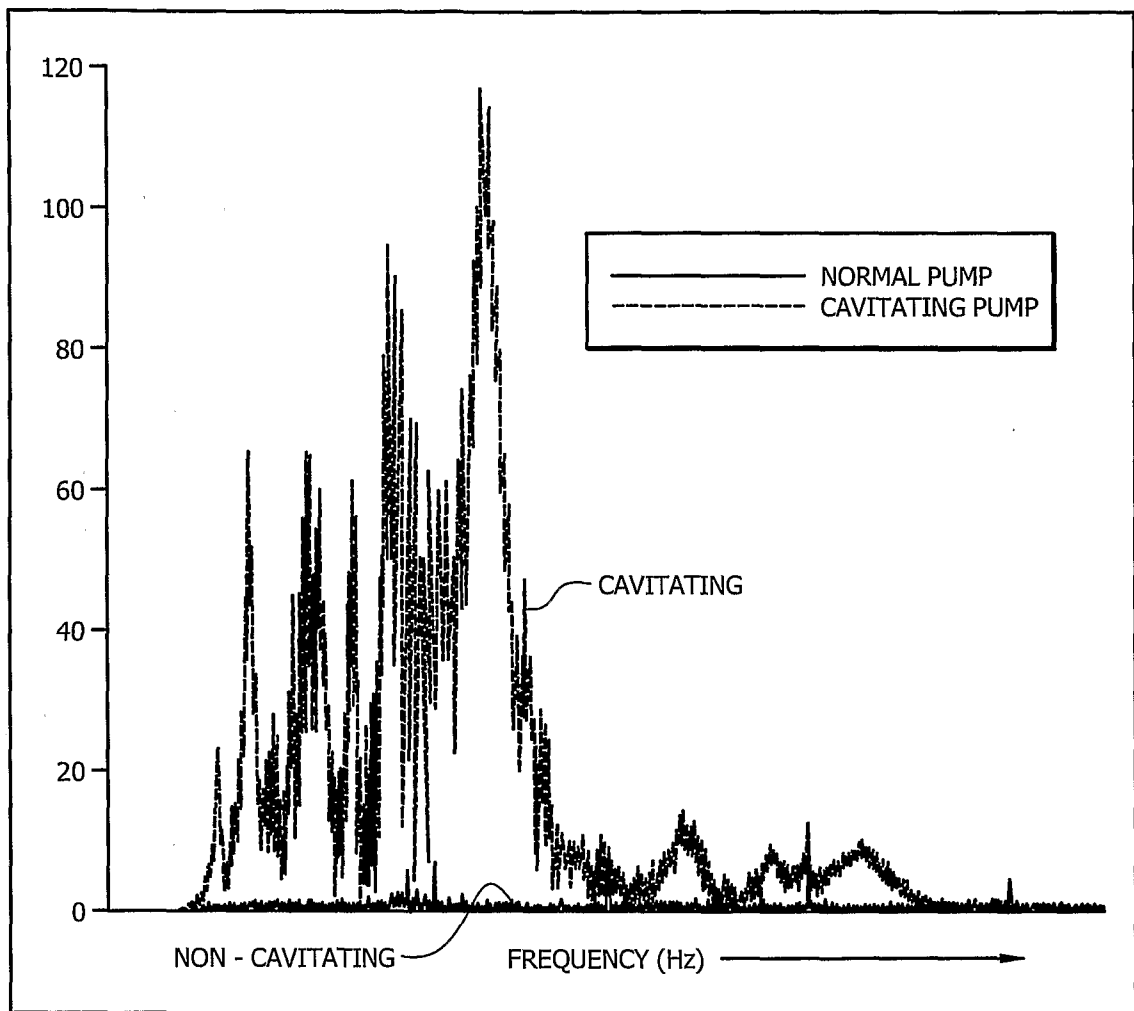


FIG. 6B

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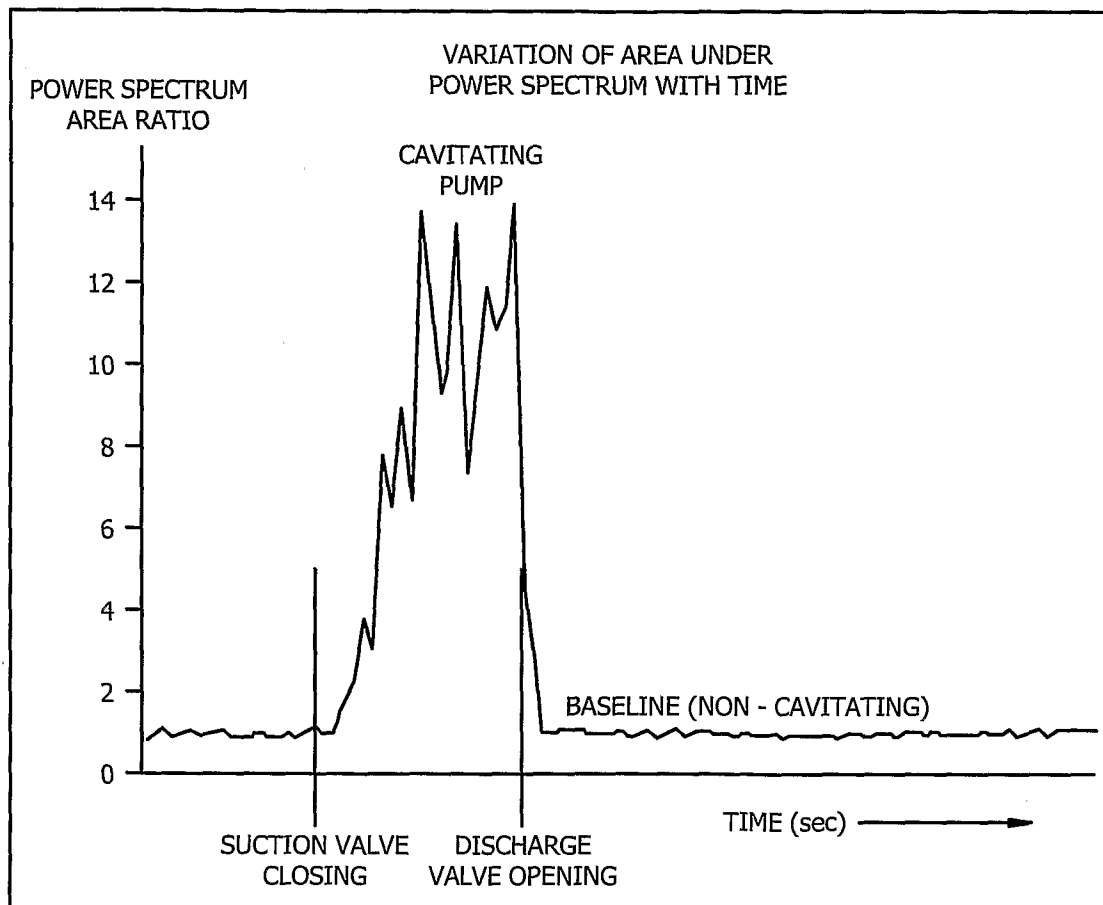


