US 20110189028A1

(19) **United States**

(12) **Patent Application Publication**

Shampine et al.

(10) **Pub. No.: US 2011/0189028 A1**

(43) **Pub. Date: Aug. 4, 2011**

(54) **PRESSURE PULSE INTERACTION MANAGEMENT IN A MULTIPLE PUMP SYSTEM**

(76) Inventors: **Rod Shampine**, Houston, TX (US); **Rajesh Luharuka**, Katy, TX (US)

(21) Appl. No.: **13/015,732**

(22) Filed: **Jan. 28, 2011**

Related U.S. Application Data

(60) Provisional application No. 61/337,041, filed on Jan. 29, 2010.

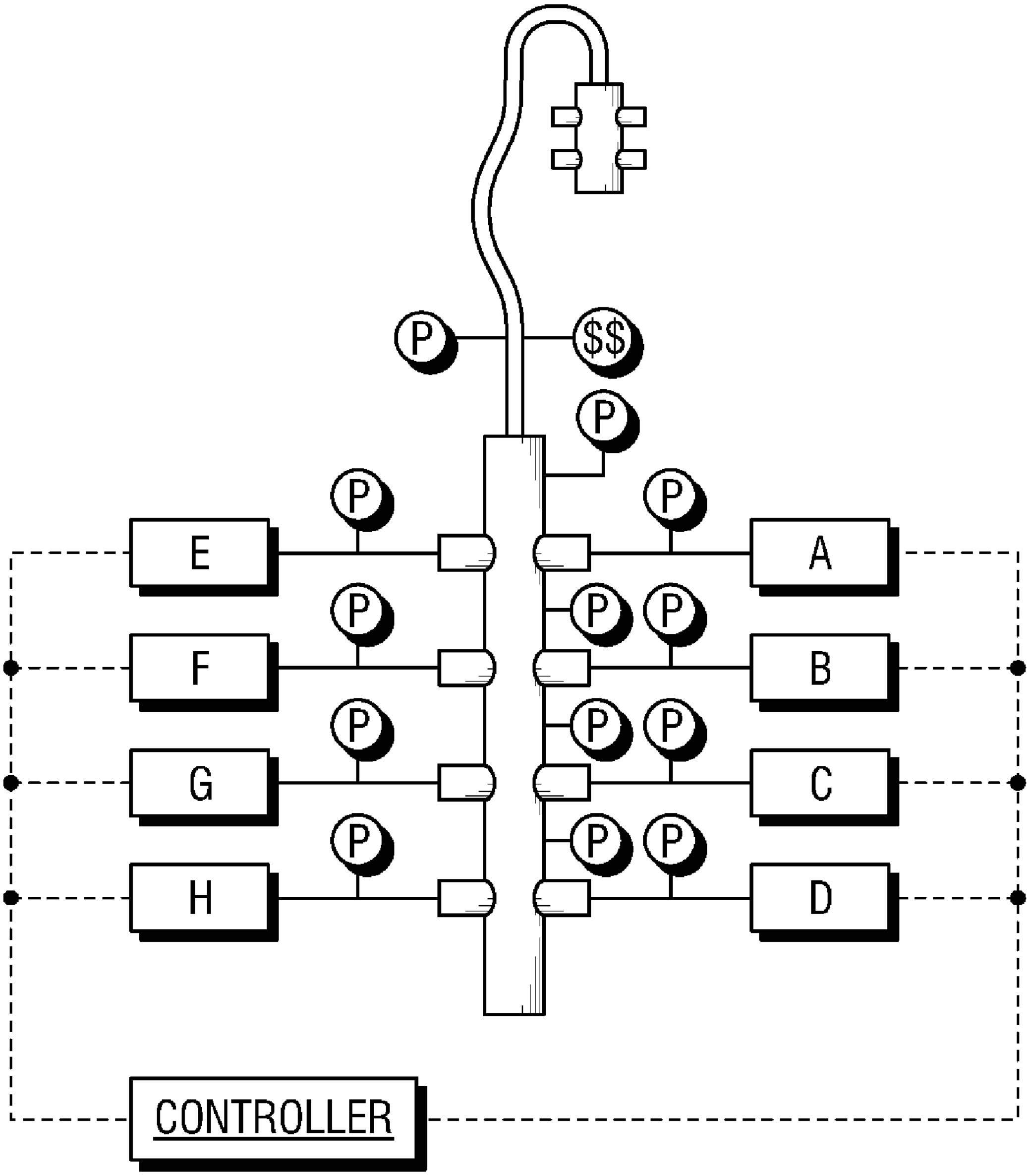
Publication Classification

(51) **Int. Cl.**
F04B 49/06 (2006.01)

(52) **U.S. Cl.** **417/53**

(57) **ABSTRACT**

Methods which include operating a plurality of pumps fluidly coupled to a common fluid line, and modulating a pumping speed of at least one of the pumps to reduce an amplitude of a pressure fluctuation in the common fluid line, where the modulating comprises maintaining an average aggregate pumping rate of the plurality of pumps.



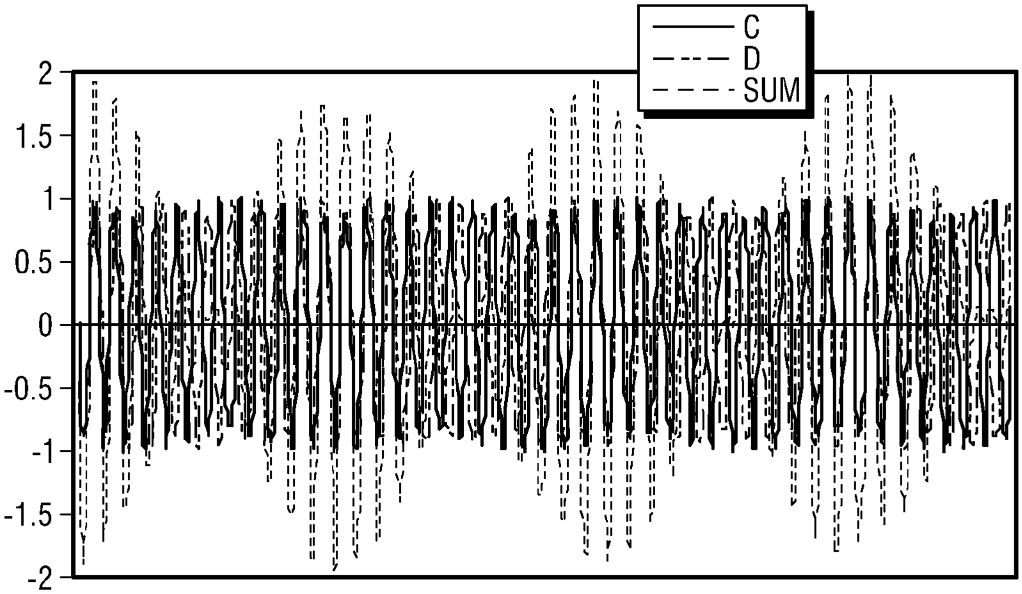


FIG. 1

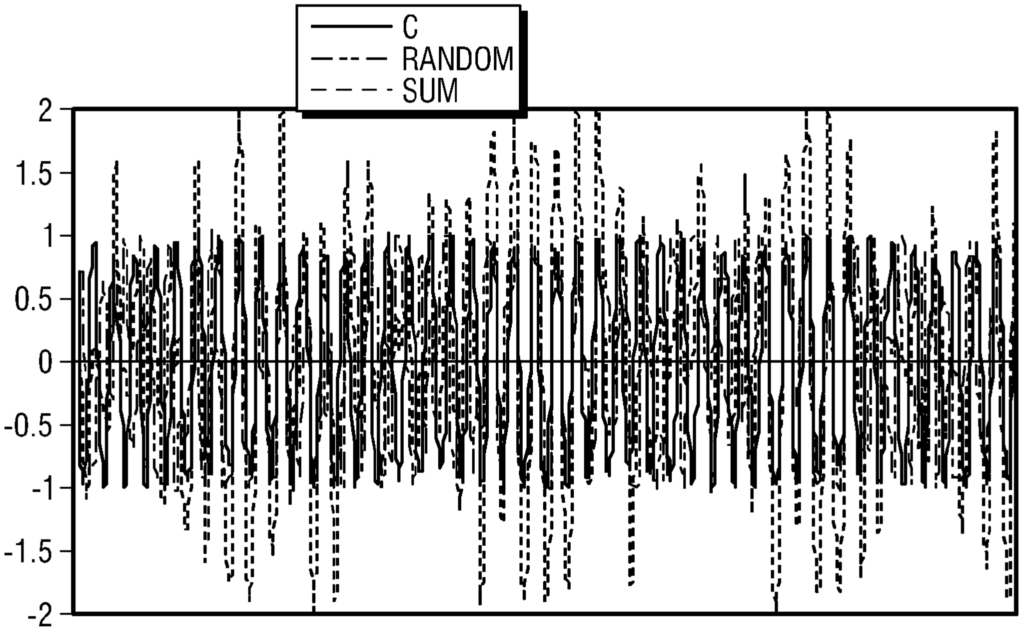


FIG. 2

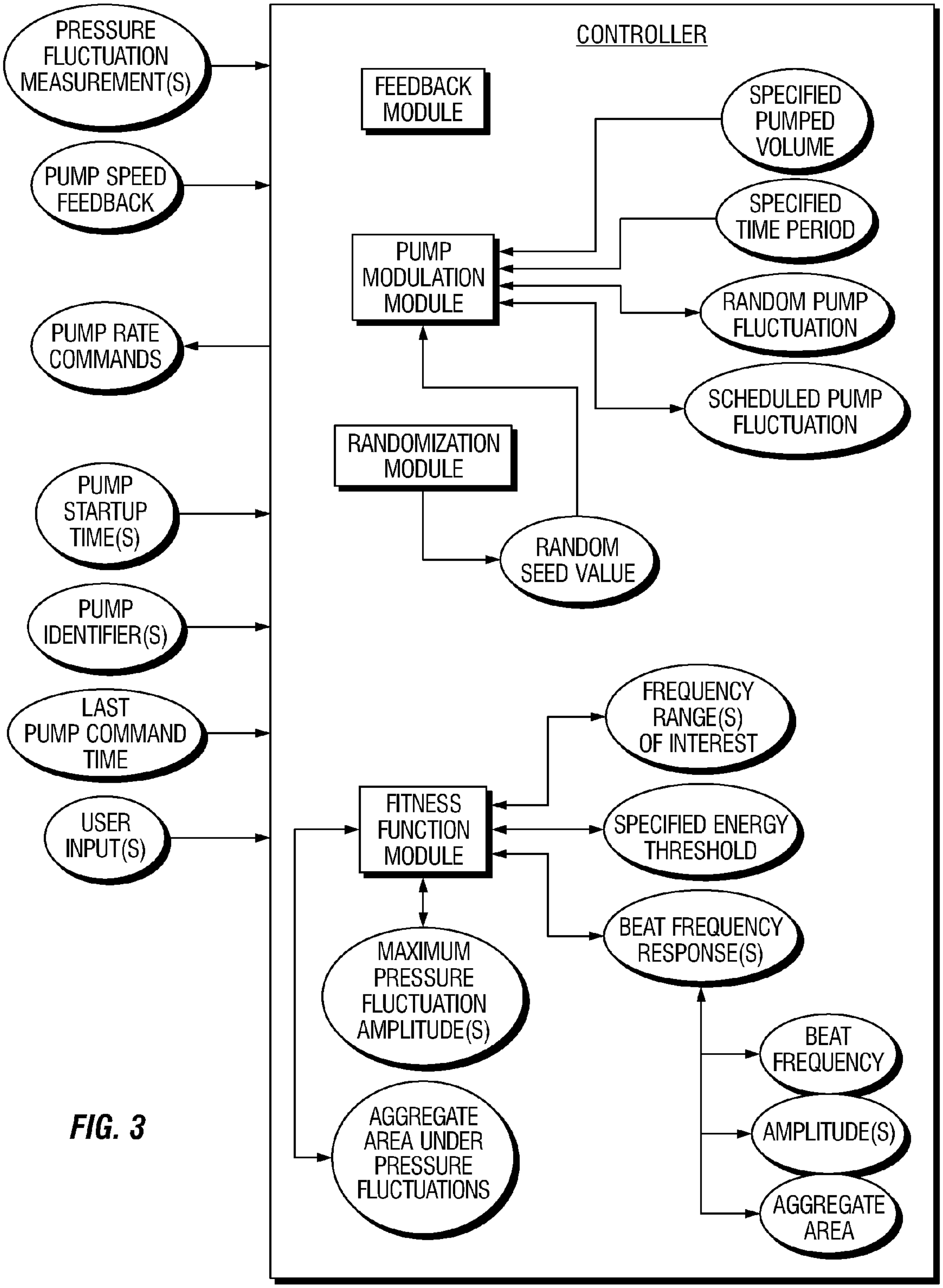

PRESSURE FLUCTUATION MEASUREMENT(S)
PUMP SPEED FEEDBACK
PUMP RATE COMMANDS
PUMP STARTUP TIME(S)
PUMP IDENTIFIER(S)
LAST PUMP COMMAND TIME
USER INPUT(S)
CONTROLLER
FEEDBACK MODULE
SPECIFIED PUMPED VOLUME
SPECIFIED TIME PERIOD
PUMP MODULATION MODULE
RANDOM PUMP FLUCTUATION
SCHEDULED PUMP FLUCTUATION
RANDOMIZATION MODULE
RANDOM SEED VALUE
FREQUENCY RANGE(S) OF INTEREST
FITNESS FUNCTION MODULE
SPECIFIED ENERGY THRESHOLD
BEAT FREQUENCY RESPONSE(S)
MAXIMUM PRESSURE FLUCTUATION AMPLITUDE(S)
BEAT FREQUENCY
AMPLITUDE(S)
AGGREGATE AREA UNDER PRESSURE FLUCTUATIONS
AGGREGATE AREA