FIG. 6C

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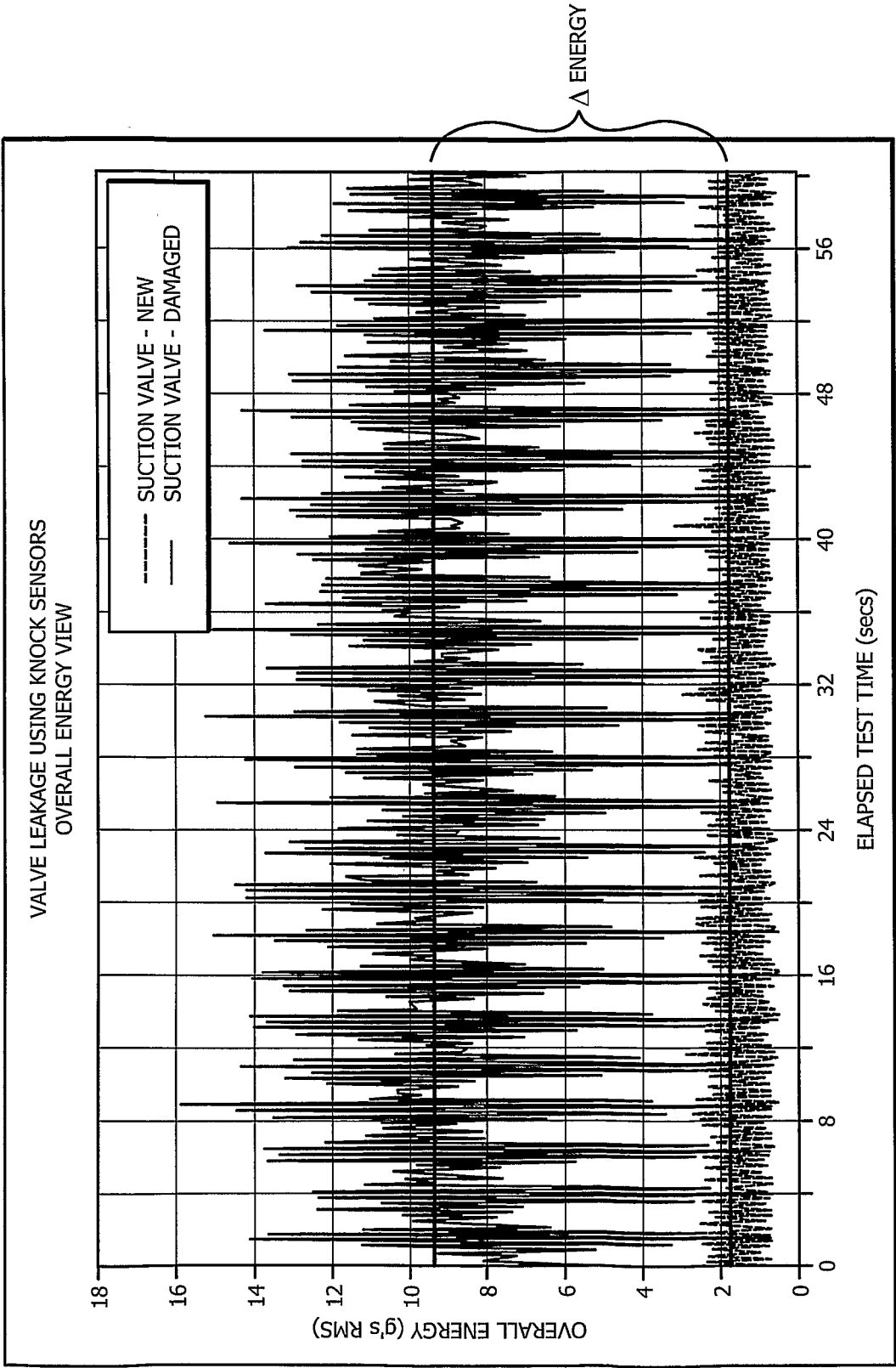


FIG. 7A

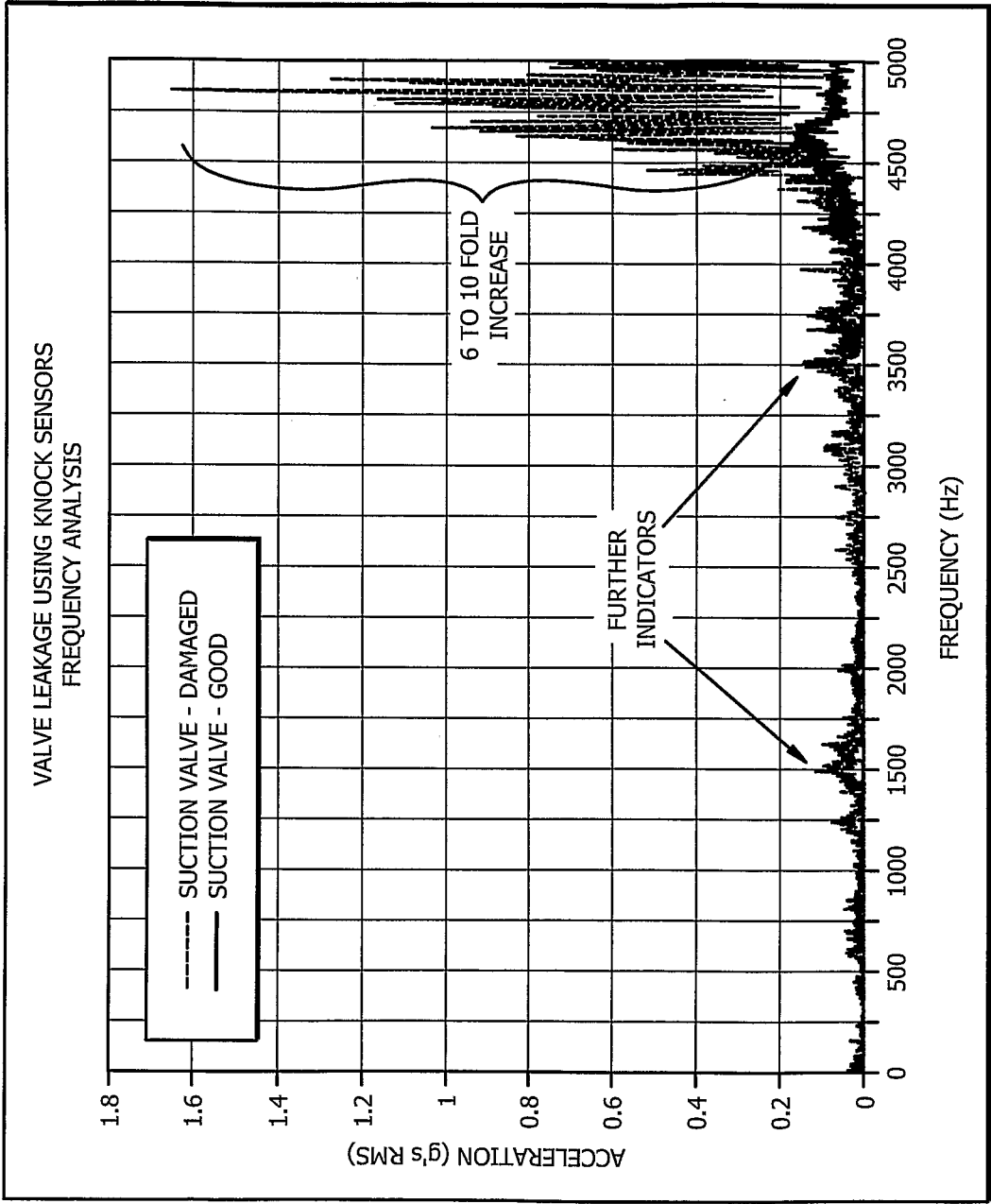


FIG. 7B

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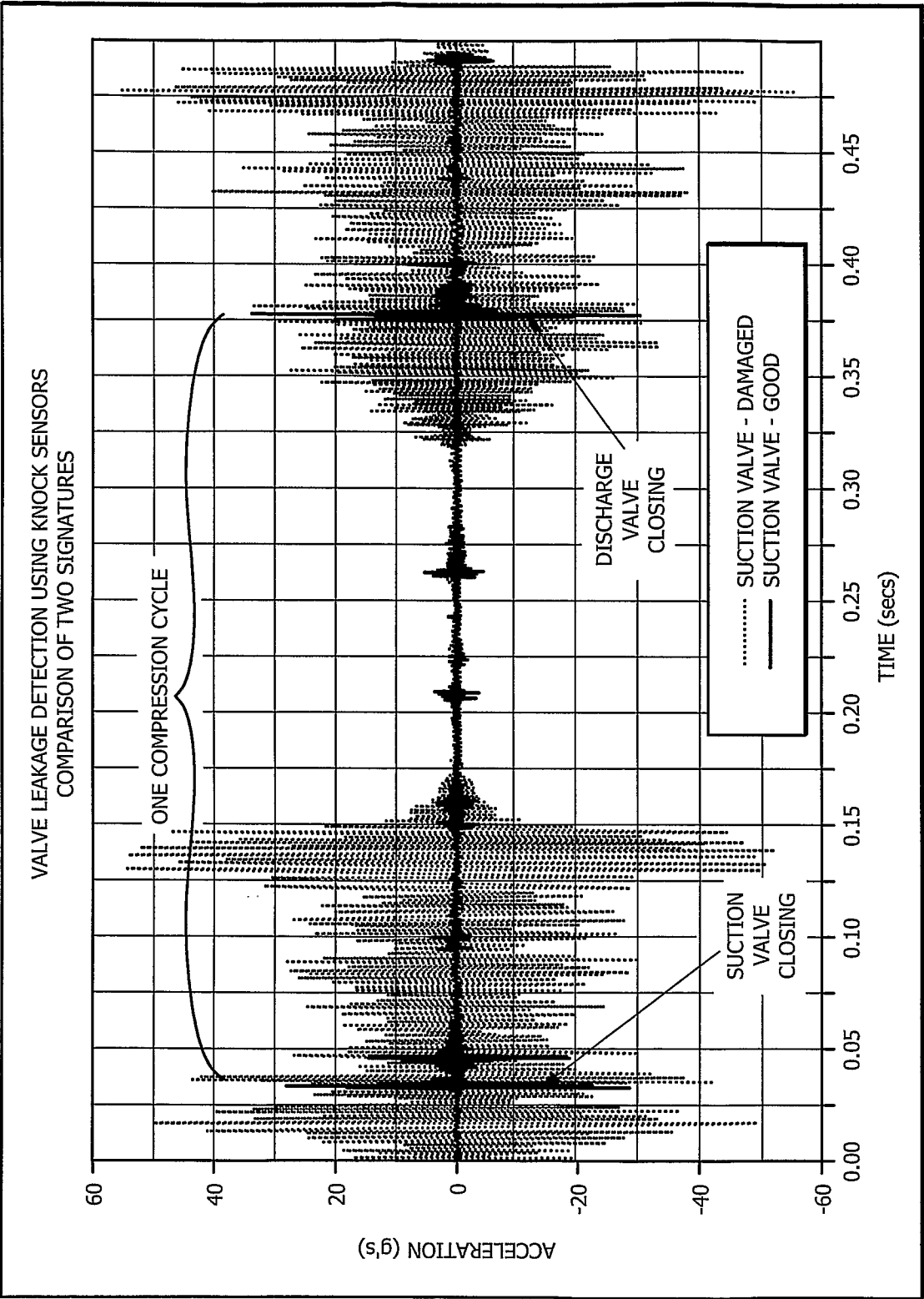