FIG. 3

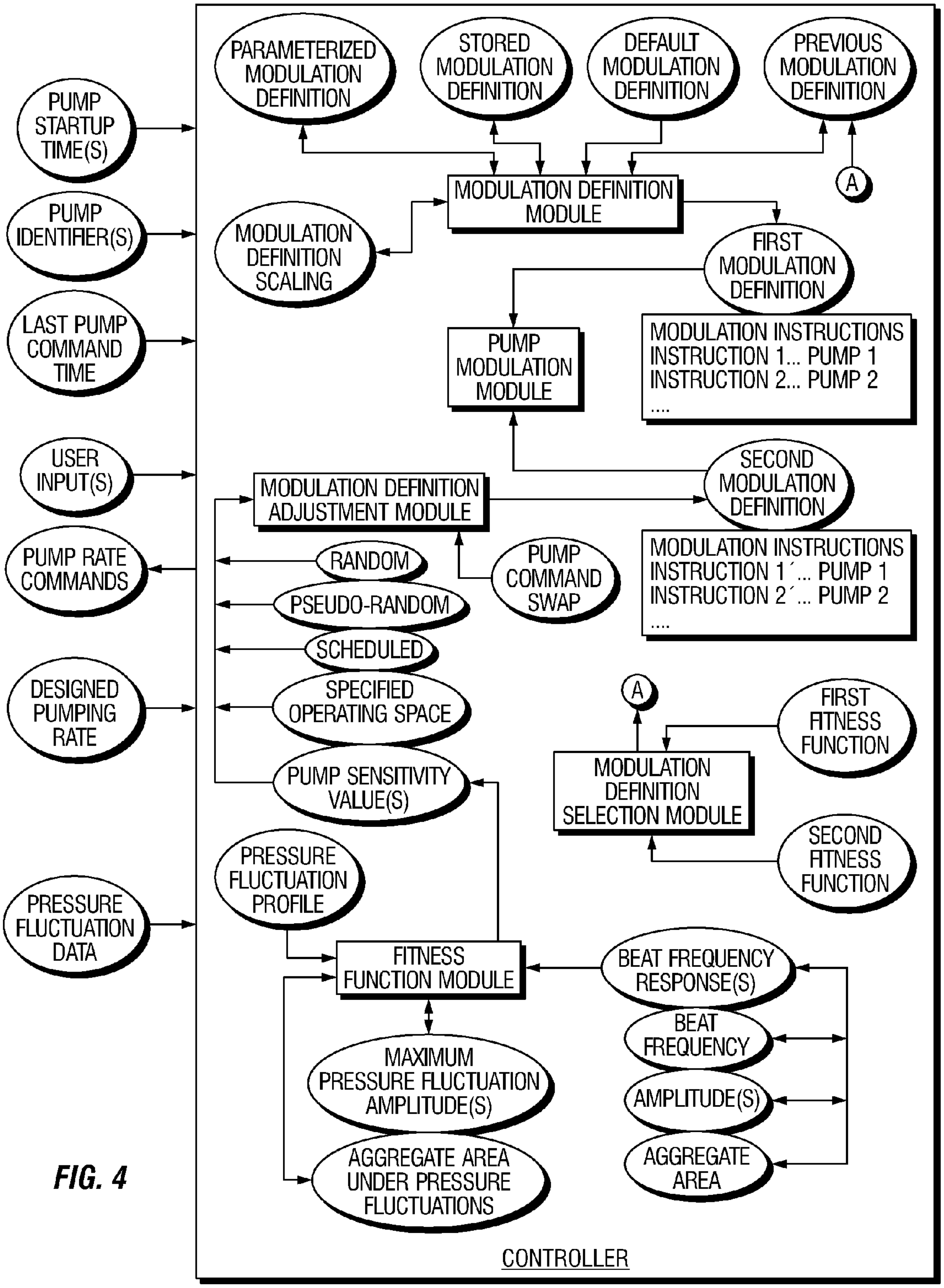

PUMP STARTUP TIME(S)
PUMP IDENTIFIER(S)
LAST PUMP COMMAND TIME
USER INPUT(S)
PUMP RATE COMMANDS
DESIGNED PUMPING RATE
PRESSURE FLUCTUATION DATA
PARAMETERIZED MODULATION DEFINITION
STORED MODULATION DEFINITION
DEFAULT MODULATION DEFINITION
PREVIOUS MODULATION DEFINITION
MODULATION DEFINITION MODULE
A
MODULATION DEFINITION SCALING
FIRST MODULATION DEFINITION
PUMP MODULATION MODULE
MODULATION INSTRUCTIONS
INSTRUCTION 1... PUMP 1
INSTRUCTION 2... PUMP 2
....
MODULATION DEFINITION ADJUSTMENT MODULE
SECOND MODULATION DEFINITION
MODULATION INSTRUCTIONS
INSTRUCTION 1´... PUMP 1
INSTRUCTION 2´... PUMP 2
....
RANDOM
PSEUDO-RANDOM
SCHEDULED
SPECIFIED OPERATING SPACE
PUMP SENSITIVITY VALUE(S)
PUMP COMMAND SWAP
A
FIRST FITNESS FUNCTION
MODULATION DEFINITION SELECTION MODULE
SECOND FITNESS FUNCTION
PRESSURE FLUCTUATION PROFILE
FITNESS FUNCTION MODULE
BEAT FREQUENCY RESPONSE(S)
BEAT FREQUENCY
AMPLITUDE(S)
AGGREGATE AREA
MAXIMUM PRESSURE FLUCTUATION AMPLITUDE(S)
AGGREGATE AREA UNDER PRESSURE FLUCTUATIONS
CONTROLLER

FIG. 4

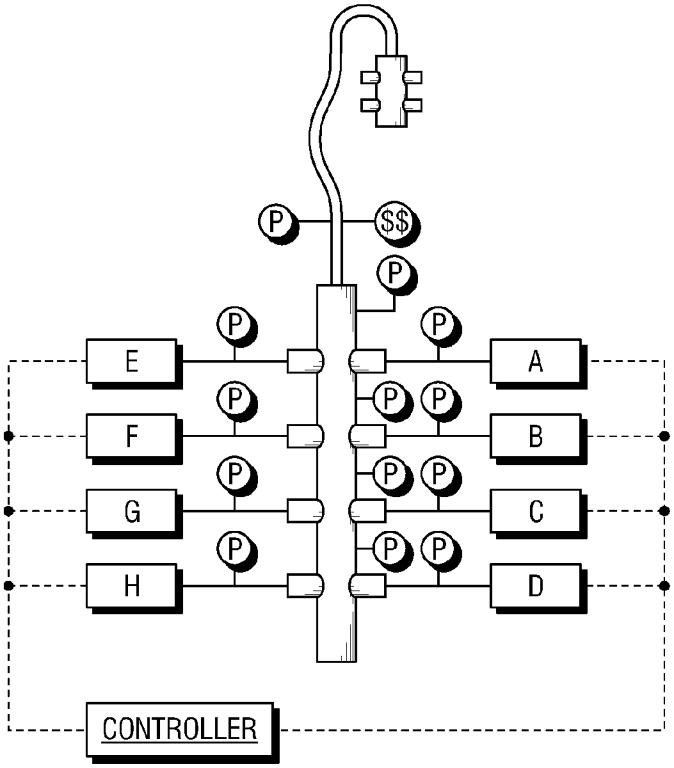

P
$$
P
P
P
E
F
G
H
A
B
C
D
CONTROLLER

FIG. 5

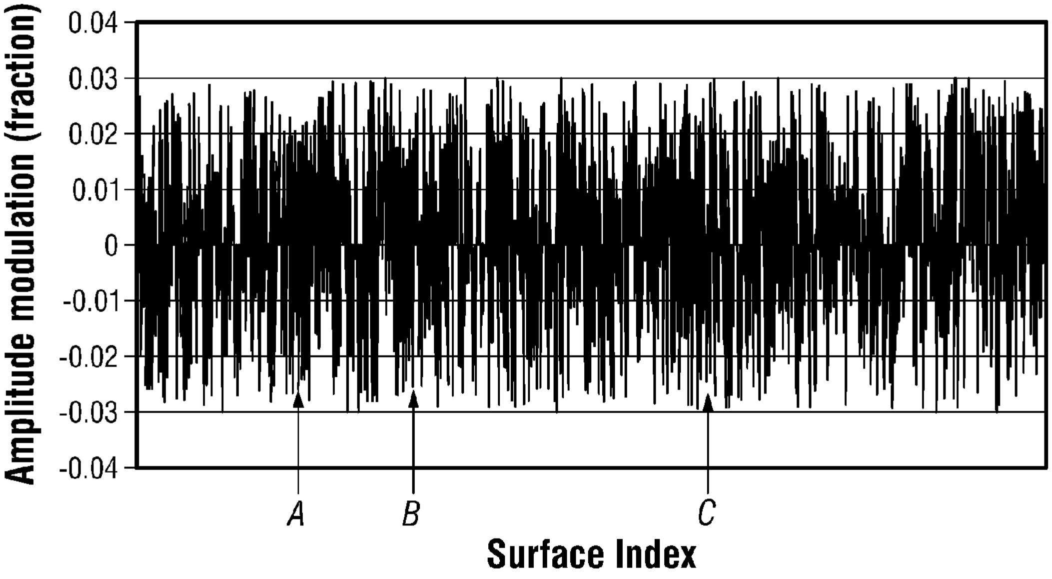

Amplitude modulation (fraction)
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
A
B
C
Surface Index

FIG. 6

PRESSURE PULSE INTERACTION MANAGEMENT IN A MULTIPLE PUMP SYSTEM

RELATED PATENT APPLICATION

[0001] This application claims the benefit of priority from U.S. Provisional Application No. 61/337,041, filed on Jan. 29, 2010, the entire contents of which are hereby specifically incorporated by reference.

BACKGROUND

[0002] The statements in this section merely provide background information related to the present disclosure and may not constitute prior art.

[0003] In some subterranean formation processes carried forth in the field, such as fracturing operations conducted at a well site, oftentimes high pumping rate requirements make necessary use of multiple pumps. In such multiple pump jobs, if one or more pumps are operating at or near the same speed, large pressure fluctuations or spikes can be produced as the plunger pulses of the plurality of pumps synchronise and desynchronise. These pressure spikes or fluctuations, can lead to failure of pressurizing equipment, such as missile trailers.

[0004] It became know that some failures were due to resonances manifesting within the piping system, which was excited by these pressure fluctuations. While chokes may be added to pump inlets on the missile trailers to significantly abate the problem, such approach can lead to pump speed synchronization which can increase the pressure pulsations by up to two orders of magnitude. Such pulsations may lead to damage the of the treating iron, pumps, or even engine transmissions.

[0005] It is an objective, of some embodiments of the invention herein below, to address and at least partially overcome problems related to pulse synchronisation.

SUMMARY

[0006] In a first aspect, some embodiments are methods which include operating a plurality of pumps fluidly coupled to a common fluid line, and modulating a pumping speed of at least one of the pumps to reduce an amplitude of a pressure fluctuation in the common fluid line, where the modulating comprises maintaining an average aggregate pumping rate of the plurality of pumps.

[0007] The modulating may include a modulation behavior selected from modulation behaviors such as inducing a random pump rate fluctuation into at least one of the pumps, inducing a scheduled pump rate fluctuation into at least one of the pumps, inducing a random pump rate fluctuation into each of the pumps, inducing a scheduled pump rate fluctuation comprising a pump offset schedule into each of the pumps, and further ensuring that each of the pumps operates at a distinct position in the pump offset schedule, and inducing a pseudo-random pump rate fluctuation into at least one of the pumps.

[0008] Modulating may be based upon a random seed value for at least one of the pumps. Some examples of such random seed value include a pump startup time, a time of a last command for the pump, and the like.

[0009] Maintaining an average aggregate pumping rate of the plurality of pumps may include modulating at least one pump such that a specified pumped volume occurs within a specified time period.

[0010] In some instances, the amplitude of the pressure fluctuation in the common fluid line may be reduced by an amplitude reduction operation such as minimizing a maximum amplitude of pressure fluctuation for a range of frequencies of interest, minimizing an aggregate area under pressure fluctuation pulses for a range of frequencies of interest, ensuring that a maximum amplitude of pressure fluctuation for a range of frequencies of interest is below a specified energy threshold, ensuring that an aggregate area under pressure fluctuation pulses for a range of frequencies of interest is below a specified energy threshold, determining a beat frequency response between at least two of the pumps, and ensuring that: a maximum amplitude of the beat frequency response is below a threshold and/or minimized; or, an aggregate area of the beat frequency response is below a threshold and/or minimized.

[0011] Any of the methods described above may further include commanding at least two of the pumps to pump at a substantially similar nominal pump rate.

[0012] Further, any of the methods described above may include operating at least one pump in all transmission gears and acquiring initial pressure pulsation data to determine resonance frequencies of the at least one pump. An operator may utilize the resonance frequencies determined in pump operation to avoid pump speeds which generate the resonant frequencies. Also, the pump operation may be controlled by software.

[0013] In another aspect, method embodiments include determining a first modulation definition by a plurality of modulation instructions, each modulation instruction corresponding to one of a plurality of pumps fluidly coupled to a common fluid line, then operating the pumps in response to the first modulation definition, determining a pressure fluctuation profile and a first fitness function for the first modulation definition in response to the pressure fluctuation profile, adjusting the first modulation definition to generate a second modulation definition, operating the pumps in response to the second modulation definition, determining the pressure fluctuation profile and a second fitness function for the second modulation definition in response to the pressure fluctuation profile, and comparing the first fitness function and the second fitness function, and selecting one of the first modulation definition and the second modulation definition in response to the comparing.

[0014] The determining a first modulation definition may include at least one operation such as, but not limited to, determining a stored modulation definition, selecting a default modulation definition, determining a modulation definition in response to a pump specific parameter selected from at least one of a pump identifier, a pump start time, and a pump last command time, utilizing a modulation definition from a previous selection of the first modulation definition and second modulation definition, accepting a user input modulation definition, determining the modulation definition in response to user inputs, and scaling a preliminary modulation definition in response to a designed pumping rate.

[0015] The adjusting may be accomplished by performing at least one of changing at least one of the modulation instructions, wherein the changing is random, pseudo-random, and/or scheduled, testing at least one of the modulation instructions over a specified operating space, and swapping at least a portion of one of the modulation instructions with another of the modulation instructions.

[0016] Any of the above methods may further include determining a sensitivity of the fitness functions to at least one of the pumps. Additionally the modulation may be modified by instructions corresponding to a pump having a high sensitivity to the fitness functions.

[0017] Determining the first fitness function may include determining at least one of a maximum amplitude of a pressure fluctuation for a range of frequencies of interest, an aggregate area under pressure fluctuation pulses for a range of frequencies of interest, a maximum amplitude of a beat frequency response between at least two of the pumps, and an aggregate area of a beat frequency response between at least two of the pumps.

[0018] In yet another aspect, embodiments may include operating a plurality of pumps fluidly coupled to a common fluid line, interpreting a pumping rate of each of the plurality of pumps, and adjusting the pumping rate of the plurality of pumps such that: a total pumping rate is maintained; and no two adjacent pumps are pumping at the same rate. The pumping rate may be determined by the rate of pressure pulse application from the pump to the common fluid line.

[0019] The adjusting the pumping rate of the plurality of pumps such that no two adjacent pumps are pumping at the same rate may include adjusting the pumping rates according to at least one of ensuring that the pumps differ in volumetric rate by at least 0.1 bpm, and ensuring that the pumps differ in plunger strokes per minute by at least 2%.

[0020] Adjacent pumps may be any two pumps having a shortest relative fluid path through the common fluid line.

[0021] Any of the methods may further involve operating at least one pump in all transmission gears and acquiring initial pressure pulsation data to determine resonance frequencies of the at least one pump.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] FIG. **1** is exemplary data illustrating a coherent beat frequency between two pumps operating at a similar nominal speed (incorporated into the specification text-color).

[0023] FIG. **2** is exemplary data illustrating an incoherent beat frequency between two pumps operating at a similar nominal speed, with an imposed modulation on one pump (incorporated into the specification text-color).

[0024] FIG. **3** is a schematic diagram of a controller for performing certain operations to modulate pump operations.

[0025] FIG. **4** is a schematic diagram of an alternate controller for performing certain operations to modulate pump operations.

[0026] FIG. **5** is a schematic diagram of a system having multiple pumps fluidly coupled to a common fluid line.

[0027] FIG. **6** is an illustration of a scheduled pump fluctuation.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0028] For the purposes of promoting an understanding of the principles of the invention, reference will now be made to the embodiments illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the invention is thereby intended, any alterations and further modifications in the illustrated embodiments, and any further applications of the principles of the invention as illustrated therein as would normally occur to one skilled in the art to which the invention relates are contemplated herein.

[0029] Referencing FIG. **5**, an exemplary system includes a number of pumps fluidly coupled to a common fluid line. A controller is in communication with the pumps, and a number of pressure fluctuation devices ("P"), which may be accelerometers, high frequency pressure transducers, or other devices that determine a parameter indicative of pressure fluctuations at various points in the system. An exemplary system includes at least two pumps, at least one of which is in communication with the controller where the controller is present. The system includes any number of pressure fluctuation devices, including in certain embodiments no pressure fluctuation devices. One exemplary system includes a device ("$$") indicative of a device that is expensive, sensitive to vibrations, critical to the performance of a pumping job (i.e. failure of the device causes failure of the job, inconvenience to the job, or otherwise induces unusual expense into the job). Certain embodiments of the system do not include a device $$.

[0030] An exemplary procedure with respect to the system includes operating the pumps fluidly coupled to a common fluid line and interpreting a pumping rate of each of the pumps. Interpreting as used herein includes any operation to determine the interpreted parameter, including at least receiving the parameter as a datalink or network communication, looking up the parameter value in a software location, receiving the parameter as an industry standard communication, determining the parameter from a sensor value, and/or calculating the parameter based on other parameters received or known in the system. The procedure includes an operation to adjust the pump rate of the pumps such that a total pumping rate is maintained (e.g. 30 barrels per minute (BPM)), and such that no two adjacent pumps are pumping at the same rate.

[0031] Maintaining the total pumping rate is an operation that is defined by specific factors related to a job that will be understood to one of skill in the art contemplating a specific embodiment of the system. For example, maintaining a pumped volume to within a specified percentage of a pumped volume over a specified time period may be acceptable for maintaining the total pumping rate. The sensitivity of the job to pump rate fluctuations, the fluid volume within a wellbore down to the formation of interest, the type of fluid and compressibility of the fluid, and other parameters known in the art will contribute to the determination of acceptable percentages. In certain embodiments, maintaining the pump rate to within a small percentage volume (e.g. less than 5%, or less than 2%) over a small period of time (e.g. less than one minute, or less than 30 seconds) will be acceptable for many wellbore treatment pumping situations.

[0032] A difference between pumping rates that determines that the pumps are not pumping at the same rate is likewise a system-specific determination. In certain embodiments, a difference in pumping rates of 2.5% is sufficient, or a pumping rate of 0.1 BPM is sufficient. One of skill in the art may perform a simple data sampling to determine how closely synchronised two pumps may operate and avoid harmonic interaction. It has been observed that two similar pumps operating at a nominal 5 BPM can experience harmonic interactions that are 100 times stronger than one of the pumps operating 0.1 BPM away from the other. In certain embodiments, the pumping rate is determined by the pump plunger stroke speed (e.g. in strokes per minute), because pumps having a different plunger head size will pump different fluid volumes over time with the same plunger stroke speed. Pumping rate is utilized herein, and although many examples include volumetric pumping rate, the use of the term pump rate also includes at least any speed related to the pumps including at least an engine speed, a plunger stroke frequency, a volumetric pumping rate, a rate of pressure pulse application from the pump to the common fluid line (e.g. a rotational speed of a compressor for a non-positive displacement pump, or the plunger stroke rate for a positive displacement pump), and a transmission rotational rate within the pumper system. A given system may include some of the pump rate concepts and exclude others, depending on the context of the example and the likely harmonic interaction factors between pumps for the given situation.

[0033] In certain embodiments, the operation to adjust the pumping rate of the pumps includes adjusting the pump rates such that no two adjacent pumps have a volumetric rate within 0.1 BPM of each other, and/or such that no two adjacent pumps have a plunger stroke rate within 2% of each other. Adjacent pumps, as used herein, include any two pumps having a shortest relative fluid path through the common fluid line, or a fluid path through the common fluid line that does not traverse other pumps. In the example of FIG. **5**, Pump "A" may be considered adjacent to pump "B". Pump "A" may likewise be considered adjacent to pump "E", although the dynamics of the common fluid line and the distance between pumps "A" and "E" may allow the pumps to be considered non-adjacent as well. In one example, pumps A, C, F, and G run a first pumping rate and pumps B, D, E, and H run at a second pumping rate, ensuring that no two adjacent pumps are operating at the same pumping rate. In another example, pumps A, C run at a first rate, pumps B, D run at a second rate, pumps E, G run at a third rate, and pumps F, H run at a fourth rate, again ensuring that no two adjacent pumps are operating at the same pumping rate, and providing even greater distance through the fluid path between pumps having similar pumping rates.