FIG. 7C

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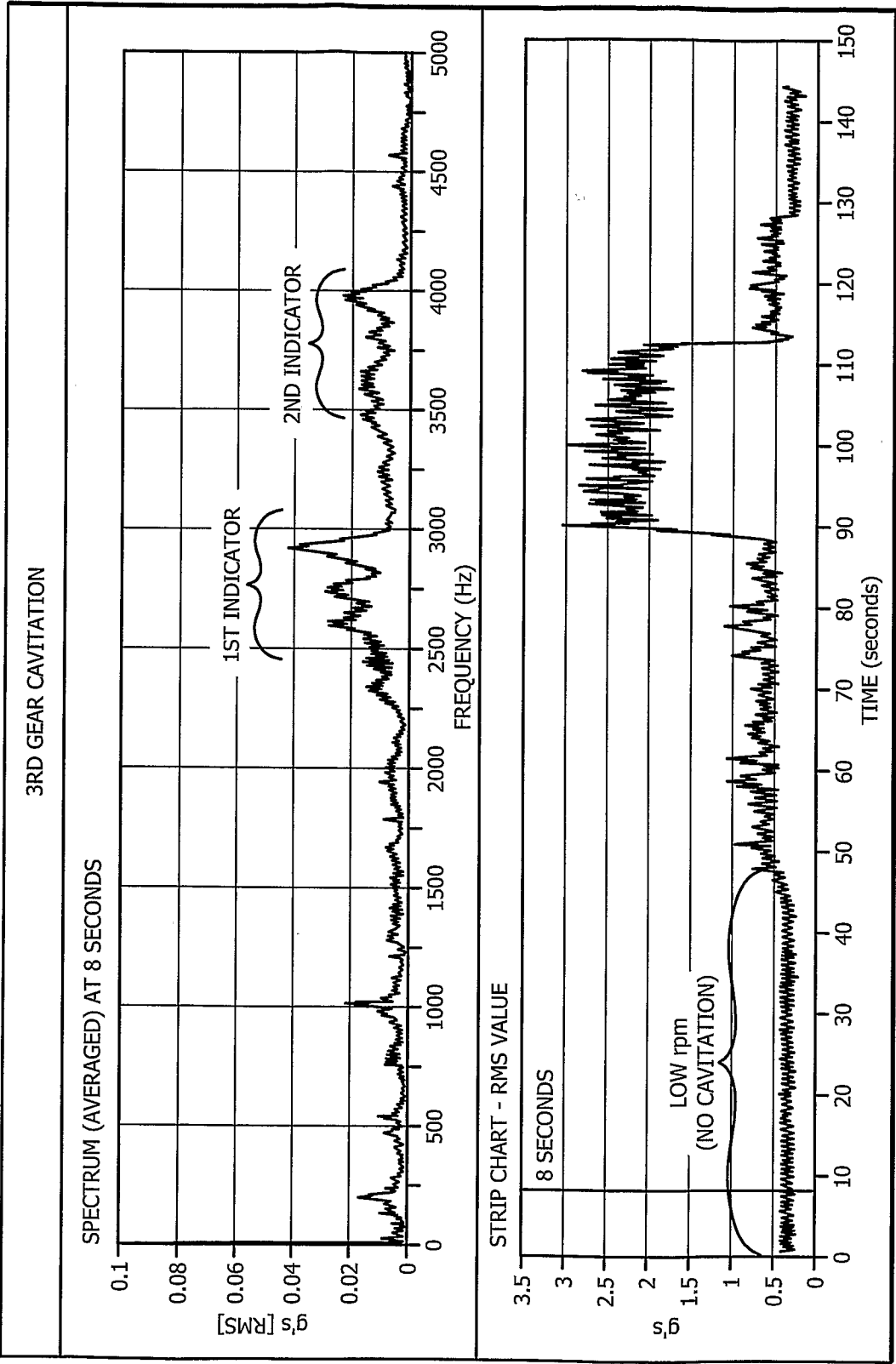