[0034] Other pumping rate combinations are understood herein, including operating each pump at a different rate, operating pumps A, G at a first rate, pumps B, H at a second rate, pumps C, E at a third rate, and pumps D, F at a fourth rate. Certain examples include operating a lowest number of discrete pumping rates that still provide a greatest distance between pumps that operate at the same rate. The number of pumping rates to be utilized may be determined by a user input, an operation of the controller, and may further be updated during a treatment operation according to applicable criteria such as a determination that the vibration profile can be improved or is too high.

[0035] Referencing FIG. **3**, a controller that performs certain operations for modulating pump rates is shown. The controller forms a portion of a processing subsystem including one or more computing devices having memory, processing, and communication hardware. The controller may be a single device or a distributed device, and the functions of the controller may be performed by hardware or software. In certain embodiments, the controller includes one or more modules structured to functionally execute the operations of the controller. The exemplary controller includes a feedback module, a pump modulation module, a randomization module, and a fitness function module. The description herein including modules emphasizes the structural independence of the aspects of the controller, and illustrates one grouping of operations and responsibilities of the controller. Other groupings that execute similar overall operations are understood within the scope of the present application. Modules may be implemented in hardware and/or software on computer readable medium, and modules may be distributed across various hardware or software components.

[0036] A procedure for pumping includes operating a number of pumps fluidly coupled to a common fluid line. The pump modulation module modulates a pumping speed of at least one of the pumps to reduce an amplitude of a pressure fluctuation in the common fluid line. The modulating includes maintaining an average aggregate pumping rate of the pumps, for example achieving a specified pumped volume during each specified time period. The pump modulation module may vary pump rates by inducing a random pump rate fluctuation into at least one of the pumps, inducing a scheduled pump rate fluctuation into at least one of the pumps, inducing a random pump rate fluctuation into each of the pumps, and/or inducing a scheduled pump rate fluctuation including a pump offset schedule into each of the pumps. The pump modulation module may operate on a most sensitive pump, on a pump that is the only pump enabled to respond to pump rate commands from the pump modulation module, on any number of the pumps, and/or on all of the pumps. Where the pump modulation module utilizes a scheduled pump fluctuation, the pump modulation module ensures that each of the pumps operates at a distinct position in the pump offset schedule.

[0037] An exemplary pump modulation module induces a pseudo-random pump rate fluctuation into at least one of the pumps. The pseudo-random pump rate may be a pump rate fluctuation provided in a predetermined series, provided by an algorithm that provides a pseudo-random output, or by other pseudo-random operations understood in the art. In certain embodiments, a randomization module provides a random seed value that the pump modulation module uses for randomizing the pump modulations. The random seed value may be utilized to seed a random number algorithm, to begin a scheduled pump fluctuation at a random point within the scheduled pump fluctuation series, and/or to start the scheduled pump fluctuation at a random time. The randomization module may determine the random seed value according to a pump startup time for each of the pumps, according to a pump identifier (e.g. a pump index entered by an operator, an ordered value or address for the pump established during communications with the controller, and/or a pump serial number established for the pump), and/or according to a time that a last command was provided to the pump.

[0038] In certain embodiments, the reducing the amplitude of the pressure fluctuation in the common fluid line includes a fitness function module determining a fitness parameter and the pump modulation module modulating the pump rates in response to the fitness parameter.

[0039] In one embodiment, the fitness function module determines a maximum amplitude of pressure fluctuation for a range of frequencies of interest. The frequencies of interest may be determined by the experience of the operator, by a test of the lines (e.g. sweep frequency energy and determine harmonic frequencies of the fluid lines), by observation of pressure fluctuations during a pumping operation, or by other techniques understood in the art. The pump modulation module may adjust the pumping rates to minimize the maximum amplitude of pressure fluctuation that occurs within the range of the frequencies of interest. The pressure fluctuation frequency may be a frequency as determined by a frequency domain transformation (FFT, Fourier, Z-transform, etc.) of information from a pressure transducer, or a by a calculated pressure fluctuation frequency according to an observed beat frequency. The maximum amplitude of a pressure fluctuation may also be determined by an accelerometer positioned at a point of interest in the system, where in one embodiment any responsive frequency of the accelerometer is a frequency of interest (i.e. the dynamics of the accelerometer may dampen frequencies that are not of interest).

[0040] In other embodiments, the pump modulation module may adjust pump rates to minimize an aggregate area under pressure fluctuation pulses for a range of frequencies of interest (e.g. the largest peaks in the frequency domain, peaks within a specified percentage of a largest peak, the top three peaks, etc.). The aggregate area may be weighted for the energy provided under the peak—e.g. adjusting for the relative energy provided by a high or low frequency peak. In other embodiments, the pump modulation module adjusts pump rates to provide a maximum amplitude of pressure fluctuation for a range of frequencies of interest that is below a specified energy threshold (that again may be a frequency-dependent value), and/or adjusts pump rates to ensure that an aggregate area under pressure fluctuation pulses for a range of frequencies of interest is below a specified energy threshold.

[0041] In certain embodiments, the pressure fluctuations are fluctuations of a beat frequency. The beat frequency may be the beat frequency between at least two of the pumps (e.g. as measured between those pumps), and the pump modulation module may adjust pump rates to ensure that a maximum amplitude of the beat frequency response is below a threshold and/or minimized, or to ensure that an aggregate area of the beat frequency response is below a threshold value, minimized, below an energy threshold value, and/or has a minimized aggregate energy within the frequencies of interest.

[0042] In certain embodiments, pumps are controlled to avoid providing energy to certain portions of the frequency spectrum. The pumps may be directed into certain frequency portions, for example one or more pumps spread their energy throughout specific bandwidths within the frequency spectrum, or sensitive areas of the frequency spectrum are specifically avoided.

[0043] In certain embodiments, at least two of the pumps are commanded to operate at a substantially similar nominal pump rate. The nominal pump rate is the pump rate provided to the pump, by a controller or operator, before the pump rate command of the pump modulation module that alters the final pumping rate. The pump rate that is substantially similar varies with the specific embodiment, but includes pumps having the same commanded set point, pumps operating within 2% of each other, pumps operating to within one significant digit on a display with each other, and pump rates that if plotted over a period of time exhibit nearly the same average pump rate and substantial crossover in the plots. Any other concepts that embody substantially similar pumping rates are contemplated herein, and certain concepts embodying substantially similar may not apply to certain embodiments. In certain embodiments, several pumps or even all of the pumps operate at substantially similar nominal pump rate. Among advantages provided by operating pumps at substantially similar nominal pump rates include simplification of the system for the operator, standardization in designing pumping treatments where the pumps perform fungible operations, ensuring that pumps exhibit similar fuel consumption simplifying logistics, and ensuring that pumps exhibit similar long-term wear characteristics.

[0044] Referencing FIG. **4**, a controller that performs certain operations for modulating pump rates is shown. A modulation definition module determines a first modulation definition including a plurality of modulation instructions, where each modulation instruction corresponds to one of a number of pumps fluidly coupled to a common fluid line.

[0045] A pump modulation module operates the pumps in response to the first modulation definition, and a fitness function module determines a pressure fluctuation profile (e.g. frequency domain data showing amplitude peaks, accelerometer peak data with or without frequency information, etc.) and a first fitness function for the first modulation definition in response to the pressure fluctuation profile. A modulation definition adjustment module adjusts the first modulation definition to generate a second modulation definition, and the pump modulation module operates the pumps in response to the second modulation definition. The fitness function module determines the pressure fluctuation profile and a second fitness function for the second modulation definition in response to the pressure fluctuation profile, and a modulation definition selection module compares the first fitness function and the second fitness function, and selects one of the first modulation definition and the second modulation definition in response to the comparing. The modulation definition selection module may select the best fitness function between the first fitness function and the second fitness function (e.g. the one having a highest value where a higher value indicates greater fitness), but in certain embodiments the modulation definition selection module may decline the second fitness function where the second fitness function is higher but the values are close—for example to promote system stability and reduce cycling between operating points.

[0046] In certain embodiments, the modulation definition module determines the first modulation definition from a stored modulation definition. The stored modulation definition may be a manufacturer-provided definition, a modulation definition stored at a system shutdown, or other stored modulation definition understood in the art. The modulation definition module may utilize a default modulation definition as the first modulation definition, for example at startup, after a hardware change occurs in the system, and/or after a power down of the system (although the controller may also save a modulation definition through a power down cycle). The modulation definition module may utilize a parameterized modulation definition as the first modulation definition—for example a modulation definition determined in response to a pump identifier, pump startup time, and/or pump last command time. The modulation definition module may determine the first modulation definition from a previous modulation definition from a prior execution cycle of the controller (e.g. the selected modulation definition by the modulation definition selection module), and/or may determine the first modulation definition in response to user inputs.

[0047] The modulation definition module may construct the first modulation definition from a number of sources, including any of the described sources or other sources understood in the art. In a non-limiting example, the modulation definition module surveys the pumps for a pump identifier when communication is initiated between the pumps and the controller (e.g. a cable from each pump is plugged into the controller), and where a pump identifier is not available for a particular pump (e.g. an older pump that does not publish a pump identifier) the modulation definition module utilizes a default instruction for the particular pump.

[0048] Certain operations of the controller may be performed by an operator or in hardware. For example, where a pump is not compatible for communication with the controller or to receive commands from the controller, the modulation definition module may determine the existence of the pump through a user input identifying the pump, and the pump modulation module may publish a pump rate command for the pump, where an operator follows the published pump rate for the pump in question. In the example embodiment, the modulation definition module and modulation definition adjustment module may determine that the pump is not automatically controllable, and assign fixed pump rates to the pump while assigning rapidly fluctuating pump rates to other pumps that are automatically controllable. In certain embodiments, a pump may be responsive to the pump rate commands through hardware devices, for example a pump may be responsive to a voltage output from the controller that has a modulated value depending upon the commanded pump rate. Any pump rate control mechanism understood in the art is contemplated herein.

[0049] In certain embodiments, the modulation definition module determines the first modulation definition by scaling a preliminary modulation definition in response to a designed pumping rate. For example, a default modulation definition may include a set of values for four pumps at a pumping rate of 15 BPM, and the designed pumping rate may be 20 BPM. In the example, where four pumps are present in the system, the modulation definition module may provide modulation definition scaling to the default modulation definition in response to the designed pumping rate. The scaling may be applied to some, but not all, of the parameters in the modulation definition as will be understood to one of skill in the art. For example, a randomized fluctuation of +/−0.5% may be applied to either 15 BPM or 20 BPM without regard to the pumping rate, but a modulation frequency rate may be changed at 20 BPM due to the change in the forcing frequency provided by the pump. Any source for the modulation definition may be scaled in response to a change in the designed pumping rate, including the previous modulation definition. It is a mechanical step for one of skill in the art, having the benefit of the disclosures herein, to determine scaling adjustments to a modulation definition.

[0050] The pump modulation module may perform any adjustments to the modulation definition understood in the art to stabilize the system, respond to changes in the system, to achieve set points, and the like. For example and without limitation, where a change in the modulation definition indicates a large change in rates, the pump modulation module may provide rate smoothing to avoid system disruption, where a large set point change has occurred the pump modulation module may suspend certain modulation operations that may reduce system response, etc. Other controller management may be included in the system, for example gains in various controllers within the system may be managed to avoid complications with the modulating or with the changes in set points in response to a change in the modulation definition. Non-limiting examples include derivative control elements may be suspended or have target points adjusted (e.g. changing from derivative of the error to derivative of a target output or derivative of a nominal non-modulated target output), integrators may be reset, have values changed, or have gains increased or reduced, etc. Other adjustments understood in the art are contemplated herein.

[0051] In certain embodiments, the modulation definition adjustment module generates the second modulation definition with an operation such as changing at least one of the modulation instructions, wherein the changing is random, pseudo-random, and/or scheduled; testing at least one of the modulation instructions over a specified operating space (e.g. sequentially manipulating a pump rate for a pump from a low pumping rate to a high pumping rate at intervals to test the operating space); and swapping at least a portion of one of the modulation instructions with another of the modulation instructions (e.g. swapping a first pump rate and a second pump rate). Any modulation instructions may be changed, including at least pump rates, modulation amplitudes and rates, modulation functions (e.g. random, pseudo-random, selection from one or more schedules), etc.

[0052] In certain embodiments, the fitness function module determines a sensitivity of the fitness functions to at least one of the pumps. The determination of sensitivity may be determined in the normal course of operations or as an intrusive procedure. For example, the fitness function may track the magnitude of changes in the fitness functions in response to changes for various pumps (including statistically de-convoluting where multiple pumps are adjusted in each iteration). In another example, the fitness function module may perform a specific sensitivity analysis, sequentially adjusting pump commands and determining the magnitude of changes in the fitness functions in response to the sequential adjustments. In certain embodiments, the modulation definition adjustment module preferentially modifies modulation instructions for high sensitivity pumps. Preferential modification may be a statistical increase (e.g. the random selector increases the percentage of adjustments for the sensitive pump) or an explicit optimization priority selection where the modulation definition adjustment module manipulates the sensitive pump (or a subset of the most sensitive pumps) until a determination is made that the optimal (possibly a local optimum that will change after other pumps are adjusted) sensitive pump parameters are determined, whereupon the modulation definition adjustment module proceeds to optimize the next subset of most sensitive pumps.

[0053] The fitness function may be any pressure fluctuation fitness parameter described herein or otherwise understood in the art. For example, and without limitation, the fitness function may be a maximum amplitude of a pressure fluctuation for a range of frequencies of interest (including maximum energy under a peak or the explicit peak amplitude), an aggregate area (including aggregate energy or explicit area) under pressure fluctuation pulses for a range of frequencies of interest, a maximum amplitude of a beat frequency response between at least two of the pumps (including maximum energy under a peak or the explicit peak amplitude), and an aggregate area of a beat frequency response between at least two of the pumps (including aggregate energy or explicit area). In certain embodiments, the fitness function is indicative of the pressure fluctuation environment of a sensitive device in the system (e.g. see "$$" on FIG. **5**).

[0054] In certain embodiments, the fitness function assigns certain pumps to certain portions of the frequency bandwidth (and may further provide a higher fitness score for the amount of distribution within each bandwidth). In certain embodiments, the fitness function protects certain bandwidths by direction the energy from the pumps away from certain frequency ranges in the spectrum. The protected frequency ranges may be known problematic ranges, ranges that are relevant to certain equipment or signal processing, or ranges reserved for equipment that is not always present but that may be present on certain occasions.

[0055] Referencing FIG. **6**, a randomized sequence is illustrated that is consistent with certain scheduled pump fluctuations herein. The randomized sequence includes 1093 values randomly distributed between +/−0.03. The randomized sequence is a prime number rendering it unlikely that two pumps proceeding through the sequence at differing rates (either due to a modulation frequency command change from the modulation definition, or because the pumps are pumping at different rates or have different plunger head sizes) will have a significant harmonic interaction, and also that any pump having a periodic disturbance (e.g. a secondary pressure pulse from a valve that is failing) will interact with the modulation in a simple ratio. However, the randomized sequence need not include a prime number of elements, as any sufficiently long sequence will also make interactions unlikely. The randomized sequence may be stored on the controller in advance, and may be entered for various pumps at differing positions (e.g. A, B, and C in the illustration) or at differing times. The amplitude of the randomized sequence may be scaled, and 3% is provided for exemplary purposes only.

[0056] As is evident from the figures and text presented above, a variety of embodiments according to the present invention are contemplated.

[0057] An exemplary pumping situation includes a fracturing operation with high pumping rates utilizing multiple pumps. In these multiple pump jobs, if one or more pumps are operating at or near the same speed, large pressure fluctuations are produced as the plunger pulses of the pumps go into and out of synchronization. The pressure fluctuations have been observed to be powerful enough to break missile trailers, and otherwise increase wear, cause damage to, and increase the chance of failure of treating iron, pumps, transmissions, and other equipment. One mechanism understood to cause failures are pressure fluctuations from the multiple pumps that match the resonance of the piping system, or other equipment vibrationally connected to the pumped fluid. Certain mitigating techniques such as choking pump inlets and missile trailers can assist with the issue, but such techniques may be undesirable due to fluid frictional losses, and operator behavior such as operating all pumps at the same speed can still increase wear and cause failures. Pumps operating at synchronised speeds have been observed to increase pressure pulsations by two orders of magnitude.

[0058] An exemplary operation includes operating a control algorithm on an individual pump to prevent pump synchronization. The control algorithm modulates the pump rate randomly up and down, and may be performed any number of the pumps, including a single pump, all pumps, or any number of the pumps.