FIG. 8A

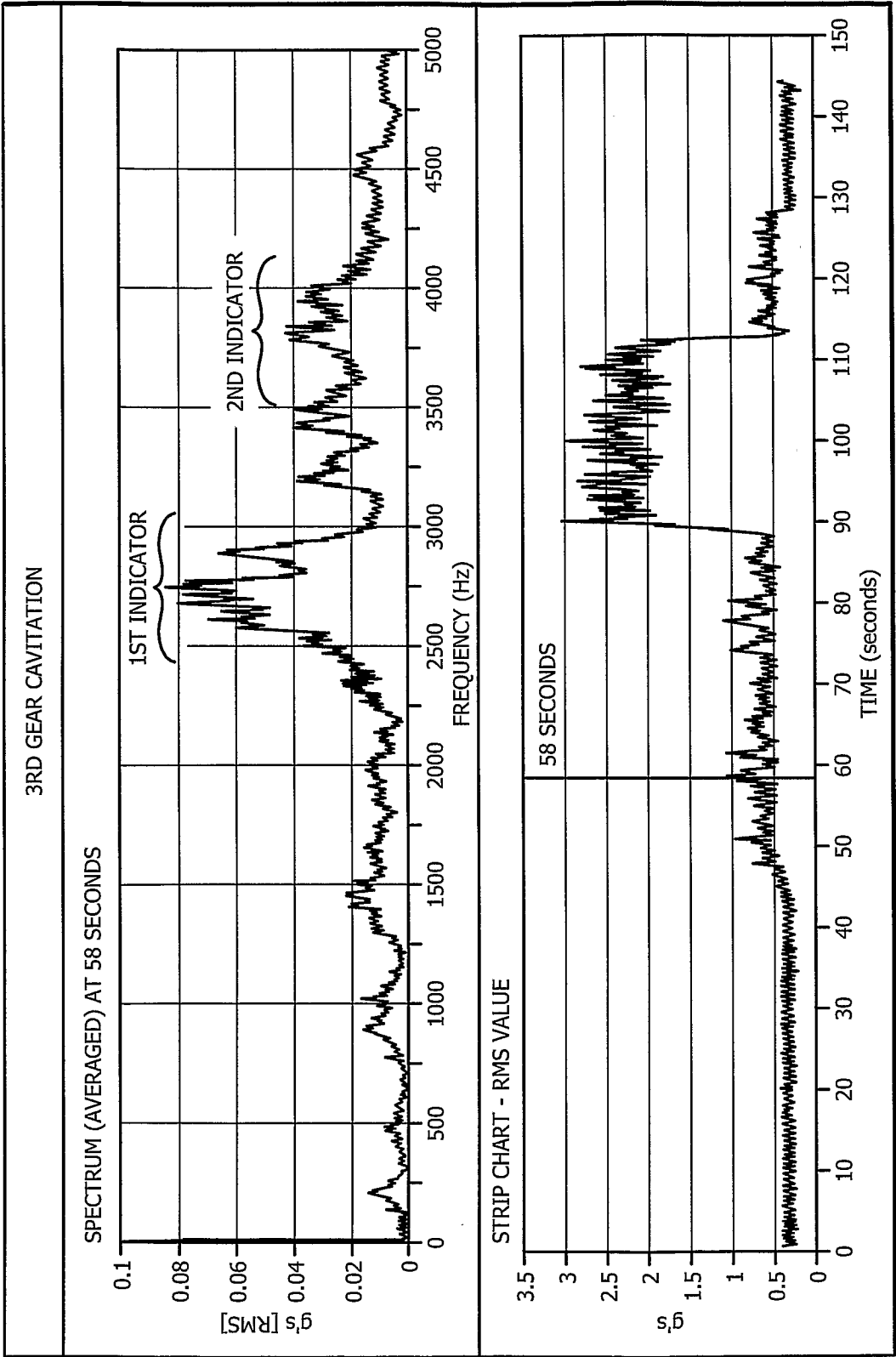


FIG. 8B

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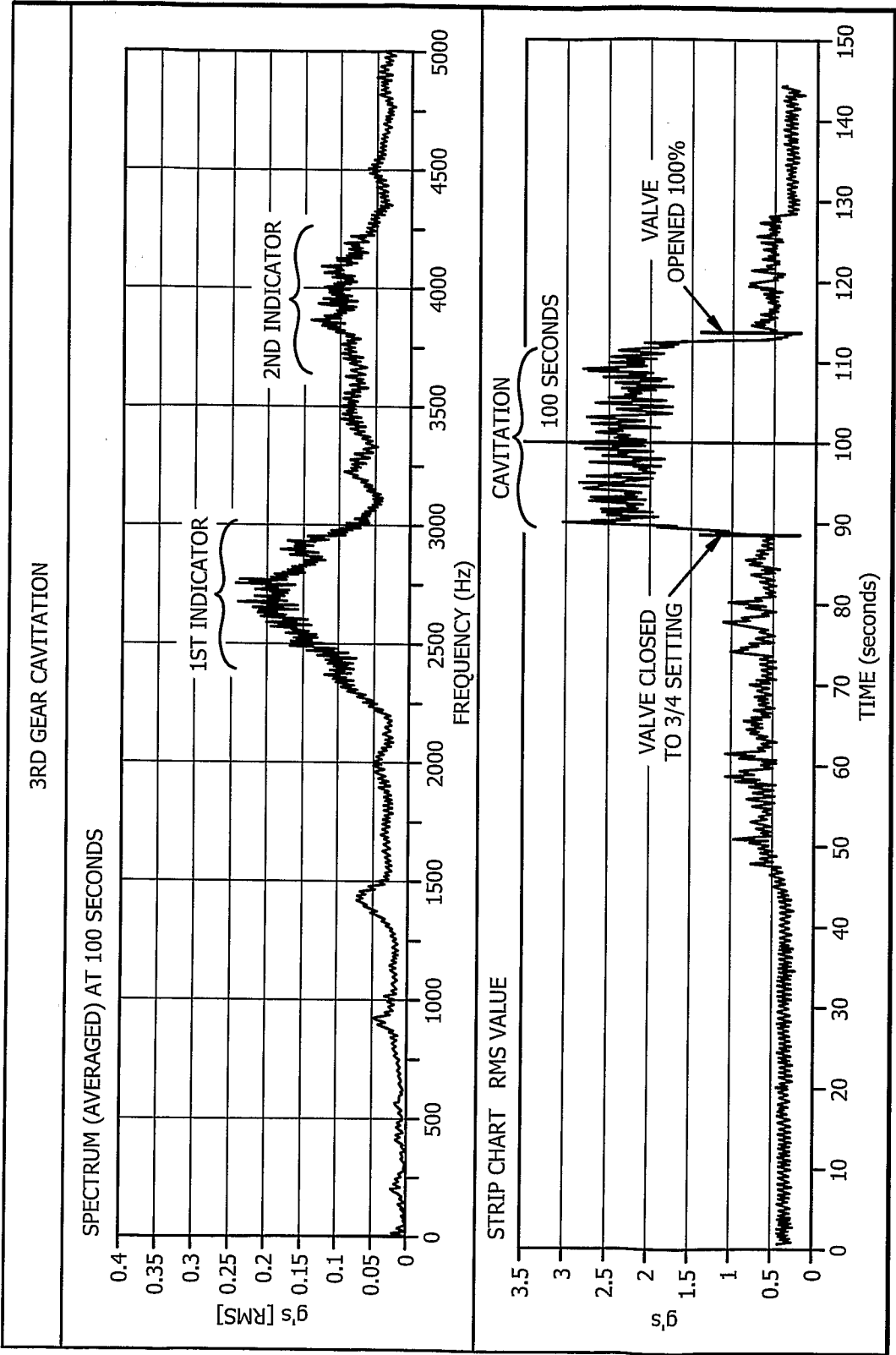
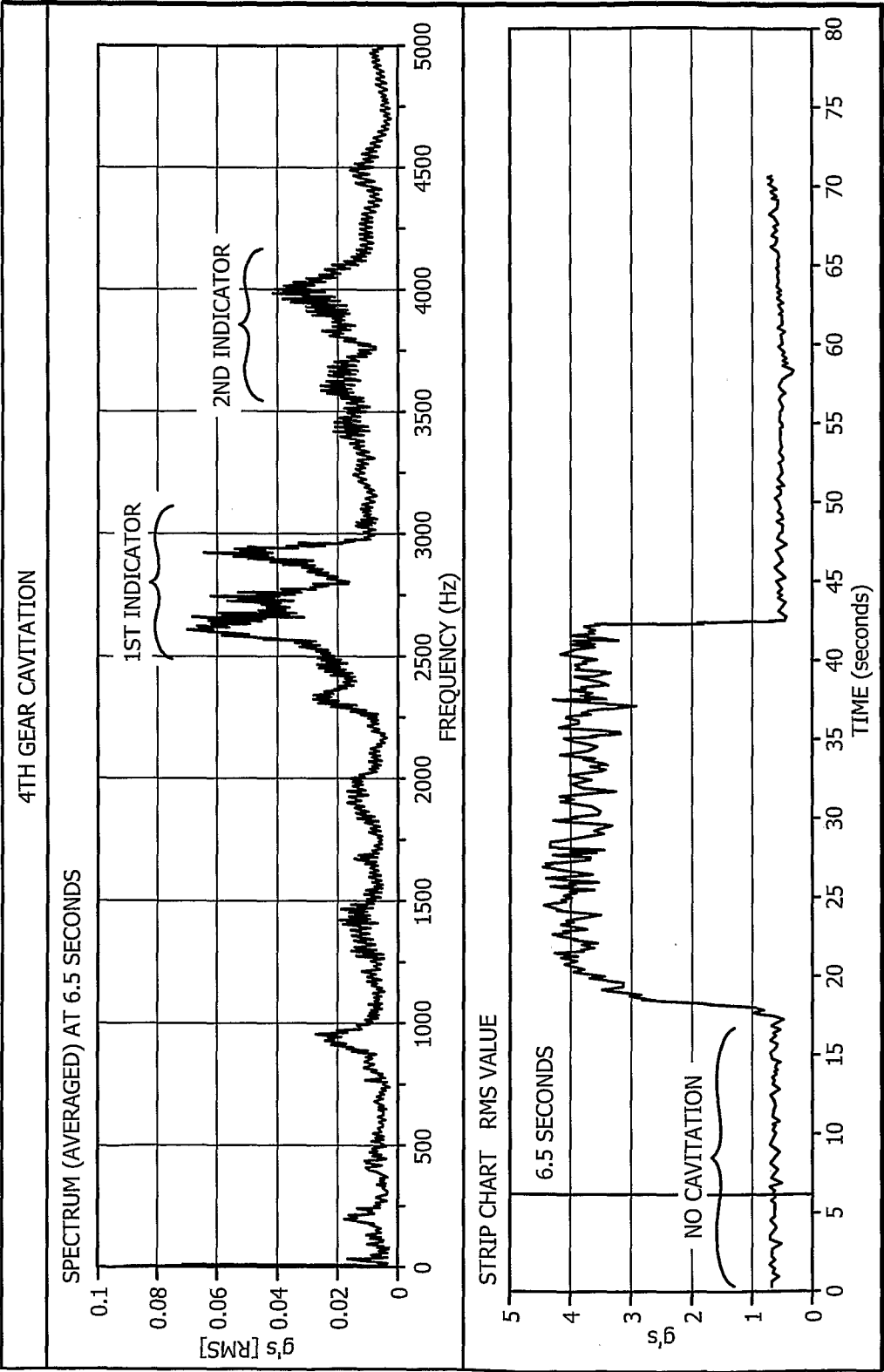
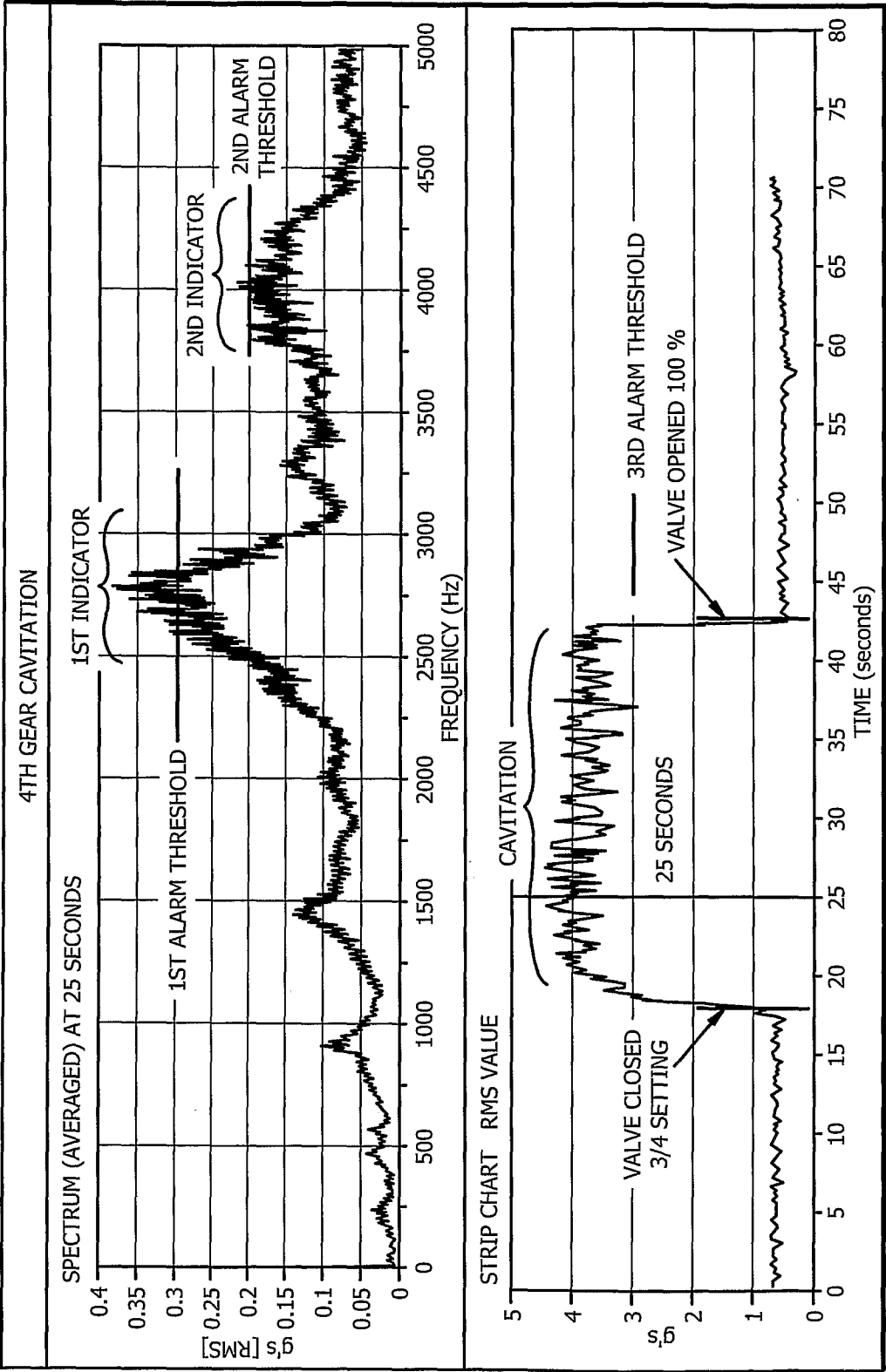


FIG. 8C

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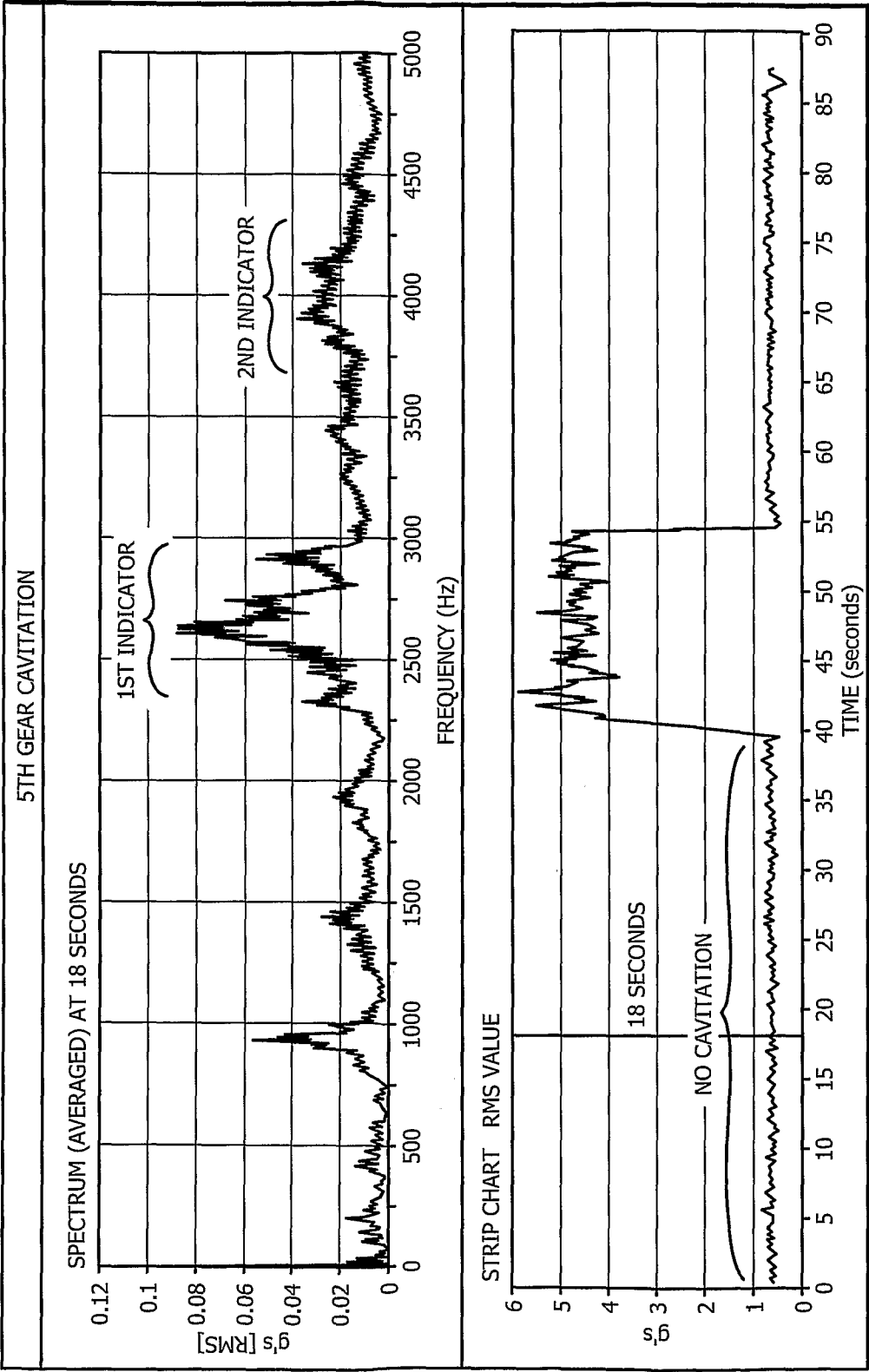