[0059] An exemplary control algorithm applies the pump rate modulation, determines a feedback signal, and adjusts the pump rate modulation in response to the feedback signal. The pressure modulation may be random (e.g. determined on an output from a random function generator or white noise algorithm), pseudo random (e.g. determined from a pre-stored randomized sequence), or scheduled. Examples of a scheduled sequence include a pre-determined sequence that does not repeat within the sequence itself (e.g. based on the values of π, e, or other non-repeating sequence), a sequence having a prime number of variation settings (in certain embodiments, a large prime number), and/or any other sequence determined such that, for a finite number of pumps following the sequence and positioned at different places serially within the sequence, the pumps will not experience significant harmonic interactions.

[0060] The feedback signal may be a vibration level from any portion of the system in vibrational communication with the pumped fluid of the pumps, including at least the discharge piping or the pumps. An alternate or additional feedback signal may be a measure of the pressure fluctuation, including an amplitude of the pressure fluctuation in either the time or frequency domain. The frequency domain may include a description of the power of pressure fluctuation peaks, including an amplitude or an area under one or more peaks, and may include frequencies of interest, predetermined frequencies, or frequencies determined during pumping operations. The frequency measure may include a description of a combined beat frequency between two or more pumps, or it may be a pressure fluctuation as measured at a single sensor.

[0061] Another exemplary control algorithm utilizes a selection algorithm that searches the pumping rate or pumping rate modulation operating space, providing improving response as the pumping continues.

[0062] Another exemplary control algorithm includes selectively changing pump rates on adjacent pumpers (or on pumpers most likely to be vibrationally coupled, including pumpers having a shortest vibrational path through the pumped fluid) to NOT match the pump rate of the adjoining pumper(s). In certain embodiments, a feedback signal or signals may be utilized to determine an optimal or improved pump rate during a job. In one embodiment, the control algorithm utilizes two pump rates, with one alternating set of pumps at a first speed and another alternating set of pumps at a second speed. In another embodiment, opposing pumps may be operated at differing pumping speeds, and the control algorithm may utilize a number of pumping speeds such that no opposing, adjacent, or otherwise closely proximate pumps operate at the same speeds. In one example, even-numbered pumps operate at 5 barrels per minute (BPM), and odd pumps operate at 5.1 BPM. Pump rates described herein may refer to volumetric pump rate, or plunger stroke rate (e.g. in plunger strokes per minute). As will be understood in the art, pumps operating at different volumetric pump rates having different sized plungers may nevertheless be operating at a similar plunger stroke rate.

[0063] Another exemplary pump modulation operation is described. The pump rate (or equivalently, the engine speed) is modulated up and down using a random, pseudo-random, or pre-defined series structured so that when the volume pumped in an interval (e.g. one minute) is summed and divided by the time interval that the average rate is equal to the rate that the pump was set for. In one example, pumps at a rate at least 0.1 BPM apart can reduce the pulsations by 2 orders of magnitude (100 times), so In certain embodiments a modulation of +/−0.1 BPM is sufficient.

[0064] The modulation occurs at a frequency to avoid spending any significant time at a given potentially damaging frequency, and to minimize the energy input at any given point in the frequency spectrum. In one embodiment, a modulation series designed to spread the pumping energy evenly across a given band (such as +−0.1 BPM) is utilized. In another embodiment, a series designed to give a distribution is not even across the frequency band is utilized. In certain embodiments, a modulation series designed to reduce a maximum amplitude of any single peak is utilized.

[0065] An alternate or additional embodiment includes minimizing pumping energy at a specified range of frequencies, and further including minimizing pumping energy at a range of frequencies that are observed to occur with other pumps in the system that do not have a control algorithm modulating the pumping rate. In one example, a first pump is fluidly coupled to a system having other pumps that operate in an open loop response to a pump rate set point, a feedback signal determines the pumping energy frequencies of the open loop pumps that are realized at the fluid outlet (or other position in proximity to the first pump), and a control algorithm modulates the first pump in response to the feedback signal. An exemplary modulation includes minimizing a pumping energy frequency of the first pump at the pumping energy frequencies of the open loop pumps as realized at the fluid outlet (or other position in proximity to the first pump).

[0066] In one embodiment, one or more modulation series are structured, and pumps are introduced into the one or more modulation series, such that no two pumps run the same series at the same point in the series. In one embodiment, a random series is generated and utilized, and in an additional embodiment a long series is entered at a random point or initiated at a random time. In certain embodiments, a parameter is utilized as a random seed, such as a pump startup time, a pump identifier (such as a serial number or an operator entered value), and/or a time of a last command instruction to the pump.

[0067] FIGS. **1** and **2** provide exemplary data illustrating a pump modulation. FIG. **1** illustrates two pumps operating at similar speeds, where the yellow trace is the sum of the pumping rates. A coherent beat frequency is observed, which would show an identifiable high-amplitude peak in the frequency domain (not shown—but the determination of frequency domain information from time domain information as illustrated in FIG. **1** is a mechanical step for one of skill in the art). FIG. **1** illustrates a first pump operating at a constant speed, with a second pump operating at the same average volumetric pumping rate with time, but with a +/−0.8% random modulation applied. Again the yellow trace shows the summed pumping rates. In the illustration of FIG. **2**, a beat frequency component is barely present, and it is clear that a frequency domain analysis would show a number of diffuse peaks with much lower amplitudes than the dominant beat frequency from FIG. **1**. In some instance, inventors discover that averaging effect of randomizing across a high number of pumps, such as 10 to 14 pumps, on actual job may have even a greater effect than shown, possibly leading to lower peak to peak pressure fluctuations in the discharge line.

[0068] Another exemplary embodiment includes randomly adjusting pump speeds during a pumping operation with a selection algorithm to adjust a combination of pump speeds that obtains an improving discharge line harmonics profile (or other harmonic feature). For example, a first set of pumping parameters may be tested and compared to a second set of pumping parameters, and a fitness value assigned to each set of parameters. The pumping parameters having the superior fitness value are selected for a next iteration of the selection algorithm. The generation of new pumping parameters to test may be random or scheduled. The pumping parameters may include pumping rates, modulation values, or modulation methods, or any other pumping parameters understood in the art. The scheduled adjustments to the pumping parameters may include testing the pumping operating space (e.g. testing values from a minimum to a maximum pump rate), testing how many different pumping rates are to be utilized (e.g. two rates on alternating pumps, four rates including differing rates for alternating and opposing pumps, a unique rate for each pump, etc.), and/or testing whether randomized pump modulation or pump rate offset values provide superior response.

[0069] In certain embodiments, the fitness function includes a maximum observed frequency peak response (typically where a lower maximum is better), an area under frequency peak responses through a frequency range of interest, a combination of these parameters (e.g. minimized area combined with a specified maximum peak threshold that is not to be exceeded). Further, the frequency ranges of interest may vary between maximum peak values and the area under frequency peak responses (e.g. to minimize a specific resonance with the maximum peak, and to minimize total energy through a different frequency range, to protect from different failure modes). Still further, the fitness function may incorporate a number of pressure pulse measurements—for example a first pressure pulse measurement may be taken between a first and a second pump, and a second pressure pulse measurement may be taken between the second pump and a third pump—and the pressure pulse measurements may be weighted or otherwise combined into a fitness function result. Where a number of pressure pulse measurements are combined, the combination may determine any type of data from each (e.g. peak maximums, peak areas, etc.), and may weight the data in any manner without limitation. Non-limiting examples include weighting pressure pulse measurements more heavily near expensive or sensitive equipment, selecting frequency ranges of interest according to observed or expected frequency resonance values (e.g. lower frequencies where a discharge line is longer, etc.).

[0070] In one embodiment, pumps may be adjusted individually or in subsets of the total number of pumps, and the selection of the individual pumps may be random or selected. In one example, out of 10 pumps on location, pumps **3** and **8** are selected. The selection of pumps **3** and **8** may be random, or in one example they are selected according to a high sensitivity to a fitness function (e.g. a small fluctuation in pumps **3** and **8** is observed to induce a large change in the fitness function). In one embodiment, the speeds of pumps **3** and **8** are swapped, keeping the same aggregate pumping rate, and the fitness function is determined. If the fitness function improves (e.g. harmonics are reduced at a position in the system), the swapped rates are kept; otherwise the old rates are restored. A next iteration of the algorithm utilizes the new rates as a baseline, and may test the same pumps, test different pumps, re-check some or all of the pumps for sensitivity to the fitness function, or perform other operations. The iterations of the control algorithm to improve the fitness function may be performed for a specified time, a specified number of iterations (e.g. hundreds, thousands, or more), until a threshold fitness function value is achieved, until an optimal fitness value is achieved (e.g. a specified number of iterations occur without improvement or with only improvement below a threshold value—although any convergence criteria understood in the art may be utilized), performed periodically (e.g. a number of iterations, a specified pause, and then repeated), and/or may be performed periodically throughout a pumping operation.