FIG. 10A

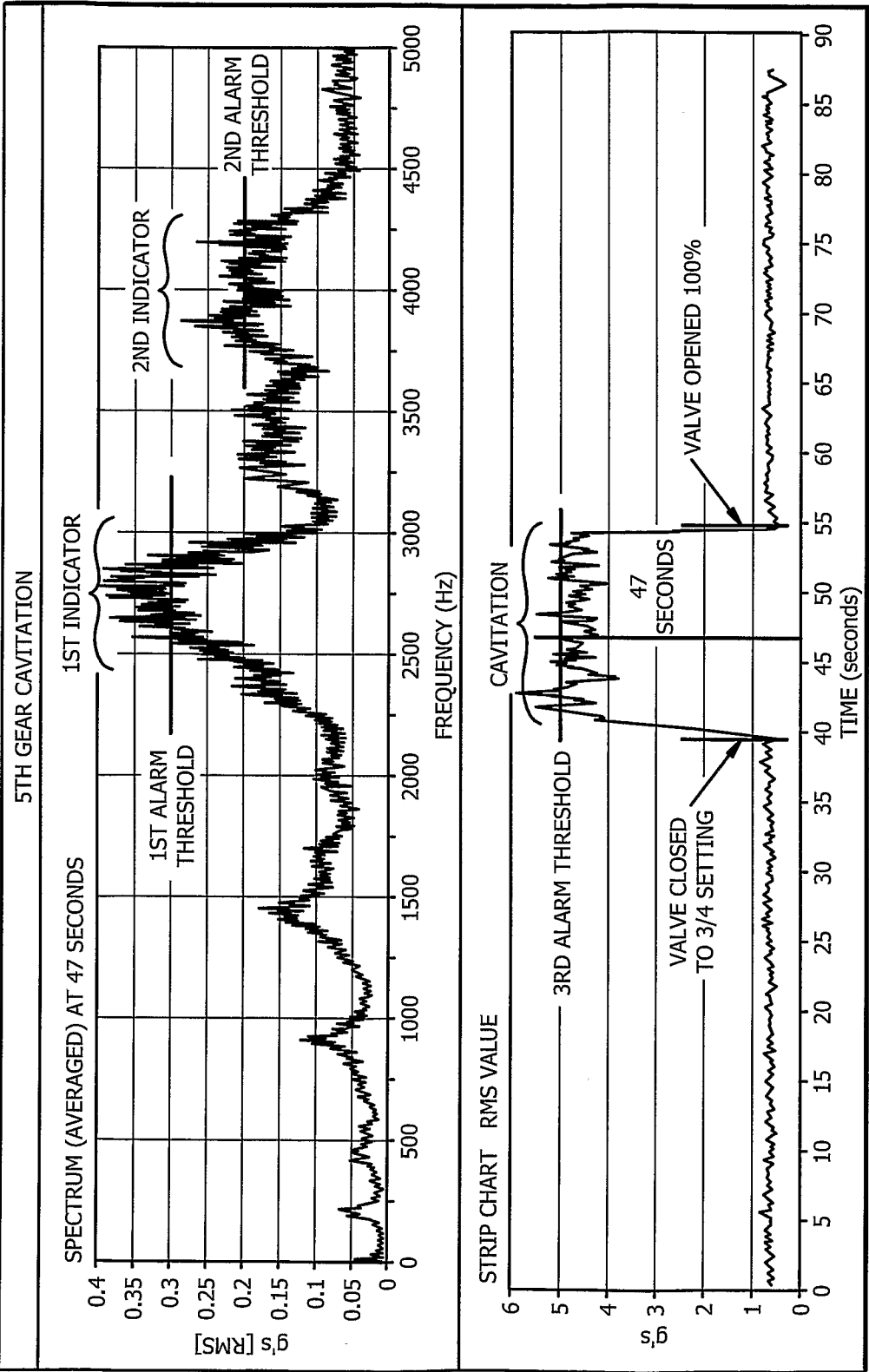


FIG. 10B

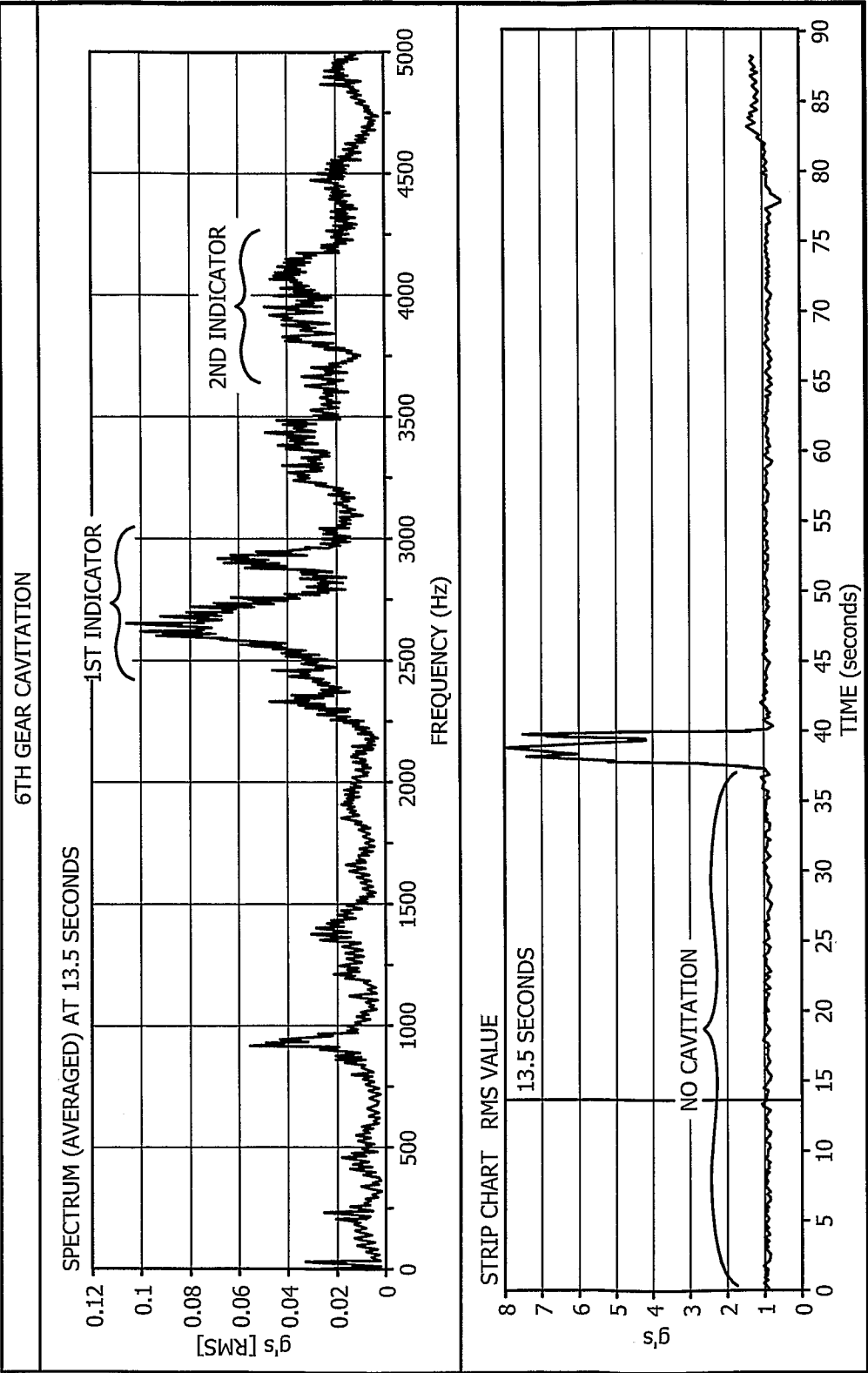


FIG. 11A

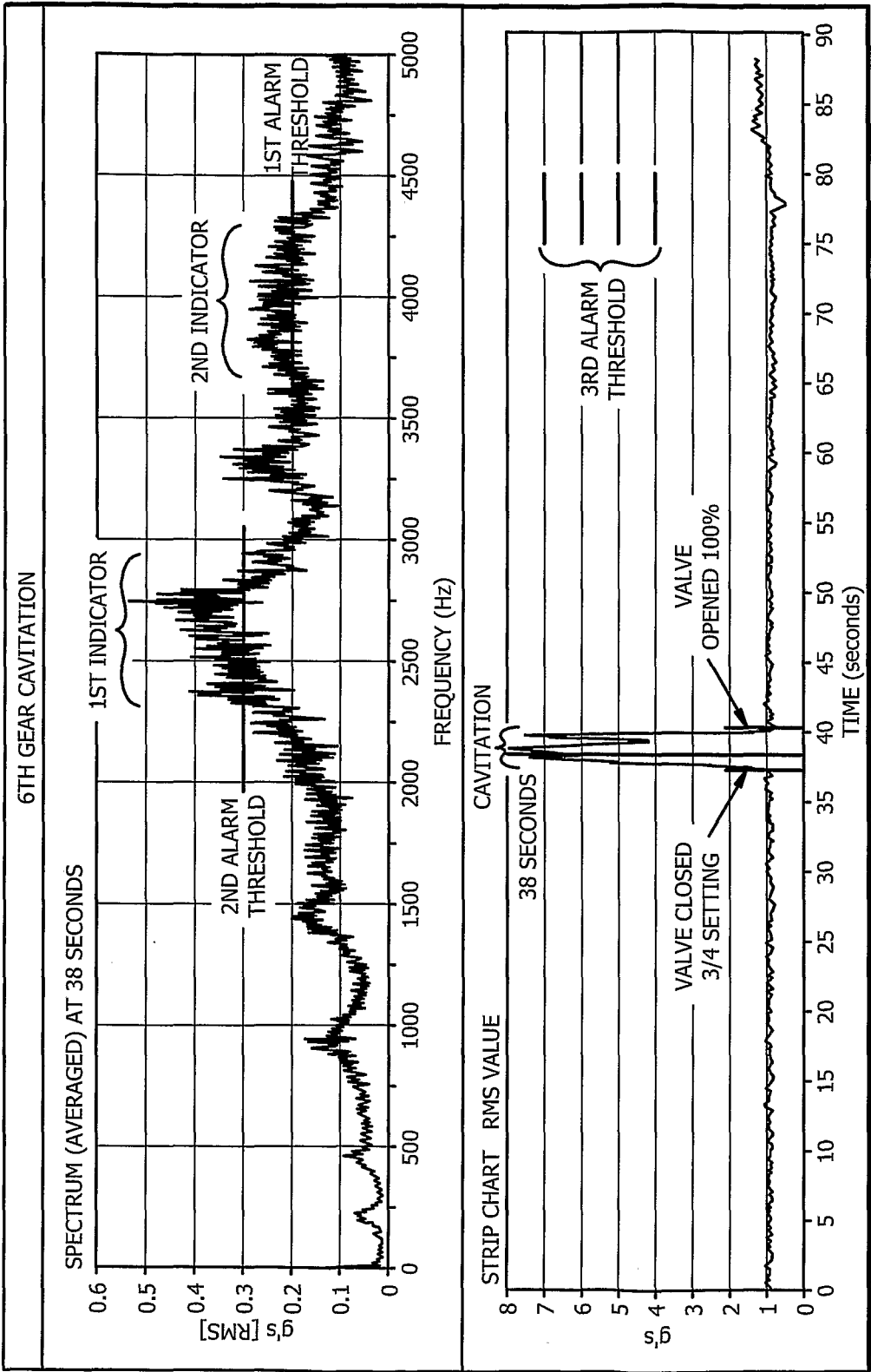


FIG. 11B

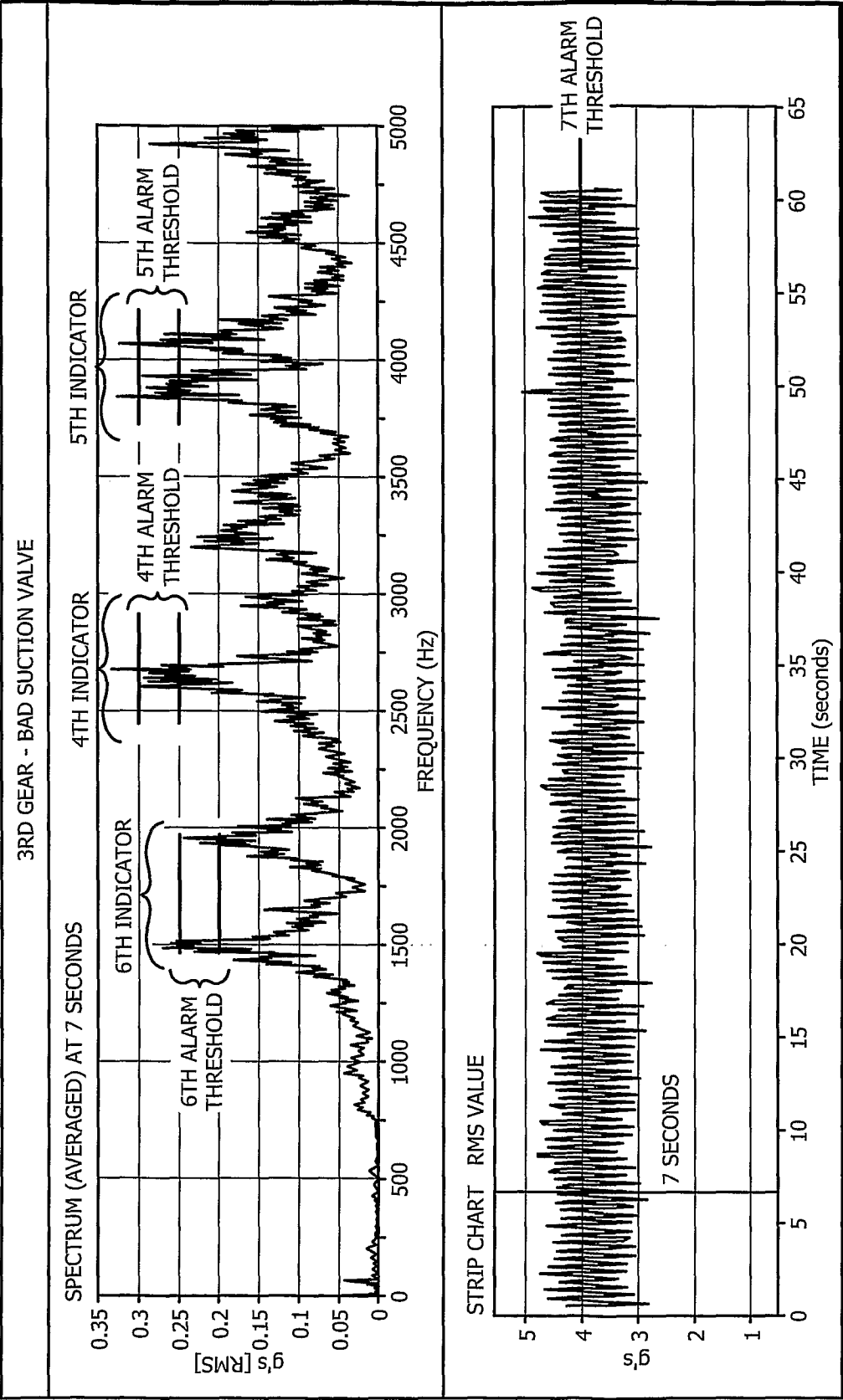


FIG. 12

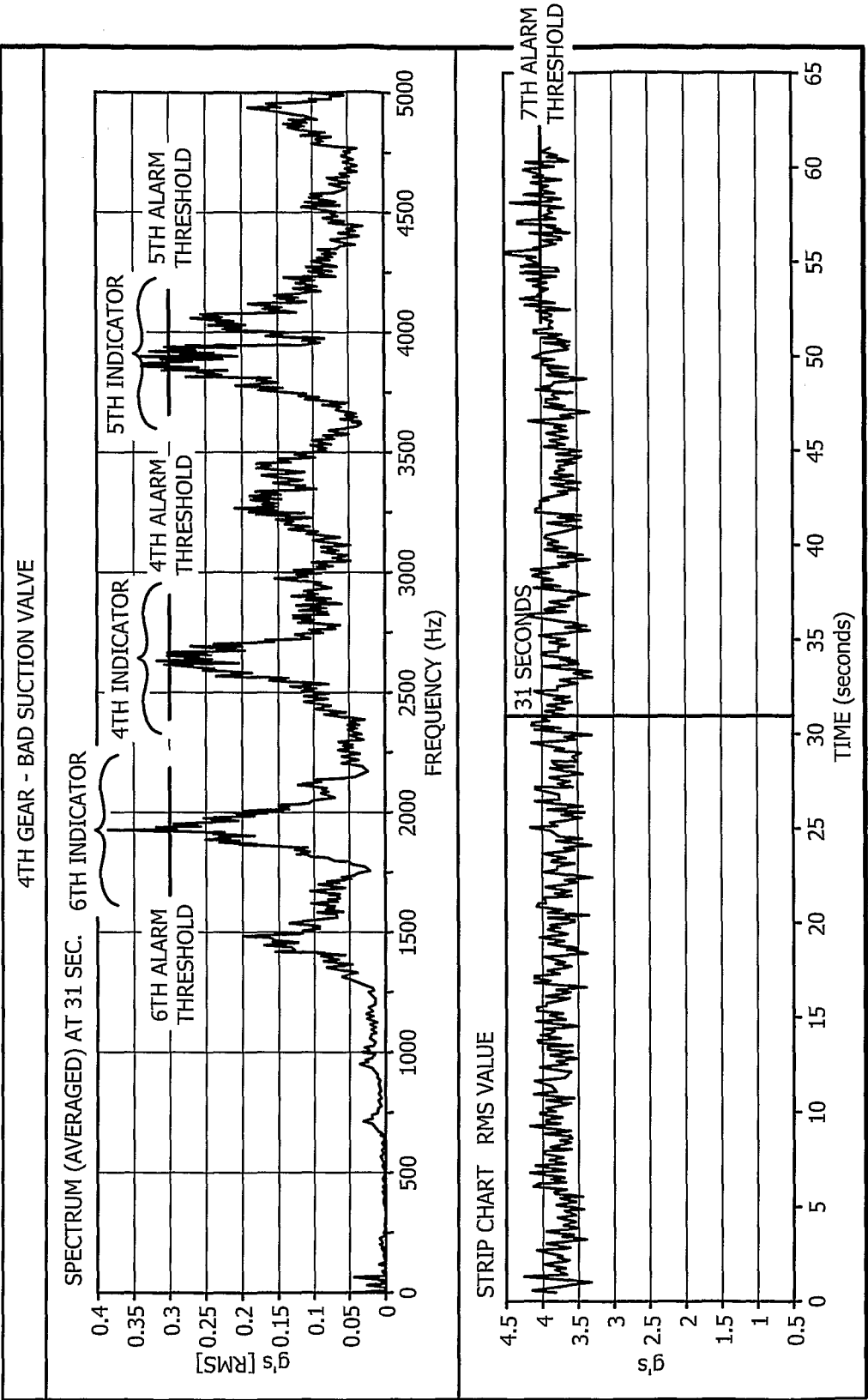


FIG. 13

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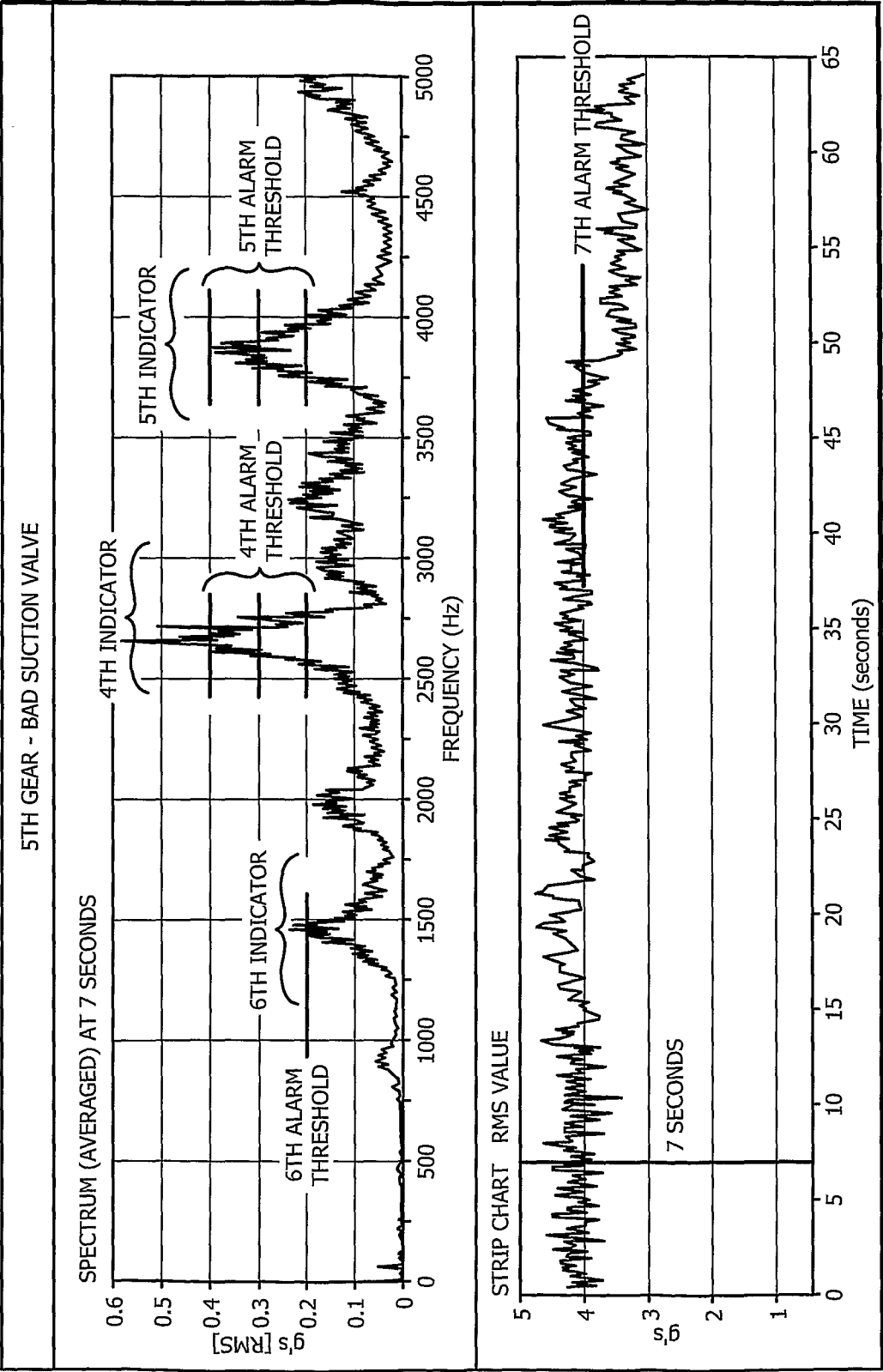


FIG. 14

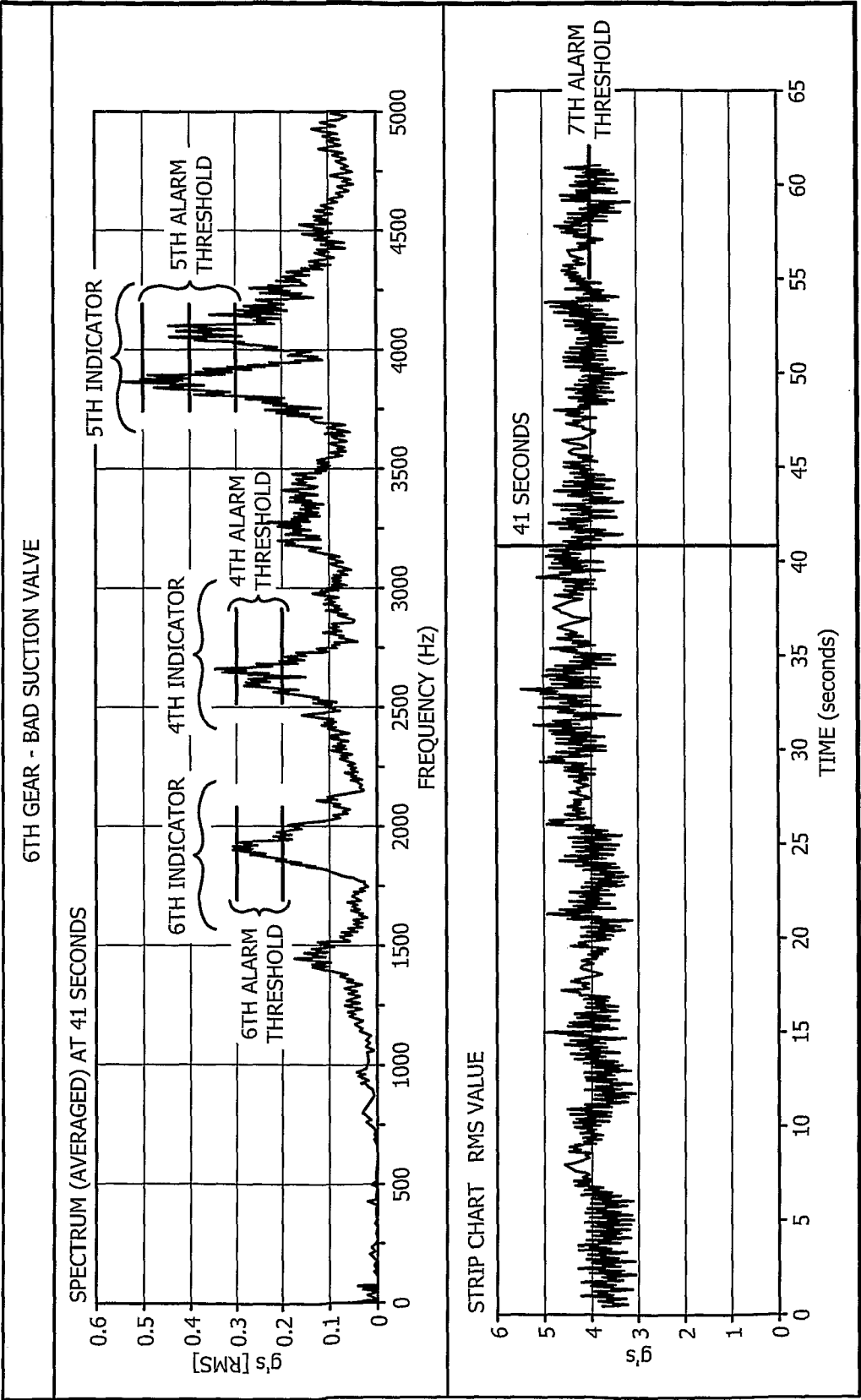


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2010/000544

A. CLASSIFICATION OF SUBJECT MATTER

INV. E21B21/06 E21B47/00 F04B51/00 G01M13/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B F04B G01M

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/079158 A1 (MERCER JEFFERY LYN [US]) 29 April 2004 (2004-04-29) paragraphs [0029] - [0031]; claims 8-13,17,50,95	1-20
X	US 2008/006088 A1 (WAGO TOSHIMICHI [US] ET AL) 10 January 2008 (2008-01-10) paragraphs [0006] - [0008]	1-20
X	GB 2 314 412 A (CZAJA RICHARD [GB]) 24 December 1997 (1997-12-24) * abstract	1-20
X	WO 2004/102052 A1 (SIEMENS AG [DE]; ENS WOLFGANG [DE]; PUETTNER ALF [DE]) 25 November 2004 (2004-11-25) * abstract	1-20
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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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Date of the actual completion of the international search

28 September 2010

Date of mailing of the international search report

07/10/2010

Name and mailing address of the ISA/

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Fax: (+31-70) 340-3016

Authorized officer

Bellingacci, F

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2010/000544

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 97/38292 A1 (ROSENHAVE PER EINAR [NO]) 16 October 1997 (1997-10-16) page 20, line 34 - page 21, line 14; figure 13 -----	1-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2010/000544

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			EP 1625321 A1	15-02-2006
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