[0071] Alternatively or additionally, the control algorithm may be performed in response to a user input. For example, a number of pumps may be connected to a wellbore and a number of operations performed over a period of time. After each shutdown, the hardware configuration may be identical at startup, and the previously determined pumping rates or modulation values may be acceptable. However, a given operation may involve a change in the hardware (e.g. a pump is added, removed, swapped out, moved, etc.) or a change in the job design (e.g. a different pumping rate than a previous job) and an operator may activate the control algorithm to re-optimize the pumps. The control algorithm may also determine that a change has occurred (e.g. by determining a change in the fitness function value) and re-optimize the pump rates or pump modulation values automatically.

[0072] Yet another control algorithm includes selectively changing pump rates on adjacent pumpers to NOT match the pump rate of a reference pumper. For example, the control algorithm may be implemented as a rule that no alternate pumps may have same pump rates. The control algorithm may additionally search for optimal pump rates during a pumping operation, utilizing a feedback pressure signal or a piping vibration signal. Alternatively or additionally, the control algorithm includes avoiding an acoustic resonance in the piping by avoiding running the pumps at certain speeds.

[0073] In some circumstances, a lower pressure pulsation may be experienced if the pump rates are selected to avoid acoustic frequencies in the piping. However, acoustic frequencies in discharge piping are dependent on the rig up which changes from job to job. A diagnostic capability may be implemented at the start of the job to sweep one or more pumps in all the gears and use the pressure pulsation data to determine the resonance frequencies of the pumping system. This information may be used to alert the pump operator of these "hot spots" or automated in the pump controls software to avoid pump speeds that excite those resonant frequencies."

[0074] Embodiments may also include a feedback loop control that uses artificial intelligence to modulate the pump rates during a job to achieve a local minima of discharge pressure fluctuations or treating iron vibration.

[0075] Random walk of the pumps speed on the job may be combined with other search methods and artificial intelligence such as genetic algorithm (GA) to obtain the best possible combination of pumps speed to obtain least discharge line harmonics. Such a method may allow continuous searching for a better combination of pump speeds independent of job layout and pumped fluid properties. In a simple form, GA may have three operators—Selection, Crossover, and/or Mutation. A set of rules may be constructed to perform these operations on the pumps and measure the "fitness" of the new combination. For example, if out of 10 pumps on location, Pump **3** and **8** are selected either randomly or due to their high sensitivity to fitness function (which would be the discharge line harmonics), their speeds may be swapped to obtain a new combination without changing the overall pump rate. If the resulting combination reduces the harmonics, maintain such and perform next round of processing, otherwise discard this combination and restart with the last set. In such a system, an expectation is that the average fitness of the pumping system will improve over time, and so by repeating this process for tens of rounds, an optimal combination of pump speeds can be discovered that may help maintain low pressure fluctuations.

[0076] While the invention has been illustrated and described in detail in the drawings and foregoing description, the same is to be considered as illustrative and not restrictive in character, it being understood that only certain exemplary embodiments have been shown and described and that all changes and modifications that come within the spirit of the inventions are desired to be protected. In reading the claims, it is intended that when words such as "a," "an," "at least one," or "at least one portion" are used there is no intention to limit the claim to only one item unless specifically stated to the contrary in the claim. When the language "at least a portion" and/or "a portion" is used the item can include a portion and/or the entire item unless specifically stated to the contrary.

What is claimed is:

1. A method comprising:

operating a plurality of pumps fluidly coupled to a common fluid line;

modulating a pumping speed of at least one of the pumps to reduce an amplitude of a pressure fluctuation in the common fluid line, wherein the modulating comprises maintaining an average aggregate pumping rate of the plurality of pumps.

2. The method of claim **1**, wherein the modulating comprises a modulation behavior selected from the modulation behaviors consisting of:

inducing a random pump rate fluctuation into at least one of the pumps;

inducing a scheduled pump rate fluctuation into at least one of the pumps;

inducing a random pump rate fluctuation into each of the pumps;

inducing a scheduled pump rate fluctuation comprising a pump offset schedule into each of the pumps, and further ensuring that each of the pumps operates at a distinct position in the pump offset schedule; and

inducing a pseudo-random pump rate fluctuation into at least one of the pumps.

3. The method of claim **1**, wherein the modulating is based on a random seed value for at least one of the pumps, the random seed value comprising at least one of a pump startup time and a time of a last command for the pump.

4. The method of claim **1**, wherein the maintaining an average aggregate pumping rate of the plurality of pumps comprises modulating the at least one pump such that a specified pumped volume occurs within a specified time period.

5. The method of claim **1**, wherein reducing the amplitude of the pressure fluctuation in the common fluid line comprises an amplitude reduction operation selected from the amplitude reduction operations consisting of:

minimizing a maximum amplitude of pressure fluctuation for a range of frequencies of interest;

minimizing an aggregate area under pressure fluctuation pulses for a range of frequencies of interest;

ensuring that a maximum amplitude of pressure fluctuation for a range of frequencies of interest is below a specified energy threshold;

ensuring that an aggregate area under pressure fluctuation pulses for a range of frequencies of interest is below a specified energy threshold;

determining a beat frequency response between at least two of the pumps, and ensuring that:

a maximum amplitude of the beat frequency response is below a threshold and/or minimized; or an aggregate area of the beat frequency response is below a threshold and/or minimized.

6. The method of claim **1**, further comprising commanding at least two of the pumps to pump at a substantially similar nominal pump rate.

7. The method of claim **1**, further comprising operating at least one pump in all transmission gears and acquiring initial pressure pulsation data to determine resonance frequencies of the at least one pump.

8. The method of claim **7** wherein an operator utilizes the resonance frequencies determined in pump operation to avoid pump speeds which generate the resonant frequencies.

9. The method of claim **8** wherein the pump operation controlled by software.

10. A method comprising:

determining a first modulation definition comprising a plurality of modulation instructions, each modulation instruction corresponding to one of a plurality of pumps fluidly coupled to a common fluid line;

operating the pumps in response to the first modulation definition;

determining a pressure fluctuation profile and a first fitness function for the first modulation definition in response to the pressure fluctuation profile;

adjusting the first modulation definition to generate a second modulation definition;

operating the pumps in response to the second modulation definition;

determining the pressure fluctuation profile and a second fitness function for the second modulation definition in response to the pressure fluctuation profile; and

comparing the first fitness function and the second fitness function, and selecting one of the first modulation definition and the second modulation definition in response to the comparing.

11. The method of claim **10**, wherein the determining a first modulation definition comprises at least one operation selected from the operations consisting of:

determining a stored modulation definition;

selecting a default modulation definition;

determining a modulation definition in response to a pump specific parameter selected from at least one of a pump identifier, a pump start time, and a pump last command time;

utilizing a modulation definition from a previous selection of the first modulation definition and second modulation definition;

accepting a user input modulation definition;

determining the modulation definition in response to user inputs; and

scaling a preliminary modulation definition in response to a designed pumping rate.

12. The method of claim **10**, wherein the adjusting comprises performing at least one adjusting operation selected from the adjusting operations consisting of:

changing at least one of the modulation instructions, wherein the changing is random, pseudo-random, and/or scheduled;

testing at least one of the modulation instructions over a specified operating space; and

swapping at least a portion of one of the modulation instructions with another of the modulation instructions.

13. The method of claim **10**, further comprising determining a sensitivity of the fitness functions to at least one of the pumps.

14. The method of claim **13**, further comprising preferentially modifying the modulation instructions corresponding to a pump having a high sensitivity to the fitness functions.

15. The method of claim **10**, wherein determining the first fitness function comprises determining at least one of:

a maximum amplitude of a pressure fluctuation for a range of frequencies of interest;

an aggregate area under pressure fluctuation pulses for a range of frequencies of interest;

a maximum amplitude of a beat frequency response between at least two of the pumps; and

an aggregate area of a beat frequency response between at least two of the pumps.

16. A method comprising:

operating a plurality of pumps fluidly coupled to a common fluid line;

interpreting a pumping rate of each of the plurality of pumps; and

adjusting the pumping rate of the plurality of pumps such that:

a total pumping rate is maintained; and

no two adjacent pumps are pumping at the same rate.

17. The method of claim **16**, wherein the pumping rate comprises the rate of pressure pulse application from the pump to the common fluid line.

18. The method of claim **16**, wherein the adjusting the pumping rate of the plurality of pumps such that no two adjacent pumps are pumping at the same rate comprises adjusting the pumping rates according to at least one of:

ensuring that the pumps differ in volumetric rate by at least 0.1 bpm;

ensuring that the pumps differ in plunger strokes per minute by at least 2%.

19. The method of claim **16**, wherein adjacent pumps comprise any two pumps having a shortest relative fluid path through the common fluid line.

20. The method of claim **16**, further comprising operating at least one pump in all transmission gears and acquiring initial pressure pulsation data to determine resonance frequencies of the at least one pump.

* * * * *